universität wien

Diplomarbeit

Titel der Diplomarbeit

On the Counter-Intuitiveness of Quantum Entanglement

Verfasser

DI(FH) Reinhard Stanzl

angestrebter akademischer Grad

Magister der Philosophie (Mag.phil.)

Wien, im März 2012

Studienkennzahl lt. Studienblatt:	A 296
Studienrichtung lt. Studienblatt:	Philosophie
Betreuer:	Univ.-Prof. Dr. Martin Kusch

Contents

1 Introduction **7**

1.1 Setting 7

1.2 Goal 7

1.3 Method and Structure 8

1.3.1 Key Principles 8

1.3.2 Experiment 9

1.3.3 Interviews 10

1.3.4 Philosophy 11

2 Quantum Entanglement **13**

2.1 Einstein, Podolsky and Rosen 13

2.1.1 Thought Experiment 13

2.1.2 Measurement 14

2.1.3 Conclusion 15

2.2 Schrödinger’s Definition of Entanglement 15

2.2.1 Definition: Entanglement 16

2.2.2 Epistemological Groundwork 16

2.2.3 Measurement 17

2.2.4 Ψ-function, Catalogue of Expectations 18

2.2.5 Entanglement by Example 19

2.3 Interim Conclusion 1 20

2.4 Bell Inequalities and Experiments 22

2.5 Interim Conclusion 2 23

3 Quantum Opto-Mechanics **25**

3.1 Introduction 25

3.2 The Experiments 26

3.2.1 Fabry-Pèrot Cavity 27

3.2.2 Radiation Pressure 28

3.2.3 Cantilever 29
3.2.4 Putting it Together 30
3.2.5 Requirements for Success 31
3.2.6 Paradigmatic Model and Experimental Forks 32

4 The Aspelmeyer Group **35**
4.1 Research Topic and Genesis 35
4.2 My Relationship to the Group 36
4.3 Facts and Figures 36
4.4 The Interviewees 37
4.4.1 Dr. Witlef Wieczorek 37
4.4.2 Dilek Demir 38
4.4.3 Dr. Nikolai Kiesel 38
4.4.4 Mag. Florian Blaser 39
4.4.5 Dr. Garrett Cole 39
4.4.6 Jonas Hörsch 40
4.4.7 Prof. Dr. Markus Aspelmeyer 41
4.5 Issues Raised by the Interviews 41

5 Counter-Intuitiveness **43**
5.1 General Definition 43
5.2 Specifics 45
5.3 Characteristics 49
5.3.1 By Comparison 49
5.3.2 Notion 53

6 Coping **67**
6.1 Aim of Science? Coherent System of Assumptions 70
6.2 New Generations of Scientists 71
6.3 Bachelard: Reason Instructed by Fabricated Experience 73
6.3.1 Pedagogics 75
6.3.2 Technology 77

7 Conclusion **81**

Bibliography **87**

Appendices **93**

A Acknowledgment 95

B Group: Supplementary Notes 97

C Transcription of Interviews 99

D Resume 137

E Abstract 139

E.1 Abstract (English) 139

E.2 Abstract (German) 140

1 Introduction

1.1 Setting

Quantum mechanics is claimed to be a very successful theory in physics. However, there is a general debate that a deeper understanding of quantum mechanics might still be lacking.[1] A general tone of puzzlement, the complications in conveying the theory to the 'layman' and a subtle need for repeated re-assurance of the foundations of quantum mechanics in the light of newly discovered effects can be seen as indicators for such an explanatory deficiency of the theory. The feature of quantum mechanics which is at the core of this discussion is quantum entanglement. It is appropriate to consider quantum entanglement as the key effect of quantum mechanics. On the one hand because it is central to the debate about the uneasiness, or let us say counter-intuitiveness, of quantum mechanics in the past and present. On the other hand because it is the key resource of recent experimental and technological endeavors.

To me as a student of philosophy and physics, this is a unique and noteworthy situation in today's sciences. It is even more interesting because of the continuing experimental progress of the last few decades. The thought experiments which provoke counter-intuitiveness are, or are on the verge of, being realized by actual experiments. Additionally, this evolutionary process is being propelled by the prospect of yielding new, unprecedented technologies.

1.2 Goal

In order to make this attractive point in time accessible for debate, I will attempt to depict a plausible picture of the situation. Although limited in cogency due to the use of examples and samples to state the thesis[2], I intend to put forward a comprehensive notion of quan-

[1] See for instance *Bokulich and Jaegger 2010, p.1.*

[2] Especially due to the fact that I have picked one experimental system, interviewed only the people involved, and I am also being educated at the same Viennese physics institute, it is apt to claim simply local validity.

tum entanglement at the intersection of fundamental counter-intuitiveness and experimental production. Put differently, I will approach the notion of the counter-intuitiveness of entanglement by regarding those carrying out the experiments. Doing so will hopefully help to clarify what is meant by scientists expressing that “quantum mechanics runs counter to their/our intuition”, to point out which essential intuitions are involved in the actual experiments, and what can be revealed about the peculiarities of this counter-intuitiveness.

1.3 Method and Structure

The method, or the general tone in which this thesis is written, is a hybrid one. I intend to depict a stimulating picture of the current situation concerning the counter-intuitiveness of quantum entanglement by utilizing different types of approaches:

- Introduction of key principles of quantum mechanics using pivotal papers of the early years
- Description of a current experimental system which tackles the counter-intuitive fundamentals of quantum mechanics
- Exploration of interviews conducted with the people developing and operating this experimental system
- Scrutinizing the statements made in the interviews in the light of key concepts of Gaston Bachelard’s epistemology

1.3.1 Key Principles

In this introductory section I will put forward the very aspects of quantum entanglement, which challenge the let us say ‘classical’ intuitions. The theoretical grounds on which counter-intuitiveness can be pinpointed are depicted by highlighting the major fundamental differences between quantum and classical mechanics. This specifically concerns the different understandings of measurement, entanglement, state and property.[3] I will refer to the original papers of Albert Einstein et al. *(EPR 1935)* and Erwin Schrödinger *(Schrödinger 1935)*. On the one hand to appreciate the historicity of this topic, and on the other hand because these initial contributions are very clear-cut and still valid.

A more universal suitability of the thesis is nevertheless not excluded, but might need further support.

[3] Wave-particle duality will not be invoked due to its rather minor contribution to the understanding of quantum entanglement.

It is important to record that this thesis follows and rests upon a minimal mainstream Copenhagen-type interpretation. Other interpretations of quantum mechanics are not really considered here, but will be mentioned selectively. It is my conviction[4] that one reason why there are a multitude of equivalent interpretations around to date (e.g. variants of Bohm's mechanics, Many Worlds,...) is that each suffers from distinct points of counter-intuitiveness. These might differ in their specific content, but they are equal in their capacity to violate classical intuition. However, it is sensible to explicate the notion of counter-intuitiveness of quantum entanglement along the lines of the mainstream[5] interpretation. It will be the tacit background of this thesis. Distinct tenets which are necessary will be introduced separately if required for argumentation; for instance Schrödinger's account *(Schrödinger 1935)*.

1.3.2 Experiment

The entry point of the thesis is a current experiment, or rather an experimental system, which tries to realize opto-mechanical entanglement. This experimental system is operated by the group *Quantum Foundations and Quantum Information on the Nano- and Microscale* at the faculty of physics at the University of Vienna, headed by Prof. Dr. Markus Aspelmeyer.[6] Their main research objective "[...] is to investigate the quantum effects of nano- and microscale systems and their implications for the foundations and applications of quantum physics. [Their] goal is to gain access to a completely new parameter regime for experimental physics with respect to both size and complexity."*(Aspelmeyer Group 2011)*

This experimental system has been chosen because it incorporates the following features: Firstly, it establishes and studies quantum entanglement, which is the characteristic feature of quantum mechanics, at a size scale close to the 'classical' macroscopic world. Hence it questions anew the passage between quantum and classical mechanics.[7] Moreover, its ultimate success, i.e. the entanglement of optical and mechanical oscillation, which is close but has not yet been reached, is a rich soil for anticipating the outcome and contemplating the meaning of the possible results. Secondly, the experimental system poses the fundamental question about the validity limits of quantum mechanics, not explicitly stated by theory and

[4] Since I do not have the necessary insights into all interpretations of quantum mechanics, it is more of a profound belief. A comparison of the major interpretations with regard to their specific counter-intuitiveness would be preferable, but is not within the scope of this thesis.

[5] At least it is mainstream in the academic education I was schooled in and which I know of from other colleagues.

[6] Henceforth referred to as the 'group' or the 'Aspelmeyer group'.

[7] For instance, see Schrödinger's cat *(Schrödinger 1935, p.812,vol.48)*

hence eminently subject to experimental probing. Thirdly, it nicely illustrates the necessary mastery over technical challenges and limits in order to make the experiments even possible.

For all those general reasons I see this experimental set-up as a typical example for the current situation in experimental quantum mechanics. Of course, being an example it certainly has its particularities. However the idea is to elucidate the questions posed in this thesis by means of this example. A vital part of the thesis will thus consist of a non-mathematical introduction to this experimental set-up.

1.3.3 Interviews

At the heart of the thesis are the interviews conducted with members of the Aspelmeyer group. I carried out seven interviews at lengths of about 30 to 45 minutes. The interviewees were chosen to be a representative sample of all group members with respect to their academic status and their involvement in the various experiments being currently implemented by the group. I thus interviewed undergraduates, graduates, PhD students, post-doctorate research fellows and the group leader. The assortment of the interviews was not carried out beforehand, but developed during the course of the interviews as it became clear to me which people were of interest.

The interviews generally serve two purposes. First they are a viable way of efficiently approaching the group and getting a glimpse of the insights of their structure and their operating principles. This will become more apparent in section *4 The Aspelmeyer Group*. Secondly, the analysis of the notion of counter-intuitiveness of quantum entanglement will be backed by reference to the statements of those people who are responsible for the actual experimental implementation of the nano- and microscale quantum systems.

The interviews were conducted in a very straightforward and frank way, as everybody, including myself, but excepting the group leader, were novices to interviews. In addition, my level of training in quantum physics allowed me to resort to a common ground of knowledge with the interviewees and hence communicate on a par. There was also no strict adherence to a questionnaire. Nevertheless, I did prepare a list of questions, but they served rather as a crib sheet and as a crutch so as not to forget to tackle all of the following key issues:

- Age, education and motivation for engaging this area of research
- The hands-on assignment within the group and the actual experiment
- The interviewee's personal take on the relationship between interpretation, theory and experiment, especially in this specific case

- Their personal take on the matter of counter-intuitiveness and how to deal with it
- How does experimenting help in comprehending the subject matter

1.3.4 Philosophy

In order to elaborate the counter-intuitiveness of quantum entanglement in more philosophical detail, I will refer to key concepts devised by Gaston Bachelard. As a French physicist, philosopher and historian of science, active in the first half of the twentieth century, he advocated a rationalist constructivist epistemology. Long before Thomas Kuhn's historicism of science and his referral to revolutionary breaks in science, Bachelard became a representative of a French tradition of emphasizing the historical dimensions of science and its ruptures *(Nickles 2011)*. In *Le Nouvel Esprit Scientifique (Bachelard 1988)*, Bachelard argues for the presence of a shift in the conception of the world in physics, considering the new insights brought forth by, for instance, quantum physics. Classical perspectives in physics, as rational they may have been in their own time, appeared to him to have become an obstacle to progress in physics. Hence a new spirit of scientific rationale was established in that era. However, Bachelard's account of discontinuity is not as radical as Kuhn's. Bachelard speaks of progress and development towards the truth. He strongly stressed the fact that successor paradigms, such as non-Euclidean geometry or quantum physics, conserve their predecessors as special cases; particularly in their historical and as a consequence in their pedagogical context. In this regard Bachelard developed an intelligible framework for describing scientific thinking and its change at the beginning of the twentieth century. I consider some of his concepts to be very fitting for studying the situation of the counter-intuitiveness of quantum entanglement.

First, as a physicist his ideas have a natural proximity to the subject matter. Reading about the pivotal physical examples for a new scientific spirit, such as the rise of quantum physics, conveys the feeling especially with someone literate in physics that he certainly captured the relevant aspects in a comprehensible way. Although Bachelard does not specifically refer to quantum entanglement, his practical ideas of how to make conceptualization intelligible in this context are very helpful and hence will be deployed in this thesis. In concrete terms, I will make use of Bachelard's idea of the epistemological profile, and to some extend his *Philosophy of the No (Bachelard 1980)*. The former will be applied to quantum entanglement in order to show and specify, at the locus of the very notion, the difference between 'normal' physical terms and quantum entanglement.[8] The latter will then be used to further

[8] See section *5.3.2 Notion*

stress the point by applying the basic idea of Bachelard's *Philosophy of the No* to quantum entanglement. In general, the idea is that every comprehension of a (physical) matter is the sum of justified criticism to (i.e. saying no to) a specific, initial and naive picture of understanding.[9] I will show that such an initial, naive picture is far from being intuitive in the case of quantum entanglement.

The second aspect which makes Bachelard a unique source for the tools used to study the counter-intuitiveness of quantum entanglement is his type of rationalism. As a consequence of the analysis of the new scientific mind, Bachelard advocates the idea that it is best described by a rationalism whose reason is instructed by fabricated experience. I definitely agree with such an understanding of what happens in physical experimental science even today. This becomes apparent when seen in the light of the experiment(s) put forward in this thesis, especially their dependence on technology and how a phenomenon like quantum entanglement is actually fabricated.[10]

As a third concept I will also briefly refer to Bachelard's historicity of science. Specifically I will pick up the idea that the historical genesis of the comprehension of a matter is also reflected in the pedagogics of the matter. For instance, although Euclidean geometry is only a special case of non-Euclidean geometry, in teaching we follow the historical order – which is also a philosophical order – from the naive realistic to the growing rationalist understanding. Hence for Bachelard, pedagogics connects the historical with the conceptual aspects. This approach will be the background for cues given at the end of the thesis when asking if and how we should cope with the counter-intuitiveness of quantum entanglement.

Certainly many other philosophers of science have dealt with each of these three aspects as well; probably in even more detail and depth. The point of restricting this thesis to Bachelard is generally due to the way these philosophical concepts are applied. My intention is not to compare different philosophical approaches in the light of a case study, namely quantum opto-mechanics. The idea is to utilize a generally fitting and intelligible set of philosophical concepts to depict the situation of the counter-intuitiveness of a physical concept, say quantum entanglement, represented by the case study. Bachelard's thoughts make it possible on the one hand to comprehensibly present the subject matter, but on the other hand also to raise further questions pointing beyond this thesis. As an early representative of the philosophy and history of science, Bachelard's epistemology anticipates many aspects fleshed out by his successors and hence sustains enough topicality to be of relevance for the questions at hand.

[9] See section *5.3.2 Philosophy of the No*
[10] See section *6.3 Bachelard: Reason Instructed by Fabricated Experience*

2 Quantum Entanglement

2.1 Einstein, Podolsky and Rosen

In order to introduce the basis of counter-intuitiveness in quantum mechanics and especially that of quantum entanglement, I will roughly retrace the influential key papers of the historical developments in this field. The starting point is the paper by Einstein, Podolsky and Rosen (EPR) *(EPR 1935)*. By devising a specific thought experiment the authors of the EPR paper intended to show that the quantum mechanical description of physical reality is incomplete. That is to say that not every element of the physical reality has a counterpart in the theory of quantum mechanics. The inability of quantum mechanics to predict the measurement result of a physical quantity with certainty[1] is, according to Einstein et al., due to the insufficiency of quantum mechanics to consider all relevant variables necessary to predict a measurement result with certainty. Therefore it is apt to assume a yet unknown hidden variable, which if found and taken into account would yield certain measurement results instead of the statistical ones put forward by quantum mechanics. Theories following this line of thought are called hidden variable theories (HVT).

2.1.1 Thought Experiment

The very core of the EPR paper is a thought experiment which can be paradigmatically explicated as follows:[2]

For a start we will consider a source which produces two objects, e.g. particles. One is sent to site A, which is commonly called Alice, and the other one to site B, referred to as Bob. Alice and Bob are very far apart; space and time separated. This means that whatever is done, for instance at Alice, has no immediate influence on what happens at Bob, because the fastest possible speed with which an influence could travel from one side to the other is

[1] See section *2.2 Schrödinger's Definition of Entanglement* for details.
[2] For more details see *(Mermin 1985)*

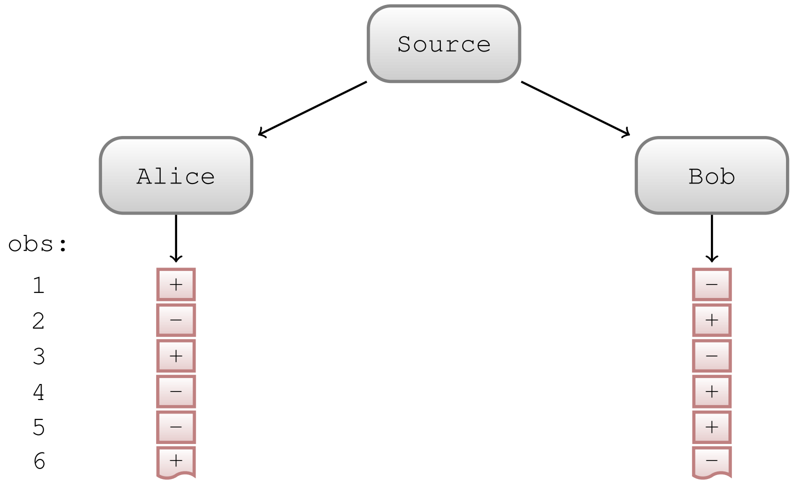

Figure 2.1: Paradigmatic EPR experiment

the speed of light[3]. Spacing Alice and Bob so far apart makes it possible to conclude that measurements conducted at Alice can in no way influence the results of measurements at Bob, if both measurements are finished in faster succession than light could travel between the two sites. This assumption of the EPR paper is generally called the locality assumption.

The second assumption is about the physical reality of properties. "If without in any way disturbing a system, we can predict with certainty (i.e. with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."*(EPR 1935, p.777)* In other words, if we are able to predict with certainty the result of a non-disturbed measurement, it is fitting to say that the specific measured quantity existed prior to the measurement.[4]

2.1.2 Measurement

Our next step is to conduct a series of measurements. Each new run is a sequence of simultaneously[5] measuring the physical quantity of the objects produced at the source and sent to Alice and Bob anew. For reasons of simplification the physical quantity measured in our example can only result in $+$ or $-$. At the end we will have obtained two lists, one of Alice's measurement results and one of Bob's; see figure 2.1. Comparing the results of the two lists, we apparently recognize that in this example there is a strong anti-correlation between the measurement results of Alice and those of Bob. At the first measurement (obs:

[3] See Einstein's Special Relativity Theory (SRT).
[4] See section *2.2 Schrödinger's Definition of Entanglement* for the differences to quantum mechanics.
[5] In order to maintain locality.

1) Alice received a + and Bob a −. Analyzing the entire lists, the modest conclusion which can be drawn is that whatever we measure at one site, the other site will have the opposite result. Due to the assumption of locality, it is impossible that the measurement result known at one site was somehow sent to the other site and manipulated the measurement there in such a way as to always show the opposite of the result of the other site. Hence, according to Einstein et al., the only possibility why we measure such an anti-correlation between the sites, which are so far apart, is that the physical quantity measured was already given with certainty at the source of the object prior to the measurement (see reality assumption). Therefore a physical process in the source – which brings about the distinct anti-correlation of the measurement results in each particular case – must be taken for granted.

2.1.3 Conclusion

The core of the matter is that quantum mechanics[6], as we will see very soon, describes the situation and its results, portrayed above, necessarily without the need for a process located in the source pre-determining the distinct physical quantities. This circumstance is primarily owing to its divergent understanding of measurement. From the standpoint of Einstein et al., this is exactly why the theory of quantum mechanics is deficient and incomplete. For the sake of having a complete theory, "every element of the physical reality must have a counterpart in the physical theory."*(EPR 1935, p.777)* Quantum mechanics lacks a theoretical representation of the real (i.e. which serves the reality assumption) physical process in the source determining the physical quantities with certainty, which is commonly paraphrased as the absence of, or the need for, a *hidden variable*.

How the thought experiment *(EPR 1935)* is seen from the point of view of quantum mechanics and its key to a solution, namely entanglement, will be put forward in the light of Schrödinger's famous paper *(Schrödinger 1935)*.

2.2 Schrödinger's Definition of Entanglement

The first person to coin the notion of quantum entanglement was Erwin Schrödinger in his 1935 article *Die gegenwärtige Situation in der Quantenmechanik* in the journal *Die Naturwissenschaften (Schrödinger 1935)*. It was a response, or as Schrödinger called it in a footnote, a confession, to the other famous article of that year *(EPR 1935)*. The approach of un-

[6] Be reminded that Schrödinger's depiction of quantum mechanics is the point of view here.

derstanding quantum mechanics, and especially entanglement, put together by Schrödinger can still be considered influential for the current, orthodox[7] comprehension of quantum mechanics. Therefore it is beneficial to provide a compact rundown of Schrödinger's reasoning in this paper. I will start by picking out the definition of entanglement and then clarify which presuppositions are implied.

2.2.1 Definition: Entanglement

> "*Maximale Kenntnis von einem Gesamtsystem schließt nicht notwendig maximale Kenntnis aller seiner Teile ein, auch dann nicht, wenn dieselben völlig voneinander abgetrennt sind und einander zur Zeit gar nicht beeinflussen.*"
>
> – *Schrödinger 1935, p.826, vol.49*

> "*Maximal knowledge of a total system does not necessarily include total knowledge of all its parts, not even when these are fully separated from each other and at the moment are not influencing each other at all.*"
>
> – Schrödinger[8]

2.2.2 Epistemological Groundwork

For Schrödinger, understanding the behavior of a *natural object* entails experimental data and some intuitive imagination, say an own image, idea or conception, which can be much more detailed than any possible experience. It is comparable to a mathematical structure or a geometric figure. For example, we have a notion of a triangle which can be fully calculated and determined by only knowing some of the possible determining parts. One side of the triangle and its two adjoining angles are enough – given the precise concept of a triangle – to determine all the other possible parameters of the triangle, such as the length of the two other sides, the third angle, the radius of the inscribed circle and so on.

Considering that *natural objects* are not geometrical figures, it is advisable not to carry this analogy too far. That is to say *natural objects* change with time, so knowing the determining parts and having a proper idea of the object's behavior in time allows us to calculate

[7] Throughout this thesis a minimalist version – meaning in terms of metaphysical statements necessary for referencing the mathematics with the experimental phenomena – of the Copenhagen interpretation of quantum mechanics is considered orthodox or mainstream.

[8] Translation by John D. Trimmer, published in *Proceedings of the American Philosophical Society*, 124, 323-38. [And then appeared as Section I.11 of Part I of Quantum Theory and Measurement (J.A. Wheeler and W.H. Zurek, eds., Princeton University Press, New Jersey 1983).]

each future state of the object. In addition, despite having an exact model in the realms of geometrical figures, we ought to take notions, ideas or models of the real world more as hypotheses. As in the case of hypotheses, we do not circumvent the arbitrariness inherent in every notion, but it can be isolated in the presuppositions and from a calculus. The classical method of a precise model aims to improve on isolating the inevitable arbitrariness in its suppositions by adapting it to the continuing experiences gathered (via experiments).

In summary, for Schrödinger, a model of a *natural object* is the image or idea and contains, for example, certain laws or relations. Each model has variables, e.g. coordinates, mass or speed, which can be observed, or rather measured, and hence are called observables. A state is the concrete realization, i.e. an instance, of the model with definite values of its observables.

2.2.3 Measurement

In a classical, naive realistic view, every observable has a specific value at all times. It might change over time, but by looking at it at one moment, i.e. at a certain state, it is fixed. Here the measurement just reads out the value of the examined observable. The inability to measure an exact value, or better put, to measure within some margin of error, is due to the imperfection of the measurement process. This naive realistic understanding of measurement presupposes the pre-existence of a value of an observable prior to its measurement. As we have already seen, this is the understanding Einstein clinged to and hence concluded that quantum mechanics was not complete in its description of physical reality.[9]

A totally different notion of measurement is the quantum mechanical one. It does not assume a pre-existing value, but considers that *'only what is measured is real'* and refuses any claim to knowledge prior to the measurement. With this notion of measurement it is possible that the observable is not necessarily pre-determined, but has a certain probability of delivering this or that value in the cause of a certain measurement. Hence this understanding and the relevant calculus can tell to which degree of prediction accuracy a measurement is feasible. In contrast to the classical view, where imperfections in determining the exact value are due to the imperfections of the measurement, the fundamental probability of obtaining a certain value remains, even given that the measurement is perfect. Schrödinger expresses this difference with an illuminating analogy. "Es ist ein Unterschied zwischen einer verwackelten oder unscharf eingestellten Photographie und einer Aufnahme von Wolken und Nebelschwaden." *(Schrödinger 1935, p.812, vol.48)* "There is a difference between a shaky or out-of-focus

[9] See section *2.1 Einstein, Podolsky and Rosen*.

photograph and a snapshot of clouds and fog banks."

As a consequence of rejecting naive realism, it is correct to presume that an observable in general has no specific value prior to its measurement. Bluntly put, since reality does not determine the measurement result, the measurement has to determine reality *(Schrödinger 1935, p.824, vol.49)*. This implies that by means of the measurement, the observable becomes the resulting value. Repeating the measurement will result in the same value; of course within error margins. In a strict sense there is no difference between the naive realistic and the quantum mechanical view; both fulfill the criteria of returning the same measurement result on repetition of the measurement. What type of repetition? So far, repeating the measurement is understood as just resetting the measurement device and making a new measurement. Sticking to the naive realistic view there is no difference if, in addition to resetting the measurement apparatus, the measured object is also set back to its initial state. Classically, a measurement is not supposed to change a pre-exiting value in the course of the measurement (non-interfering measurement) and hence the measured value of the object is no different whether it is the result of the first measurement or a later one. However, according to the quantum mechanical view there is a uniqueness to the first measurement of a system. As the measurement determines the previously unknown, or to be more precise undetermined, value of the observable, there is no interaction-free measurement and every measurement of the same object which follows the first one only replicates the result of this first determining measurement. Consequently, in order to acquire information on how the measured object and the measurement apparatus interact and which distribution of observable values one receives, it is necessary to repeat a series of 'first' measurements. This means that after each measurement everything (measurement apparatus and measured object) has to be reset to, or to put it more suitably, re-prepared in its initial state. The result of such a sequence of *ab ovo* measurements is a statistical distribution of the values of the measured observable resulting from the interaction between the specific state the measured object is in and the measurement process/apparatus.

2.2.4 Ψ-function, Catalogue of Expectations

The instrument of describing and predicting the probability of these measurement results is the Ψ-function. It completely represents the system and can been seen as a catalogue of expectations. From a classical point of view the Ψ-function seems to be incomplete[10], because it does not determine which specific value will be the result of the measurement,

[10] See section *2.1 Einstein, Podolsky and Rosen*

but merely provides the probability of measuring a specific value. However, a specific Ψ-function always has to be considered complete from the perspective of quantum mechanics. This holds true because in quantum mechanics adding a proclaimed unknown observable or hidden variable to the Ψ-function changes it completely. Different Ψ-functions express that the system in in different states, while complementary, identical Ψ-functions express that the systems are in the same state.

2.2.5 Entanglement by Example

For example, let us assume we have two separated, non-interacting objects, which thus have different Ψ-functions. Now we make them interact and become one system in one state. In the classical view we would sum up the properties (specific values of the observables), alter them by some proper laws of interaction and have a set of properties for the new combined system. Separating the two objects once more would result in two objects with again two independent sets of properties. Of course they would not have the same values as before, due to the interaction with each other, but now after the separation they are no longer interdependent. This is the understanding of Einstein et al. of the physical process in the source of the EPR experiment (see figure 2.1).

From the quantum mechanical point of view, we do not have any pre-measurement values, but probability distributions. Making the two objects interact results in a new Ψ-function for the total system. As an Ψ-function does not predefine any specific values, there is the possibility that due to the interaction of the two objects, the total Ψ-function is comprised of more than the sum of the two separate ones. To be even more accurate: It is appropriate to say that if two systems interact with each other, the Ψ-functions do not interact, but they cease to exist individually and only one for the total system remains *(Schrödinger 1935, p.848, vol.50)*. This even holds true after the two objects have been separated again. Schrödinger dubbed this phenomenon *entanglement*.

The following simple example demonstrates this quantum mechanical interrelation between the two systems after interacting *(Schrödinger 1935, p.845, vol.50):*

$$q = Q \qquad and \qquad p = -P \tag{2.1}$$

This set of equations stands for: If the measurement of the observable q of the first system returns a certain value, a measurement of the observable Q of the second system results in the same value. And the result of a measurement of p in the first system will have the same result as a measurement of P in the second system, but with opposing sign and vice versa.

The measurement of either p or P or q or Q dissolves the entanglement, because as illustrated above in the section about the quantum mechanical understanding of measurement, measuring determines a specific value and every further measurement yields the same result. Knowing one value renders the entanglement relation useless. If we want to experimentally test whether this entanglement relation is a good model, we need to make many repetitions of *ab ovo* measurements. The results, whatever the actual values are, will show that there is this kind of entanglement relation (see equations 2.1) between those two systems. The reliability of this test depends on the amount of repetitions of *ab ovo* measurements made; the more there are, the more probable is the conclusion of having an entanglement drawn from the measurements.

What would be the picture if we remained within the classical naive realistic view? It is also possible to have a correlation between the two systems after separation as illustrated above. However, the values exist prior to their measurement. Hence in order to explain the specific sequence of, in this point of view, certain results of *ab ovo* measurements, we have to suppose there is a process controlling this, namely a 'hidden variable'.

2.3 Interim Conclusion 1

The thought experiment of the Einstein et al. paper *(EPR 1935)* links the following three fundamental statements about physics in such way that in order to avoid contradiction not all of them can be held to be true. Thus at least one of them must be rendered false.

Completeness: Quantum mechanics is a complete theory. According to the EPR paper this means in a strict sense that every element of physical reality has its counterpart in this physical theory.

Reality: If we can predict with certainty the result of a measurement of a physical quantity without disturbing the measured system, then there is an element of physical reality corresponding to this physical quantity.

Locality: Results of a measurement at one site do not influence the measurement result in distant (space and time separated) sites by any dynamical mechanism faster than the speed of light.

For Einstein et al. the reality and the locality assumption are matters of the very foundations of physics and are certainly nothing to be abandoned lightly. Therefore they concluded that quantum mechanics does not exhaustively describe physical reality, and opted for the existence of a hidden variable.

The thought experiment and its showcase of the three contradicting statements is completely differently resolved according to Schrödinger's view of quantum mechanics. As we have seen, Schrödinger supports a different understanding of measurement and thereby undermines the classical assumption of reality of the EPR paper. Moreover, and that is the key, by taking the essential principles of quantum mechanics seriously, he ends up with *quantum entanglement*. This very notion allows quantum mechanics to give a complete description of the physical situation of the EPR thought experiment, but at the cost of subverting the reality assumption and/or the locality assumption. It is not done by blatant opposition, calling the statements at stake simply false, but by rendering these assumptions irrelevant and pointless.

An important thing to note is that this dismissal of the classical reality and/or the locality assumption was not seen as automatically applying to the entirety of physics. In the early days, quantum mechanics was seen as a theory of very small size scales: atoms, particles, and so on. This fact can already be found in the very same paper by Schrödinger. There, besides developing the notion of entanglement, he emphasized the weirdness of applying these fundamentals of quantum mechanics to human scale objects by means of his famous Schrödinger's cat experiment *(Schrödinger 1935, p.812, vol.48).*

In summary, we have examined two different understandings of how to interpret the EPR thought experiment and what conclusions to draw from it. The Einstein et al. and the Schrödinger perspectives rationally argue in favor of clinging on to fundamental assumptions which they want to preserve at the price of having to dismiss others. Both are equal in their power to explain the EPR thought experiment. At the time of the emergence of these two views there was no instance, preferably experimental evidence, that could decide which understanding was the correct one. Therefore this rather metaphysical question tended to be treated hypothetically and thus did not have the publicity and the verve which we perceive it to have nowadays.[11] The actual reason why the EPR thought experiment and the questions connected with it gained relevance in the 1970s was the development of a testing scheme (inequality) by John Stewart Bell *(Bell 1964)*. In this way an instance was found that could experimentally decide which one of the two perspectives is correct.

[11] "[...] (EPR) paper had 36 citations before 1980 and 456 more through June 2003." *(Redner 2005, p.3)*

2.4 Bell Inequalities and Experiments

The question developed up to now is whether it is possible to understand quantum mechanics in terms of a hidden variable, thus being a local realistic theory, or not. Despite an early, and to some extent deficient, attempt by von Neumann to prove that it is mathematically impossible to have such a *hidden variable* in quantum mechanics, it was John Stewart Bell who devised an inequality to test this question (*Bell 1964*; *Compendium 2009*, *p.24f*). Every local realist theory strictly complies with this inequality and quantum mechanics, on the contrary, violates the inequality. Conducting an experiment which tests the inequality (Bell experiment) can show that the predictions of quantum mechanics are accurate because the inequality is breached and hence there is experimental affirmation that quantum mechanics cannot be understood in terms of a local realistic theory. In consequence either the locality or the reality assumption, or maybe even both, have to be dismissed or considered pointless.

In 1981 Aspect et al. *(Compendium 2009, p.14f)* carried out much-noticed experiments resulting in a violation of the CHSH inequality[12] and thereby confirmed that quantum mechanics is the case. Again, in principle any local realistic theory satisfies the inequality. The experiments show that the inequality is breached. Therefore any local realistic theory is incapable to account for the experimental results. Whereas quantum mechanics handles them very well. Since these first experiments of the CHSH inequality conducted by Aspect et al. in the early eighties, there have been many different types of experiments carried out affirming the violation of the inequality. (*Gröblacher* et al. *2007*; *Rowe* et al. *2001*; *Scheidl 2009*; *Weihs* et al. *1998*, to name just a few.)

Nonetheless, owing to actual limitations of the experimental capabilities of today, there are still three types of possibilities to explain the results of these Bell experiments by holding on to local realistic approaches. These categories of loopholes are called *Fair Sampling/Efficiency*, *Freedom of Choice* and *Locality* *(Compendium 2009, p.348f)*. Each of these loopholes have been closed individually, and also two of them at once *(Quantum 2007; Scheidl 2009)*. There has been no *experimentum crucis* excluding all of the loopholes. However, the better and more prudent the experiments are set up, the more complicated and the more devious it becomes to sustain an explanation of these loopholes in terms of a hidden variable theory.

[12] A derivation of the Bell inequality *(Compendium 2009, p.24f)*

2.5 Interim Conclusion 2

Again, the thought experiment of the EPR paper devises a relation of three fundamental statements of physics which renders at least one of them mutually exclusive to the others. Consequently either quantum mechanics is incomplete, measured quantities are not distinct prior to their measurement, or there is something like a superluminal way of interaction. Einstein et al. insisted on the priority of the last two and therefore held quantum mechanics to be incomplete. Quantum mechanics, however, here according to the description of Schrödinger, defines itself very well as complete and consequently rejects the naive understanding of reality and somehow also locality.

Both points of view refer to the same observable phenomena, i.e. *results* of the thought experiment. Up until Bell there was no factual experimental criterion to opt for one or the other. He conceived a criterion to distinguish between the predictions of local realistic theories and quantum mechanics (Bell inequality). This made it feasible to conduct experiments, and there have been many of them[13] which have certified[14] that quantum mechanics is complete, as it is able to describe every element of the physical world. The very mechanism, or better say the notion, which derives from the fundamentals of quantum mechanics[15] and fully allows us to describe the relevant phenomena, is called *quantum entanglement*.

[13] A very good indicator for the profoundness of the implementation of Bell experiments, at least for me, is the existence of set-ups for laboratory training of physics students.

[14] Of course the loopholes still have to be kept in mind.

[15] See section *2.2 Schrödinger's Definition of Entanglement*.

3 Quantum Opto-Mechanics

3.1 Introduction

A current field of quantum physics which will serve as a showcase and is very illustrative in terms of counter-intuitiveness, is quantum opto-mechanics. In order to give a swift insight into this area, I will start out with a common narrative about the origin or genesis of this area of research. It is a short, mostly causal, explanation of why scientists became engaged in this special topic and why "the surf is up"; citing the title of a paper *(Aspelmeyer 2010)* summarizing the spirit of optimism at a conference in July 2009. Although many papers in this blossoming field are comprised of similar introductory sections, I will only refer to one *(Vitali* et al. *2007)*.

With reference to Schrödinger, the first to coin the term, entanglement is "the characteristic trait of quantum mechanics", and hence the key to the insights of the fundamentals of quantum physics – indeed of the physical reality – and a resource for the field of quantum information processing (e.g. quantum cryptography, teleportation, computing ...). Quantum mechanics and consequently entanglement have been situated in the realm of the very small, and extrapolations to the human scale have resulted in odd peculiarities; see Schrödinger's cat *(Schrödinger 1935, p.812, vol.48)*. Up until now experimental expertise and craftsmanship in quantum physics was limited to the preparation, manipulation and measurement of photons, ions, atoms and at best some molecules *(Gerlich* et al. *2011)*.

However, in principle quantum mechanics does not pose any limitations to the scale of the systems to be entangled. Thus, in order to learn more about the fundamentals of quantum mechanics – plainly put, the passage between classical physics and quantum physics –, it seems straight-forward to face the challenges of producing entanglement with increasingly larger macroscopic systems and to test whether one stumbles across any fundamental impassibility apart from technical ones. Of course there is a large range of systems in physics which can be considered macroscopic. Some of them are experimentally workable with current and near future technologies, including and without further explanation or reference, single-particle interference of macro-molecules, entanglement between collective spins of atomic ensembles, or entanglement in Josephson-junction qubits. Nevertheless, the iconic prototype of a 'classical' system in physics is the mechanical oscillator, such as a pendulum or a mass on a spring.

Thanks to the huge advancements in microfabrication[1] in recent years, it became feasible to produce micro- and nano-mechanical oscillators with very high precision. How can these small mechanical systems be controlled, i.e. prepared and measured? One obvious approach is to utilize a resource which seems to be well-known[2] and well suited for the quantum realm; photons. Combining these two domains, i.e. setting the mechanical system in motion through the radiation pressure of the light and also measuring its movement by light, brings about a paradigmatic experiment in the field of opto-mechanics. If it is the goal to attain quantum effects with such a set-up, as is the case here, it is apt to call it quantum opto-mechanics. On a theoretical level, several proposals which were written years before their technical realization was possible describe what has to be done and which parameters have to be met in order to achieve entanglement for such 'massive' systems.

However, a demonstration of quantum effects like entanglement using mechanical oscillators has not been carried out so far. The roadblocks in the way of accomplishing the goal mostly consist of the necessary technology and its stable deployment. Therefore it is fair to say that opto-mechanics is currently in the position of a fast-developing field which is on the verge of meeting its target. It has rich prospects in terms of applying and furthering the knowledge and skills gathered in its development. Reaching the quantum regime, i.e. see effects specific to quantum mechanics, with macroscopic systems, especially 'classically' mechanical ones, could not only trigger insights into the fundamentals of quantum mechanics, but also improvements and applications in areas like high precision measurement, quantum computation and storage, and many more not even conceivable to date.

3.2 The Experiments

The following experimental set-up which is being developed by the Aspelmeyer group conforms with the very picture of a 'classical' mechanical oscillator and nicely fits in with the motives about quantum opto-mechanics presented above. It can be seen as the initial or

[1] MEMS or NEMS, as it is often abbreviated, describes electromechanical structures in the scale of micro- or nanometers. The field originated from microelectronics and inherited many of its production toolsets, such as lithography, etching, doping and so on.

[2] The Viennese quantum community has established quite some expertise in setting up experiments which use photons as means for showing quantum effects *(Quantum 2011b)*.

paradigmatic experiment. Most of the other experiments currently conducted by the group are a deduction and advancement thereof.

The general goal of the experiment is to produce quantum entanglement between an optical system, i.e. a stream of photons, and the oscillation of a suspended microscopic mirror pushed by the radiation pressure of these photons *(Vitali et al. 2007)*.

3.2.1 Fabry-Pèrot Cavity

For a starting point it is beneficial to explain what a Fabry-Pèrot cavity is and does. Developed in 1897 it consists of two parallel semitransparent mirrors at a specific distance. Light with a given frequency introduced at one side of the set-up enters the cavity via the first mirror, gets partially reflected by the second mirror and thus returns back to the first mirror, gets partially reflected there, returns again to the second mirror and so forth. Hence most of the light is reflected back and forth within the cavity. However, the mirrors are only partially reflective so some of the light leaves the cavity through the second mirror, i.e. gets transmitted through the cavity. The interesting measurement parameters of this cavity are the intensity of the transmitted light and the phase shift between the light sent into the cavity and the light leaving the cavity.

Inside the cavity the light waves reflecting back and forth interfere with each other. Depending on the length of the cavity, i.e. the distance between the two mirrors, there is either a constructive interference and consequently a high intensity of the transmitted light or a destructive interference which nearly annihilates the transmitted light at the output (see figure 3.1).

In other words, the intensity of the transmitted light is very sensitive to the length of the cavity. If the length of the cavity is tuned to constructive interference between the injected light and the reflected light, the transmitted light is of high intensity. However, detuning the length of the cavity by a very small amount destroys the constructive interference rapidly. The tiny shift in the light waves reflecting within the cavity add up to destructive interferences due to the many reflections taking place and each contributing to the growing shift between the injected light and the reflected light in the cavity.

This makes the Fabry-Pèrot cavity a simple, but trusted tool for measuring lengths, refractive indices of matter, gravity waves[3], spectroscopy and so on.

[3] E.g. the Laser Interferometer Gravitational-Wave Observatory *(LIGO 2011)*

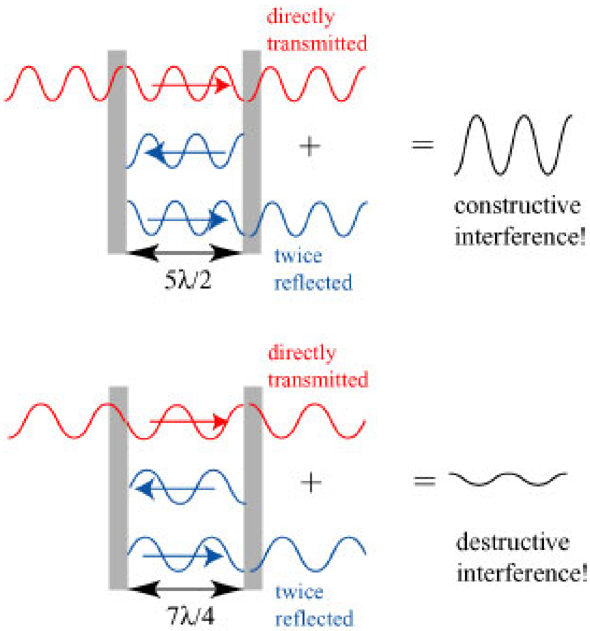

Figure 3.1: Interference within the Fabry-Pèrot cavity. Source: *SkullsInTheStars 2008*

3.2.2 Radiation Pressure

As early as 1871, James Clerk Maxwell theoretically concluded that electromagnetic radiation exerts pressure on the exposed surface. This phenomenon was effectively demonstrated by experiments in the early years of the twentieth century *(Lebedew 1901; Nichols and Hull 1903)*. However, radiation applies a very weak force on the lighted object, and hence it is rather hard to detect. In order to reach the domain in which the radiation pressure is detectable, the mass of the lighted object has to be very small and its surface very reflective. In a simple, classical picture this can be depicted as a stream of photons, meaning light, hitting the surface like particles with a certain impetus. The impetus of a photon hitting an object is fully transferred to the object only when the photon is reflected and not absorbed. On a larger scale, the effect of radiation pressure has been shown by the Japanese Aerospace Exploration Agency[4]. In May 2010 they deployed a spacecraft which as one of its impellents unfolded a large, thin kite which allowed it to sail with the radiation of the sun (solar wind); similarly to a kite surfer on earth using the wind for propulsion.

[4] See *(JAXA 2011)*

3.2.3 Cantilever

In physics a cantilever is a beam supported only at one end. A simple example for a cantilever is a diving board. Pushed by a momentary force, it oscillates with its resonant frequency. The oscillation diminishes at a certain rate due to external resistances like air drag, but also because of its suspension. A cantilever is a mechanical oscillator, like a pendulum or a spring.

In order to perform experiments which couple quantum optics with macroscopic mechanical oscillators, it is necessary for the cantilever to meet certain criteria:

- The optical quality of the mirror at the tip of the cantilever has to be very high; i.e. it has to be very reflective. Over 99.99% of the photons hitting the mirror have to be reflected and not absorbed. In addition, the light beam hitting the mirror can only be focused to a certain degree, hence the size of the mirror has to be practically somewhat larger than several micrometers (μm) in diameter.
- Each cantilever has a specific oscillation frequency which depends on its size, its form, the material it is made of and its suspension. There are thus many parameters which have to be tuned in order to fabricate a cantilever in the desired frequency range. In this experimental set-up an oscillation frequency of several megahertz is typical.
- The mass of the cantilever is also essential as it determines the amount of coupling between the light and the cantilever. The smaller the mass of the cantilever, the more the radiation pressure of the light is able to deflect it. Hence small changes in the intensity of the light lead to a strong deflection of the cantilever, and it becomes apt to call them well coupled. For those reasons it is crucial to minimize the mass of the cantilever, but of course only in respect of the other constraints already mentioned. A typical mass of the cantilevers used is 50 nanograms (ng).

As a consequence of this manifold of essential parameters to be adjusted, it is vital to have as much control as possible over the process of designing and fabricating the cantilevers. The person who has the skills, expertise and practical know-how to handle this task for the group, put also for other groups, is Garrett Cole.[5] With a background in material science and engineering, unlike the rest of the group, he manages the production of the cantilevers. Another group member who has developed knowledge and skills about the fabrication of the cantilevers is Simon Gröblacher. He started to acquire experience in this area during the course of his dissertation *(Gröblacher 2010)*, which is about the very experiment presented

[5] His interview statements are notable due to his specific assignment, educational background and his unique access to quantum opto-mechanics.

here. However, because Gröblacher took on a post doctoral position at Cornell University and Cole has already been carrying out microfabrication since the turn of the millennium, it is apt to say that Cole is the focal figure concerning the production of the cantilevers for the experiments.

The actual process of fabrication requires methods well known from computer chip production and nano technology like lithography, evaporation and etching. Examples of the cantilevers deployed can be found in figure 3.2.

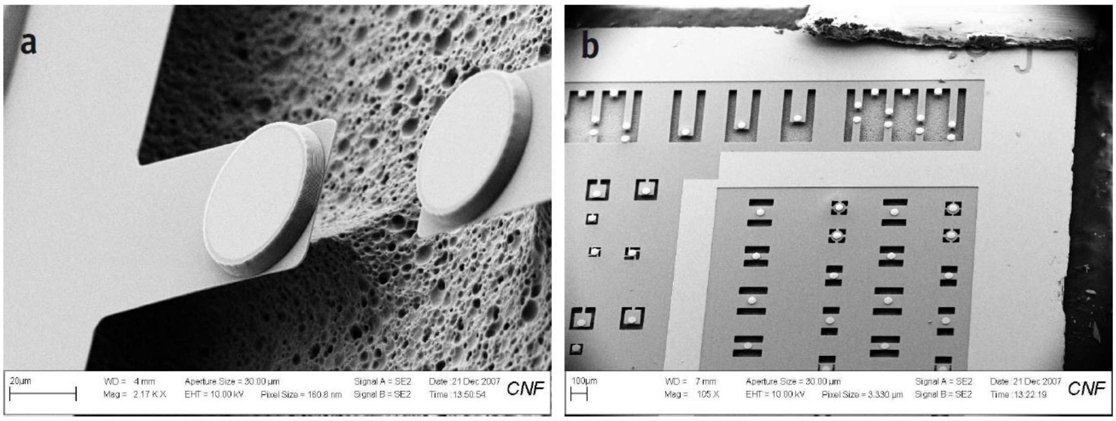

Figure 3.2: **a:** Scanning electron microscope (SEM) image of a pair of cantilevers ($\varnothing_{mirror} = 20\mu m$).
b: chip with mechanical resonators of different sizes and shapes. Source: *Gröblacher 2010, p.84*

3.2.4 Putting it Together

The main idea of this opto-mechanical set-up is to couple the oscillation of the light within the Fabry-Pèrot cavity with the mechanical oscillation of a cantilever. In order to accomplish such a coupling, we take a Fabry-Pèrot cavity, the length which correlates to the frequency of the light to have constructive interference. Then we replace the second mirror of the Fabry-Pèrot cavity by the small mirror on the tip of a cantilever (see figure 3.3, symbolized by the mirror with the spring). Henceforth, laser light with a constant frequency enters the cavity through the fixed semitransparent first mirror and reaches the second mirror on the cantilever. The light is reflected from this second mirror and due to the radiation pressure the cantilever is deflected. As a consequence of the deflection of this movable second mirror, the length of the cavity is detuned. The formerly constructive interference becomes destructive and the light in the cavity diminishes. In other words, the radiation pressure on the cantilever mirror ceases and the cantilever returns to its initial position. In this way the length of the cavity returns to the optimum for constructive interference, which is once more the starting point for the next iteration of this recurring process.

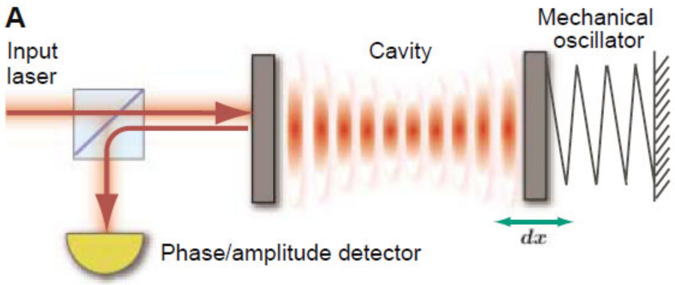

Figure 3.3: Fabry-Pèrot cavity with movable mirror. Source: *Kippenberg and Vahala 2008*, *p.1172*

The outcome of this set-up is the oscillation of the intensity of the light in the cavity, i.e. that there is constructive or destructive interference depending on the deflection of the cantilever, i.e. the length of the cavity. However, this dependence is not unidirectional, because conversely the deflection is reciprocally dependent on the intensity of the light in the cavity. Hence there is an interdependent coupling between the light wave and the deflection of the mechanical oscillator.

3.2.5 Requirements for Success

In order to accomplish entanglement it is necessary that the coupling between the optical and the mechanical regime is larger than the decoherence[6] of the two. So the coupling has to be improved and the decoherence reduced.

The rate of decoherence[7] is mainly dependent on temperature. Temperature is motion and as the cantilever is massive it vibrates badly due to its thermal motion. In order to bring the cantilever to its ground state[8], it is necessary to cool it close to absolute zero temperature. This is done by placing the cavity including the cantilever in a cryostat[9] which cools it to 4 K (kelvin). Deeper temperatures such as 20-100 mK (millikelvin) were achieved by using a custom made closed-cycle dilution refrigerator.

The way to increase the coupling between the optical and the mechanical regime is to im-

[6] See the concept of decoherence (*Bacciagaluppi 2008*; *Compendium 2009*, *p.155ff*).
[7] The rate at which the interaction of the system with its environment destroys its quantum state and makes it classical.
[8] The system is in its lowest possible energy state.
[9] A device to maintain cold temperatures. In this case it is a vacuum chamber cooled by liquid helium.

prove the quality of the optical and the mechanical parts. As already mentioned[10], the mirror on the cantilever in particular has to have very high reflectivity to utilize almost every photon for deflecting the cantilever. The mass, shape and suspension of the cantilever (see figure 3.2) are also crucial and subject to intensive engineering and development. Moreover, the optical components like the lasers need proper stabilization, for example by locking the emitted frequencies via feedback. Overall it can be stated that it takes quite an effort to exclude environmental influences and to detect quantum entanglement. As pointed out before, entanglement is established in this experimental set-up between the intensity of the light in the cavity and the deflection of the cantilever. The idea is that if the two observables exhibit a correlation which cannot be explained classically, entanglement between them has been produced. This means that the two entangled observables can only be described by assuming an indivisible joint state of the intensity of the light and the deflection of the cantilever.

3.2.6 Paradigmatic Model and Experimental Forks

On a fundamental level the opto-mechanical experiments are conducted to show that quantum effects can also be found in macroscopic systems. Up to now quantum mechanical effects have been demonstrated and utilized in systems of a rather small scale, like massless photons, elementary particles, atoms, and up to the size of molecules[11]. In comparison to these small entities, a typical cantilever can be seen by the naked eye and consists of in the order of 10^{20} atoms[12], instead of just a few.

On these grounds it is fair enough to call these opto-mechanical systems macroscopic. It is a considerable leap forward from the scales with which quantum mechanics has so far been tested to be applicable. As already discussed, quantum mechanics does not state any theoretical limit to its domain of applicability based on size, mass and so on. Of course there are interactions with the environment which hinder quantum effects[13], but circumventing them experimentally allows us to test the limits of the applicability of quantum mechanics.

However, these main physical principles put forward here do not constitute the full-blown experimental set-up. They rather have to be understood as something like a general model or master form for quantum opto-mechanics. The concrete realizations are a derivation thereof. In the case of the Aspelmeyer group the following set of experiments are conducted to tackle varying aspects of the topic or to circumvent specific difficulties in the course of implemen-

[10] See section *3.2.3 Cantilever*
[11] E.g. fullerene C_{60} (*Quantum 2011c*).
[12] Approximated by assuming that the cantilever consists of 50 nanograms of silicon.
[13] See concept of decoherence (*Bacciagaluppi 2008*; *Compendium 2009*, *p.155ff*).

tation. This list of experiments worked on by the group members should neither be taken as complete, nor equal in their status, nor in their relevance, nor limited to the group. The attribution of certain persons to a specific experiment (cited in the brackets) must be taken lightly, as it obscures the presence of mutual assistance and the harnessing of individual skills throughout the group (e.g. see Garrett Cole). Besides all of these shortcomings, it is enough to structure the group.

Master form: This is the implementation of the paradigmatic experiment described above. (Dr. Witlef Wieczorek, Dr. Simon Gröblacher, et al.)

Levitating nano balls: Here the oscillating cantilever is replaced by nano balls held into position by the radiation pressure of additional light beams[14]. (Dr. Nikolai Kiesel, Mag. Florian Blaser, Uros Delic)

Tabletop: A tabletop implementation of the paradigmatic model. The goal is to demonstrate the principles. Reaching the quantum regime, i.e. the occurrence of quantum effects, is not part of this experiment. This project has been developed in the course of a diploma thesis. (Dilek Demir)

Pulsed opto-mechanics: Instead of constantly applying a light beam to the cantilever, it is pulsed. The positive features of this method are the reduced dependency on the temperature of the system and the improved ability to observe space-like separated entanglement[15]. (Mag. Michael Vanner et al.)[16]

Coupled cavities: In a collaboration with the Quantum Information Theory Group at the University of Potsdam[17] a diploma thesis is under development. The idea is to mechanically couple two, and maybe many more, of the cavities described above in order to investigate quantum effects with such more complex systems. It is planned that it will not only comprise of a theoretical examination of the problem, mostly carried out in Potsdam, but also of an experiment here in Vienna. (Jonas Hörsch, Dr. Garrett Cole)

[14] Like a pair of light pincers.
[15] The cantilever and the pulse of the light are entangled, although they are at different locations.
[16] This is the only experimental set-up for which I was not able to interview any of the participants. However, they released a paper on this topic very recently *(Vanner et al. 2011)*.
[17] Headed by Jens Eisert and Markus Aspelmeyer as one of their visiting professors.

4 The Aspelmeyer Group

4.1 Research Topic and Genesis

The key resource of information for this diploma thesis are the people and their current research within the group *Quantum Foundations and Quantum Information on the Nano- and Microscale* at the Faculty of Physics at the University of Vienna. Their main research objective "[...] is to investigate quantum effects of nano- and microscale systems and their implications for the foundations and applications of quantum physics. [Their] goal is to gain access to a completely new parameter regime for experimental physics with respect to both size and complexity."*(Aspelmeyer Group 2011)*

The group originated as a spin-off of the initial research about quantum opto-mechanics started at the *Institute for Quantum Optics and Quantum Information (IQOQI 2011).* The IQOQI group around Anton Zeilinger, of which Markus Aspelmeyer was a vital member, innovated and carried out a lot of experiments using photons to demonstrate and utilize quantum effects. Around 2005 the idea came up to also apply this core competence to mechanical systems. Henceforth Aspelmeyer et al. began their work in the field of quantum opto-mechanics. On the basis of the publication of some initial papers about laser-cooling of micro-mechanical resonators around 2006, it became possible to set out and finance the projects solely from external funds. In 2009, Aspelmeyer accepted a call for professorship at the University of Vienna. This resulted in the actual foundation of the group *Quantum Foundations and Quantum Information on the Nano- and Microscale* at the Faculty of Physics at the University of Vienna, which Aspelmeyer now heads. Although it was a move from the Austrian Academy of Sciences to the University of Vienna it was not a break, but an evolution. It is important to note that there is close collaboration and interrelation among the Austrian quantum research facilities; personnel- and resource-wise. In this case it is nicely illustrated by the fact that both institutes occupy neighboring buildings connected by a sky-walk. Moreover, a core of the people now leading the experiments within the Aspelmeyer group started out in the former facility. Despite or even because of that, the actual relocation of the laboratories was only recently completed in April 2011.

4.2 My Relationship to the Group

I am studying physics and philosophy at the University of Vienna. One of the main reasons for me to study physics was the wish to comprehend quantum mechanics and its assertions. Hence I attended various lectures, seminars and talks, some given by Aspelmeyer. In the course of developing this diploma thesis it soon became clear to me that I wanted to refer to actual experimental research work. A colleague of Aspelmeyer gave me the tip to ask him, because of his vein for philosophy. I approached Aspelmeyer in December 2010, presented my idea and found a sympathetic ear. Early in January 2011 I held a talk to most of the members of the group, again to present the outline of the diploma thesis and to generally agree on cooperation and on conducting the interviews. I then initially approached Witlef Wieczorek with a request to introduce me to the experiments and inform me about the relevant literature needed to acquire the technical and physical details of the matter.

The contact with the group – all of them are indeed very kind – was kept very modest. It is important to note that I was never a part of the group and never attended their day-to-day work. I am an onlooker trying to figure out a comprehension of quantum entanglement on the basis of their personal statements about the topic. Although this looks like a harsh limitation on the possibilities of gathering information about the group, which is not the primary task of this thesis anyway, it allowed me to focus on the specific material (the interviews) and the questions posed. A profound and fair characterization of such a research group would indeed demand a greater and longer amount of involvement. On that account the description of the group contains very few observations on my part about the group, and consists almost completely of statements by the group members themselves; i.e. the interviews.

4.3 Facts and Figures

In the period the interviews were taken, from May to July 2011, the group consisted of the following 15 people.[1]

- Prof. Dr. Markus Aspelmeyer *(Group Leader) [i]*
- Mag. Florian Blaser *[i]*
- Dr. Garrett Cole *[i]*
- Uros Delic

[1] See *Aspelmeyer Group 2011* section 'People'.

- Dilek Demir *[i]*
- Dr. Simon Gröblacher
- Mag. Sebastian Hofer
- Jonas Hörsch *[i]*
- Dr. Rainer Kaltenbaek
- Dr. Nikolai Kiesel *[i]*
- Jonas Schmöle, MSc.
- Mag. Alexandra Seiringer *(Administration)*
- Alexey Trubarov
- Mag. Michael Vanner
- Dr. Witlef Wieczorek *[i]*

I conducted seven interviews amounting to half of the group, as indicated by *[i]* in the list above. In terms of their degrees/qualifications, I tried to pick a representative sample to represent the under-graduates, graduates, PhD students and post-doctoral research fellows accordingly. Another motive for this selection was the assignment of the people to the various experiments[2].

4.4 The Interviewees

The information presented in this section is a summary of the statements given by the respective interviewees concerning their age, academic career, and assignment within the group. Detailed curricula vitae are available of some of the interviewees on the group's staff website[3].

4.4.1 Dr. Witlef Wieczorek

Wieczorek is a thirty-two year old post-doctoral research fellow, who studied physics at the Technical University of Berlin (TU Berlin) and graduated with a diploma thesis on quantum dots. He worked for four years as a post-graduate on multi-photon entanglement at the

[2] See section *3.2.6 Paradigmatic Model and Experimental Forks*.
[3] See *Aspelmeyer Group 2011* section 'People'.

Ludwig Maximilian University in Munich (LMU Munich) *(Interviews 2011d, §4).*

In his regular curriculum he did not encounter the issues of different interpretations in quantum mechanics. However, at a summer school held by Reinhard Werner and Jens Eisert at the TU Berlin he was introduced to the EPR problem and the Bell experiments *(Interviews 2011d, §10-13).*

In the Aspelmeyer group, Wieczorek is responsible for the realization of the paradigmatic experiment using cavities with mirrors on cantilevers. Until of late he worked together with Simon Gröblacher, who wrote his dissertation on this experiment and is now Post-Doc at the California Institute of Technology. Currently Wieczorek is teamed up with Jonas Schmöle et al. on this experiment *(Interviews 2011d, §31-32).*

4.4.2 Dilek Demir

Demir is twenty-two years old and an undergraduate. After studying physics at the University of Vienna, she was, at the time the interview was held, finishing her diploma thesis on radiation pressure effects on macroscopic systems *(Interviews 2011a, §5,9,11).*

Although she had never heard of quantum physics before studying physics, she quickly became attracted by quantum mechanics. Instead of attending some boring lectures, she started reading papers and books about the topic; such as the EPR thought experiment. Beyond that, Demir also attended together with some of those who are now her colleagues, the extra-curricular Monday lectures on quantum physics which back then were organized by Aspelmeyer *(Interviews 2011a, §23).*

Her assignment, and also the topic of her diploma thesis, is the development, i.e. design, build-up and measurement, of a kind of table-top implementation of the paradigmatic experiment, in order to nicely demonstrate radiation pressure. It is not set up to show any quantum effects, but aims at simplicity and yet precision *(Interviews 2011a, §11-15).*

4.4.3 Dr. Nikolai Kiesel

Kiesel is a thirty-four year old post-doctoral research fellow who studied physics at the Ludwig Maximilian University in Munich (LMU). He joined the Zeilinger group in Vienna for his diploma thesis on three-photon entanglement[4] and his dissertation on four-photon

[4] On the W state, because the GHZ state (Greenberger, Horne, Zeilinger) has already been implemented in Vienna.

entanglement. In 2008 he moved to the Aspelmeyer group *(Interviews 2011c, §16).*

He did not become drawn into this area of physics until almost at the end of his studies. A seminar held by Harald Weinfurter, who at that time worked with the Zeilinger group, got him interested in the experimental field of quantum mechanics *(Interviews 2011c, §4, 13).*

Kiesel started up and is currently heading the experiment on utilizing levitating nano balls instead of mirrors on cantilevers. His collaborators are Florian Blaser and Uros Delic. Additionally Kiesel participates in managing and representing the group *(Interviews 2011c, §19,23,30).*

4.4.4 Mag. Florian Blaser

Blaser is a post-graduate and thirty years old. He started studying physics at the University of Neuchâtel (Schwitzerland) and came to the University of Vienna in 2005 to write his diploma thesis on the simulation of mechanical systems. Except for some time after graduation working in the software industry, he has been part of the opto-mechanical experiments since the very beginning with Zeilinger's group. Now he is doing his PhD with the Aspelmeyer group *(Interviews 2011f, §6-12).*

Blaser became interested in quantum entanglement and read some books about quantum information, which was not well covered in his small home university. While reading the relevant papers he discovered that the group at the University of Vienna was very active and successful in this field of research. Hence he applied successfully to write his diploma thesis with the Zeilinger group *(Interviews 2011f, §16).*

Blaser works together with Nikolas Kiesel and Uros Delic on the experiment using levitating nano balls. At the time of the interview he was programming LabView[5] to automate and improve the measurement process. Anyhow, he like almost all other experimenters is also occupied with setting up and aligning the optics, the electronics, and so on *(Interviews 2011f, §31,38-39,43).*

4.4.5 Dr. Garrett Cole

Cole is a thirty-two year old research fellow who is a sort of a lateral entrant to the group. He has a bachelor's degree in materials engineering from California Polytechnic State University. In addition he went to the University of California, Santa Barbara to study electronics

[5] Graphical programming environment to develop measurement, test and control applications.

and photonic materials. Cole completed his PhD in 2005 on MEMS-Tunable Vertical-Cavity Semiconductor Optical Amplifiers. After graduation, he was employed for a year in the industry and for two years at the Lawrence Livermore National Laboratory (LLNL Center for Micro- and Nanotechnology). Since October 2008 he has been working at the Austrian Academy of Sciences and the University of Vienna *(Interviews 2011b, §5-7).*

Cole is well-qualified and experienced in the area of nano- and micro-fabrication, including design and implementation. His dissertation was on mechanically tunable diode lasers, which are in some ways similar[6] to the paradigmatic set-up in quantum opto-mechanics. In the course of his employment at the LLNL Center for Micro- and Nanotechnology, he became more and more interested in the physical fundamentals of his work. After reading into the topic, he came across the work of Aspelmeyer and contacted him. As a result, a collaboration was initiated which had Cole, while still working at the LLNL, fabricate various samples of nano-mechanical devices for testing in Vienna. In 2008, due to a lack of perspectives at the LLNL, he seized the opportunity to finally join the Viennese quantum community *(Interviews 2011b, §7-11).*

Although Cole is mainly located within the Aspelmeyer group, his skills and expertise in micro-fabrication are also made use of by other groups and collaborations. At the time the interview was held he was engaged in building a test bench to characterize, quantify and optimize the mechanical response of the fabricated cantilevers, prior to deploying them in the more time-consuming experiments *(Interviews 2011b, §27-31).*

4.4.6 Jonas Hörsch

Hörsch is a twenty-five year old undergraduate studying physics at the University of Potsdam as a member of the Quantum Information Theory Group around Jens Eisert. He recently started work on his diploma thesis, which is about mechanically coupled micro-cavities. It is a cooperation between the Eisert and the Aspelmeyer groups, as there are also plans to test the theoretical findings on these coupled systems experimentally[7] *(Interviews 2011e, §3-9, 15).*

At this early stage in his diploma thesis, Hörsch is still mainly acquiring insights into the design and simulation of the mechanical components and the experimental environment here in Vienna. However, as a first step he and Cole have already designed some initial

[6] They also consist of a cavity, but which is tuned by moving the small mirrors to change the cavity length. The deflection of the mirrors due to radiation pressure, as exploited in quantum opto-mechanics, has been an unwanted side effect in the context of these lasers.

[7] I.e. micro-fabrication by Cole

prototypes, whose production is to be launched soon *(Interviews 2011e, §21-31)*.

Hörsch was introduced to and became interested in quantum information theory via the lectures of Jens Eisert. The University in Potsdam mainly concentrates on the theoretical elaboration of quantum information theory and hence lacks the scope of its application. Therefore he joined the field of quantum opto-mechanics and collaborates with the Aspelmeyer group *(Interviews 2011e, §37)*.

4.4.7 Prof. Dr. Markus Aspelmeyer

He is thirty-seven years old and a professor at the University of Vienna. Aspelmeyer studied at the Ludwig Maximilian University in Munich (LMU) and later on also studied philosophy at the Munich School of Philosophy[8]. He took a bachelor's degree in philosophy and wrote his diploma thesis and dissertation in physics about the investigation of structural phase transitions of crystals (solid-state physics). Always up for a challenge, he switched his area of research after graduation and became Post-Doc with the Zeilinger group in Vienna. Since 2009 Aspelmeyer has been Professor of Physics at the University of Vienna and head of the *Quantum Foundations and Quantum Information on the Nano- and Microscale* group *(Interviews 2011g, §8-11)*.

His self-proclaimed main task is to interact and communicate with his group as much as possible. For that reason he tries to be in the laboratories and lend a helping hand whenever possible. In this way Aspelmeyer tries to provide new impulses to the group and set the course of the research. Another main part of his work is of course to keep the funding for all the experiments pouring in *(Interviews 2011g, §21-25)*.

4.5 Issues Raised by the Interviews

After having introduced the interviewees with regard to their academic vita and assignment in the group, it is time to illustrate the key topics which emerged in the course of the interviews. The central issue is certainly the counter-intuitiveness of quantum entanglement, but the emphasis of its analysis is strongly oriented towards the answers given by the interviewees. The two key topics which I discerned from the entirety of the interviews and which will serve as my work order for the rest of the thesis are the following:

Counter-intuitiveness: With certain nuances, the interviewees had difficulties in putting

[8] Hochschule für Philosophie München

their tentativeness about the matter into words. Certainly the more educated, involved and interested in these fundamental questions about the comprehension of quantum mechanics a scientist is, the more she is able to express and discuss the topic at hand with precision. In short, the group leader is of course more articulate with regard to the subject than an undergraduate. On these grounds it seems appropriate to develop a fitting account of the counter-intuitiveness of quantum entanglement. Firstly by introducing a very general definition of counter-intuitiveness.[9] Secondly by carving out the specifics regarding quantum entanglement as introduced at the beginning of the thesis[10], and thirdly by characterizing the specific counter-intuitiveness by employing key epistemological thoughts from Bachelard.[11]

Coping: A key issue for the interviews was the question of whether experimenting helps in overcoming the difficulties of comprehension. The short and superficial answer is probably no. However, this certainly demands a more detailed examination. Abstracted to a more comprehensive level, the issue raised is how to generally cope with the counter-intuitiveness of quantum entanglement. Does science and do scientists need to cope with it? [12] What basic considerations can be spelled out concerning the possibility of experiments being of assistance in evolving our reasoning in order to accommodate the difficulties of comprehending the matter? [13]

Again, this extraction of the central issues tackled within the interviews not only summarizes the main content of the interviews, but can also be regarded as a motive for the elaborations which follow. Moreover, relevant quotes from the interviews will be deployed as evidence for supporting particular arguments. Hence the further study of a definition of counter-intuitiveness and the handling of the counter-intuitiveness will rest on three pillars: The actual context of quantum opto-mechanics and the respective experiment previously introduced, the perspectives expressed in the interviews, and the set of tools consisting of key concepts of Bachelard's epistemology.

[9] See section *5.1 General Definition*.
[10] See section *5.2 Specifics*.
[11] See section *5.3 Characteristics*.
[12] See section *6.1 Aim of Science? Coherent System of Assumptions*.
[13] See section *6.2 New Generations of Scientists* and *6.3 Bachelard: Reason Instructed by Fabricated Experience*.

5 Counter-Intuitiveness

5.1 General Definition

In principle there is nothing exceptional about the term "counterintuitive". Every sensible language user knows the meaning of this adjective and makes more or less frequent use of it in the proper context. Nonetheless I will first spell out a definition and then continue from there. According to the Merriam-Webster dictionary, *counterintuitive* means that something is "different from what you would expect". In the same dictionary, the term is described as something "not agreeing with what seems right or natural" *(Merriam-Webster 2011a)*.

Hence the adjective *counterintuitive* labels facts and circumstances as not corresponding to what one has assumed. If, as the second definition implies, the expected appears to be right or natural, it is a slippery slope which I am not inclined to travel. In the case of quantum entanglement, but also very generally in science, claims of justification based on what seems right or what seems natural are very problematic. Thus it is sufficient to initially concentrate on the function of the adjective *counterintuitive* to indicate a difference between an issue and what we have expected about the issue.

How central this idea of countering is will become clearer by studying the difference between it and something which can be called *non-intuitive*. At first glance the latter is used to manifest the case of not having any intuition, and hence any expectation, at all with regard to the subject matter. For instance, it seems close to impossible to actually form an intuition about higher dimensional (higher than three dimensions) or warped (curved) spaces.[1] However, on second thoughts calling something *non-intuitive* in normal parlance has a very similar usage pattern as *counterintuitive*. If a subject matter is not intuitive, it is also not according to our expectations. Therefore the difference between *non-* and *counter-intuitive* appears to be a matter of gradation. Calling something *non-intuitive* is a weak indication of its non-conformance with intuition. By contrast, labeling something *counterintuitive* is a

[1] Some mathematicians might claim to have developed an intuition about those constructs. This is definitely something worth taking a closer look at, but certainly not in this thesis.

much stronger claim that our intuitions are contradicted by the subject matter. We use it to state that a matter of fact is in conflict with, or resists, our intuitions. Basically it is a term to emphasize the problematic nature of a contradiction between intuition and a matter of fact.

Another approach to a general understanding of *counterintuitive* springs from a definition of *intuition*. In general, again according to the Merriam-Webster dictionary, *intuition* is "a natural ability or power that makes it possible to know something without any proof or evidence" (Merriam-Webster 2011b). Taking a look at entries on *intuition* in other books of reference (Encyclopaedia Britannica 2011; EnzyklPhilWiss 2010; Rorty 1967), allows us to, probably more universally, define intuition as an *immediate apprehension*.

The key to this definition of *intuition* is to consider *immediate* in two ways here. At first we can of course think of it in a more chronological manner, i.e. something is assumed or known from intuition due to the unavailability of distinct proof or evidence. That is, we draw on intuitions about a subject matter owing to a lack of knowledge about it. However, as soon as there is sufficient proof or evidence, i.e. some process of gaining additional knowledge and inference is involved, the intuition either dissipates, becomes irrelevant or is definitely validated as justified, unjustified, right or wrong. In this way the intuition is marginalized or superseded as soon as there is relevant proof or evidence. Hence no matter if the intuition and the subject matter do coincide or not, we might not care anyway, as proof or evidence is valued much higher in this case. Supposing that intuitions are not in accordance with the facts of the matter, we might be inclined to use the weaker label *non-intuitive* here.

The second way of considering the immediacy in the definition of *intuition* is in a, let us say, logical manner. In contrast to adopting intuitions as a placeholder which are superseded by more knowledge about the matter, intuitions in this sense function as more immediate access to the matter in parallel with proof or evidence. Hence it is not a question of when the intuition has been formed or whether the knowledge about the subject matter is already in place, but rather the idea that the immediacy of the apprehension in the course of having intuitions is relevant. If, as in our instance, intuitions do not coincide with our available knowledge of the matter, we can make the strong case for labeling them *counterintuitive*. This means that we allow the immediacy of our intuitions to be considered enough to maybe even challenge or cast doubt on the available proof or evidence.[2]

In sum, the point I wish to make here is that *counterintuitive* not only qualifies a subject matter as being not in accordance with our immediate apprehension (= intuition) of the matter, but especially emphasizes its problematic contrariness. How this understanding specifically

[2] Certainly this is only the case if the speech act is not considered an empty phrase. For instance, experts bragging about the unintelligibility of the matter in order to intimidate or impress non-experts.

applies to the counter-intuitiveness of quantum entanglement will be studied in the following section.

5.2 Specifics

A way to provide a generally conclusive definition of counter-intuitiveness in the realm of quantum entanglement which is suite to the subject is unfortunately not that straightforward. One of the major difficulties is that a definite contradiction between a concrete intuition and a specific datum of quantum mechanics strongly depends on the respective interpretation of quantum mechanics and its corresponding assumptions. This means that a specific elaboration of the counter-intuitiveness of quantum entanglement is bound to and only valid in the light of the interpretation chosen. For instance, the notion of quantum entanglement only makes sense in a couple of interpretations of quantum mechanics. Thus, the notion of counter-intuitiveness in the realm of quantum mechanics first of all indicates that there is some sort of conflict between intuitions and scientific facts and that is the only commonplace which can be generally stated. Again, how this contradiction manifests itself in detail hinges very much on the specific understanding or interpretation of quantum entanglement actually put forward.

In this thesis, as already mentioned, the presentation of the counter-intuitiveness of quantum entanglement will be carried out against the background of a somewhat mainstream Copenhagen-type interpretation. In order to be even more precise, I consider the description of quantum mechanics by Schrödinger *(Schrödinger 1935)* sufficient for the task. Other interpretations of quantum mechanics are not considered in this thesis, because I am convinced that each (e.g. variants of Bohmian mechanics, many worlds ...) individually contains a certain sore point of counter-intuitiveness. This means that although their content is different, they all share the peculiarity of challenging fundamental intuitions which are classically held about the world. An interpretation not burdened with counter-intuitiveness would be the most probable candidate for quickly becoming the general doctrine in this field. As this is not the case, it is sensible to take the notion of the counter-intuitiveness of quantum entanglement for its function of generally marking a contradiction between a theoretical or experimental phenomenon in quantum physics and common intuitions about the world. However, in order to analyze the notion it has to be studied in a specific context, say adopting the perspective of a certain interpretation; as the following will show.

We will briefly recall the core issue introduced in the preceding part of this thesis to begin with. The central EPR thought experiment is basically comprised of three statements which cannot be simultaneously true. Hence at least one of them is mutually exclusive to the others, or meaningless in a way. First, the completeness assumption: A theory is complete in the strict sense that every element of physical reality has to have an appropriate counterpart, i.e. must be represented in the theory. Second, the reality[3] assumption: If we are able to predict with certainty the result of a measurement of a physical quantity without disturbing the measured system, then there is an element of physical reality which corresponds to this physical quantity. Third, the locality assumption: Measurement results at one site do not influence the measurement results in far apart (space and time separated) sites by any dynamical mechanism faster than the speed of light. Einstein et al. relied on their knowledge and their intuitions about the *classical* physical world and insisted on the validity of the two assumptions about the reality and the locality of physical phenomena. Therefore, due to the cogency of the thought experiment they concluded that quantum mechanics – in describing the EPR thought experiment – cannot be complete. Again, assuming two of the three statements to be true excludes the other. As the theory of quantum mechanics cannot be considered complete in the eyes of Einstein et al., they proposed fixing it by generally extending the theory by a hidden, not necessarily known, variable.

In contrast, quantum mechanics, here according to the description of Schrödinger, is perfectly complete as a theory and there is no need for – or even more strongly, it strictly forbids – the assumption of hidden variables being a part of it. All physical phenomena are properly describable by quantum mechanics, although new concepts like quantum entanglement are the consequence. Now that the completeness of quantum mechanics is the pivotal requirement, one or both of the other assumptions (reality, locality) of the thought experiment have to be circumvented, invalidated or rendered meaningless.

Both points of view refer to and explain the same observable phenomena, i.e. *results* of the thought experiment, but differ with regard to their counter-intuitiveness. As can easily be seen, the position of Einstein et al. is perfectly consistent with the common, *classical* intuitions about the physical world; namely the reality of physical quantities independent of their measurement and the impossibility of instantaneous[4] impacts of simultaneous measurements conducted far apart. Quantum mechanics does, however, contradict or render meaningless these common *classical* intuitions and hence can be regarded as counterintuitive.

[3] The notion of *reality* certainly has huge implications in the philosophy of science. It is definitely not my intention to touch upon any of the vast discussion about reality and its various understandings. Here *real* is used in a very naive physical sense. In this context it rather means that the value of a physical quantity is determined at any given time independently of its measurement. This applies throughout the thesis.

[4] With respect to Einstein's special relativity theory, superluminal.

Besides the difference in such soft criteria like compatibility with common intuitions, there was no factual reason to pick one over the other. It was John Stewart Bell who conceived a criterion (Bell inequality) to test differing predictions of classical hidden variable theories and the theory of quantum mechanics. A great number of experiments (Bell experiments), conducted during the last four decades affirmed[5] that statements made on the basis of the theory of quantum mechanics are the case. Any hidden variable theory is inherently unable to accommodate for the experimental data produced. Consequentially, hidden variable theories, although tending to be rather immediately intelligible and intuitive, are ruled out due to experimental evidence. In reverse the theory of quantum mechanics is experimentally underpinned, but does not coincide with common intuitions about the world.

Hitherto this does not sound like a very unusual situation for modern day science. Many scientific theories are not compatible with the respective common intuitions held about the world. In addition, despite the fact that the compatibility of a theory with everyday intuitions can be a criterion for the actual theory choice, much like simplicity or beauty, fortified evidence arguably has more weight in this respect. However, the counter-intuitiveness of quantum entanglement may not be different to other counterintuitive theories in principle, but it certainly is in gradation. The specific trait of the situation of quantum entanglement is that the intuitions contradicted by evidence are the most fundamental ones. They are such a fundamental part of our comprehension (perception) of the world that doubting them is indeed imaginable, but nevertheless close to impossible to conceive. This is not only the case for the layman, but also for the people involved with (experimental) research. For example, statements like the following are not in a minority among those interviewed for this thesis.

> "*I reckon one will never understand entanglement.*" [6]
>
> – Witlef Wieczorek, *(Interviews 2011d, §83)*

Even in a more detailed account we can easily see a fundamental difficulty in expressing the issue. Moreover, it becomes apparent that it is not a settled matter, but demands constant rethinking. Which is a nice indicator that something is not as expected; and thus corresponds with the previously introduced definition of being counterintuitive.

> "*There are a lot of question marks in quantum mechanics. And theoretically it is interesting, because matters normally evident do become not so evident any more. So in the EPR experiment for example, you have to read the paper twenty thousand times and you still won't understand it. Because there is always something in there you didn't see before. And it is rather interesting to me that you can always find something you have to understand anew. It is*

[5] The loopholes have to be kept in mind of course. *(Compendium 2009, p.348f)*
[6] Translated by the author.

> *somehow this contradiction: It should be like this, but quantum mechanics says it is different. But why? And then you can start pondering about it. I find that pretty cool.*" [7]

– Dilek Demir, *(Interviews 2011a, §45)*

The relationship between puzzlement and our intuitions, as well as the perception of quantum entanglement as being counterintuitive, is even more directly expressed by this quote:

> "*We are simply used to the fact, out of intuition, that if a body has some property, this property is actually there. Or that it is somehow indeed realized. This has to be totally dismissed with quantum mechanics. Rather, many properties are not determined before a measurement was made. [...] Hence the phenomena are counterintuitive. Well, you can somehow imagine them, but? The maximum one can do is to get used to it.*" [8]

– Jonas Hörsch, *(Interviews 2011e, §61)*

These quotes just hint at the intricate understanding and the limited means to accurately articulate one's personal puzzlement. On a more general level, the substance of the counter-intuitiveness of quantum entanglement comes to light when we take a look at the core idea of quantum opto-mechanics[9] which the experiments of the interviewee are based on.

The exciting momentum of quantum opto-mechanics is its implementation at size scales which are close to the human everyday world. This is basically due to two reasons: First, it underlines the theoretical independence of quantum effects with respect to the size of the system it is realized with. Secondly, it also reveals the question of where to draw the line between the *classical* realm and the quantum realm; if there is one.

In detail, as already shown in the very implementation of quantum opto-mechanics in the paradigmatic experiment introduced in this thesis[10], the starting point is a mechanical oscillator. In our case it is a cantilever of nano scale which is easily comprehensible in classical mechanical terms. First, it is fitted with a little mirror on its tip and mounted as one part of a cavity (two opposing mirrors). Next, laser light is introduced into the cavity, which travels back and forth between the two mirrors. The light in the cavity interferes with its own reflections. Depending on the length of the cavity, the light oscillating interferes either constructively or destructively, and accordingly the intensity of the light is higher or lower. However, as one mirror of the cavity is the cantilever, it becomes deflected by the radiation pressure of the light. The higher the intensity of the light, the higher the deflection of the cantilever. As the cantilever is deflected, the length of the cavity changes, and consequently

[7] Translated by the author.
[8] Translated by the author.
[9] See section *3.1 Introduction*.
[10] See section *3.2 The Experiments*.

the interference changes, thereby changing the intensity of the light in the cavity. This again leads to a modification of the deflection and hence the modification of the cavity length. Thus the circle is complete. In sum the experiment realizes a correlation between the intensity of the laser light and the displacement of the cantilever. Up to now this is very easily intelligible solely by the use of classical terms. However, after excluding all of the interfering disturbances (e.g. by extensive cooling and suspension) the correlation between those two observables, the intensity of the light and the deflection of the cantilever, will cease to be classically explainable. The coupling produced between the optical and the mechanical regime emerges entangled. That means that the very same conclusion which Schrödinger generally reached when devising quantum entanglement can be realized here[11] with a system normally conceived as classical. The cantilever, an emblem of classical mechanics, has become a matter of quantum effects at size scales visible to the naked eye.

This specific experimental set-up, besides other things, comprises the counter-intuitiveness of quantum entanglement. Its intention is to realize quantum effects with commonly accessible concepts (cantilever, cavity, radiation pressure, ...), and accordingly runs into results not expected in the common classical comprehension of the physical world. Certainly according to the approach of quantum mechanics, the results of the experiments are altogether expected. However, the crux of the matter is that the classical way we commonly apprehend our world leads us to label the results of the experiments counterintuitive. This concept of counter-intuitiveness is, of course, not restricted to the specific implementation of experiments yielding quantum effects, but can also be characterized on a more general level; which will follow next.

5.3 Characteristics

5.3.1 By Comparison

When studying intuitions more closely, it often turns out that they are mostly not referred to in a positive way. Either they are commonly mentioned as a last resort for minimal justification in the absence of any evidence or proof of a matter. Or they are deployed to dismiss something as specifically implausible and irrelevant. For instance, using the non-compliance of a subject matter with our intuitions as a knockout argument in debate. In other words, intuitions are mostly silently at work in our perception and judgement of the world. They surface most obviously when they conflict with contradicting beliefs or empirical data.

[11] It is safe to be modest as the actual realization has not been accomplished yet.

Hence the most apparent form of intuitions is when something is counterintuitive. This is where one usually becomes aware of intuitions.

I would like to put forward the following two familiar examples to illustrate the situation. The first one concerns the Müller-Lyer illusion; probably the most famous geometrical-visual trick (see figure 5.1).

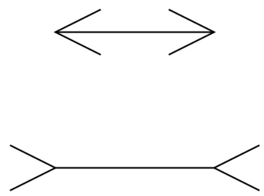

Figure 5.1: Müller-Lyer Illusion. Source: *Illusionism.org 2008*

We came to realize, e.g. through measurement or by believing the testimony of others presenting us with the illusion, that the lengths of both lines (without the arrows) are equal. However, we visually perceive the upper line to be shorter than the lower one. Thus it is intuitively backed to claim that the lengths of the lines are different. Although we have perfect knowledge about the illusion, i.e. that it is a visual trick and what the correct comprehension of it ought to be, it is not possible to overcome our intuition about it. It is very important to note that intuition in this case is equated with the conditions of the human sense of vision, including physical and psychological characteristics. This may not be permissible, or is at least up for debate. Nevertheless, the point to be made with this example is not where the intuition comes from, but thta it is an intuition denoting the situation of something *seeming* to be the case to a person. George Bealer stresses the *seeming* as the important difference between an intuition and a belief *(DePaul and Ramsey 1998, p.208).* In the Müller-Lyer illusion it still *seems* to the viewer that one of the lines is longer than the other, although she neither infers nor believes in the difference in length. Bealer points out that the seeming persists in spite of the countervailing belief.

The second example will not only bolster, but also broaden the understanding of traits of intuition. In nearly every physics class this experiment is conducted to demonstrate the laws of free falling objects. Of course there is a whole lot to know and say about the laws of free fall in terms of physics and the history of science. What we will specifically look at is the following tricky question: *If you drop a feather and a steel ball from the same height, which one will hit the ground first?* The common intuition in this case can be described as follows: It seems to the person asked that the steel ball is heavier than the feather; it therefore falls faster and hence hits the ground first. This is exactly the doctrine of Aristotle and scholasticism, criticized for instance by Giovanni Battista Benedetti[12] and refuted by Galileo Galilei's work.

The physically correct answer demands a counter question to clarify the environment of the set-up; and that makes the initial question so tricky. Is the fall set up in a force free environment, except for gravity, or not? For example, the case of dropping a feather and a steel ball in a vacuum[13] results in both hitting the ground simultaneously. Conducting the same experiment in a medium like air would result in the steel ball hitting the ground earlier, because the feather suffers more air drag due to its shape. A law-like statement would sound like this: Without any forces[14] in place, except gravity, all bodies, independent of mass, shape and material, fall with the same rate of acceleration and hence hit the ground at the same moment if dropped from the same height.

This is presumably the most well-established and millionfold experimentally demonstrated fact in physics. Every person who has ever had physics classes in her life is expected to hold this belief, or science education would have failed its assignment big-time. However, it can be denied that the intuition about heavy objects falling faster is eradicated by this belief. When asked unexpectedly, let us say brutally woken from well-deserved sleep at 3 o'clock in the morning, many people, even the well educated, are not immune from giving the intuitive answer. This does not indicate that we gave the intuitive answer just because the correct belief slipped our mind. The situation is rather that intuition is more immediate and belief is always in need of some contemplation. Immersion in environments where the correct conception of the case is very visible, or familiarization (for example through repetitive reflection of the case) might reduce the need for contemplation. We will return to this matter in due course (see section *6 Coping*).

The reason why I referred to the free fall example is because many more people are able to personally relate to the intuitiveness of it than to the perspective of quantum mechanics. Thus it is a beneficial undertaking to highlight the parallels of these two cases.

The starting point is the phenomenon of the different velocities of falling objects in air. The analogon in the case of quantum entanglement would be the EPR thought experiment. In each case there are basically two hypotheses explaining the phenomenon. In the free fall example, the Aristotelian and the Galilean. On the quantum entanglement side there is the

[12] He devised a simple thought experiment to disprove the scholastics: Connecting two falling balls with a (mass-less) rod does not change the velocity of fall, although the overall mass of the body increases (*O'Connor and Robertson 2009*).

[13] A gravitational field is implicitly assumed, as without it there would be no fall at all.

[14] Like resistances (e.g. air drag) or magnetism.

	Free fall	**Quantum entanglement**
Phenomenon	Objects falling with different speeds (in air)	EPR thought experiment
Hypotheses	Aristotle vs. Galileo	Einstein vs. Schrödinger
Experiment	Galileo, school experiments	Bell experiments
Invalidated	Aristotle	Einstein (all local realistic theories)
Intuitive	Aristotle	Einstein (all local realistic theories)
Counter-intuitive	Galileo	Schrödinger

Table 5.1: Structural comparison of the free fall example with the quantum entanglement case.

Einstein picture and the Schrödinger picture. In addition there are experiments by Galileo and Bell which in each case flatly invalidate one of the hypotheses, namely the Aristotelian and the Einsteinian picture. However, both experimentally excluded hypotheses are those that are closely related to prevailing intuitions. Hence both cases, i.e. the free fall example and quantum entanglement, are a matter of counter-intuitiveness.

Unfortunately, like all good analogies this one also has to come to an end. Although the free fall example shares its form of counter-intuitiveness with the quantum entanglement case, it is very well appeased by another intuition. Here it is air drag, which is not much less intuitive and commonly accessible. The physically correct description of free fall in air does indeed conflict with the direct intuition of heavier objects falling faster, but is perfectly intelligible using the other everyday life concept of air drag. This means that gaining a very simple piece of additional knowledge, like the existence and resistance of air drag, marginalizes the wrong intuition about objects which fall faster.[15] The distinction to the quantum entanglement case are the intuitions violated; e.g. the reality and locality assumption have no proper *intuitive* alternative. Thus far these fundamental intuitions have only been rationally negated and hence this situation is far from being reconciled with a common perception of the world. There is nothing similar in the quantum entanglement case to what the intuition of air drag does in the free fall case.

The ongoing search for a more fitting interpretation of quantum mechanics is a good indicator. For instance, assuming physical objects without properties prior to their observation or "spooky action at a distance" *(EPR 1935)* are hard to comprehend without a plausible

[15] This classical example is very well comprehensible in terms of the definition of intuition as the absence of proof and evidence. See section *5.1 General Definition*.

story that relates it to the commonly perceived world. This intricacy of the situation not only manifests itself at the level of countering intuitions, but can also be shown in the very notion of quantum entanglement.

5.3.2 Notion

After carving out some of the characteristics representative for the counter-intuitiveness of quantum entanglement, we will now take a closer look at the notion itself. Up to now we established counter-intuitiveness along the lines of a phenomenon which contradicts our classical expectations instructed by the world we live in (e.g. see reality and locality assumption). However, as the notion of quantum entanglement arose from this situation, it is very suggestive to wonder whether counter-intuitiveness finds its expression in the comprehension of the notion alone. The tool box I am going to use in order study this matter is equipped with, to my mind, suitable conceptions of Gaston Bachelard's epistemology.

Introduction to Bachelard's Epistemology[16]

Bachelard generally assumes science to be an alternation between empiricism and rationalism. Instead of both extremes being in diametric opposition, he perceives it as a dialectic relation. Bachelard argues that an empiricism is always in need of clear, deductive laws in order to be conceivable and teachable. In addition, a rationalism is not very convincing without credible evidence and applications in reality. Hence in order to prove the value of an empirical law, it has to become a basis for logical considerations. Vice-versa, a logical consideration becomes admissible when it can become the basis for an experiment. Therefore Bachelard does not advocate a dualism, but a dialectic relation where one is complemented by the other. For him, scientific thinking is to enter the epistemological area between theory and practice, mathematics and experience. In order to comprehend a law of nature scientifically, it is necessary to understand it as both, a phenomenon and a noumenon[17] *(Bachelard 1980, p.20f).*

Although this relation between empiricism and rationalism is balanced per se, Bachelard detects a privilege in contemporary physics in direction of rationalism proceeding to experience. His cue is the rise and the weight of mathematical considerations in current physics. This analysis can also be deemed valid for today's physics. Mainly because much of today's

[16] This introduction is a rendition of the prologue *(Bachelard 1980, p.17-30).*

[17] Caution: not Kant's noumena (Ding an sich), but rather the general idea about something that can only be recognized by the mind

physics relies conceptually on ideas which arose in the period Bachelard is referring to; the first half of the twentieth century. Moreover, the very subject of this thesis is a prime exemplar for what he calls applied or prospective rationalism[18]. At the very beginning there is a rational consideration, say the EPR thought experiment or quantum entanglement, imposed by other tenets founded in known facts, e.g. blackbody radiation *(Compendium 2009, p.39f)*. Then this rational consideration becomes the subject of a program of experimental realization. On the surface, a thought experiment is mostly intended to explicate a theory (or make another theory look preposterous); as in the EPR case.[19]. Hence there is no need for realisation in the first place, except in the mind. That is probably one reason, besides the technical hurdles, why it took quite some time until an experimental realization was finally devised in the case of quantum entanglement; see the Bell experiments. Furthermore, it is not the blunt implementation of the physical setting of the EPR thought experiment that matters, but the realization of the rational idea behind it. Namely to scrutinize whether quantum entanglement is the consequence of specific non-classical assumptions *(see Schrödinger 1935)* or proof for the deficiency of quantum mechanics within the framework of classical assumptions *(see EPR 1935)*. The Bell experiments clearly[20] *realize* quantum entanglement as a phenomenon and the consequence of non-classical assumptions.

According to Bachelard, not only the phenomenon is necessary for scientific comprehension, but also the noumenon. What is the noumenon of quantum entanglement? Is it a clear-cut rational term knowable by its physical definition alone? Where does the counter-intuitiveness of quantum entanglement come into play? Is it inherent to the very notion? The instrument of choice for answering these questions is the concept of the epistemological profile devised by Bachelard.

Epistemological Profile

In the book *Philosophy of the No*, Bachelard explains the idea of the epistemological profile *(Bachelard 1980, p.55ff)*. Hiss starting point is to call into question the generality of the realism held by scientists. Is a scientist a realist in all her thoughts and conjectures? Does one and the same mind deal with differing gradations of realism in its thinking? Besides, do these gradations depend on the notions concerned, the progression of the beliefs and the theoretical concepts of the prevailing era? According to Bachelard, a specific notion

[18] *Rationalisme prospecteur (Bachelard 1980, p.21)*

[19] The scientific tool of the thought experiment is certainly more complex than put forward here *(Brown and Fehige 2011)*

[20] Again, the loopholes concerning Bell experiments have to be kept in mind. *(Compendium 2009, p.348f)*

is always characterized by a pluralism of philosophical cultures or aspects with diverging weights. The epistemological profile is an instrument to illustrate the psychological effects which different philosophical positions have on understanding a notion. An explanation can be offered based on Bachelard's own example, the notion of mass:

Bachelard distinguishes five basic philosophical approaches which condition the different aspects of our personal application of the notion of mass. Naive realism, positivist empiricism, Newtonian or Kantian rationalism (classical), complete rationalism (relativistic) and his dialectic rationalism. At first glance this really looks like a fatal contraction of the vast and diverse field of philosophy into five branches. Nevertheless, if we pay attention to the analogy Bachelard had in mind, then his approach becomes more reasonable. Think of the visible spectrum of light from violet to red; it is a continuous spectrum. Each color merges into the neighboring one and provides all different kinds of shades of color. The same applies to all the possible shades of philosophies. However, within the spectrum of light, pure spectral colors[21] are identifiable. In an analogous way, Bachelard designates five basic philosophies which allow us to categorize the vast spectrum of philosophies. It is implicit with his approach that the categories devised are not very clear-cut and in turn also consist of a spectrum of different shades. Just as yellow implies all different kinds of yellow.

Again, the visual depiction of the epistemological profile is intended to illustrate the relative relation of the five philosophies to each other on the x-axis, like a spectrum. The different values on the y-axis of the graph account for the different frequencies of usage, which can also be interpreted as a relative measure for the relevance of our beliefs regarding this notion. Exact values are of no matter here because, according to Bachelard, such an epistemological profile always refers to a specific notion held by a specific personal mind in time and space. Only a complete collection of the epistemological profiles of all fundamental terms could become the object of what he calls philosophical spectral analysis, which for Bachelard would be the basis for a comprehensive psychology of the scientific mind. Admittedly we will not get that far here, but will use the epistemological profile as an instrument to reflect on the comprehension of counter-intuitive notions; specifically that of quantum entanglement.

To begin with, we promptly introduce Bachelard's very accessible example of the notion of mass. In principle, almost every person should be capable of sketching her own epistemological profile of her personal scientific understanding of the notion of mass through introspection. Just like Bachelard, we will take the profile given in figure 5.2 as a common one for our time and culture. Such an assumption is appropriate because in this regard not

[21] Colors that are caused by a relatively narrow frequency band of light in the visible spectrum. Violet, blue, green, yellow, orange and red.

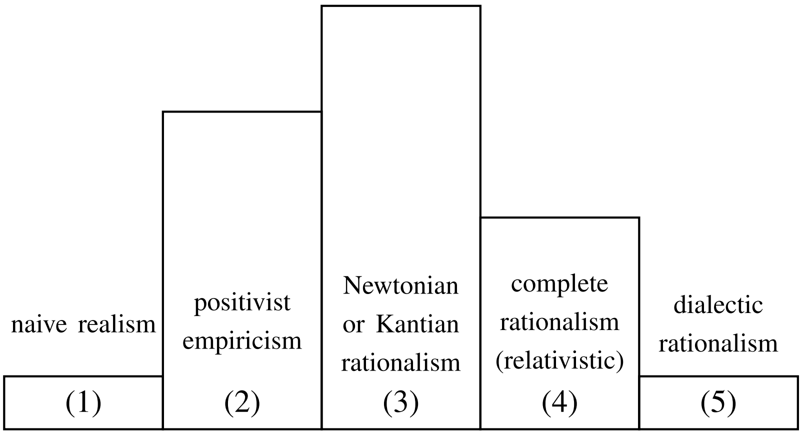

Figure 5.2: Epistemological profile. Source: Bachelard 1980, *p.57*

much has changed, although more than seven decades have already passed since his writing. In addition, the most frequent usage of the notion of mass will nowadays resort to a Newtonian or Kantian rationalistic understanding (3). This is what is mainly taught in our general education system, namely classical mathematics and elementary physics (classical mechanics).[22] Nevertheless, it must be granted that growing importance has been laid on the relativistic understanding of mass by the likes of Einstein.[23] Anyway, it is still not that accessible, as the classical rationalism described before is very pervasive[24]. Hence a completely rationalistic (relativistic) understanding of mass accounts for a smaller share (4). The positive empirical comprehension of mass is of course strongly represented (2). Weighing is an activity which is not only important to science, but also widespread in our daily lives. It relates a distinct number to a distinct mass.[25] The scrutinizing glance at the bathroom scale, a frequent routine for many, is a telling form of behaviour in this regard. Besides, from time to time we do think of mass in a naive realistic way (1). Namely in metaphors where we relate mass to nothing concrete but an undefined amount of some quantity. For instance a mass of apples, without weighing them or putting them in any rationalist scientific context. This involves a naive realistic understanding of mass; like just stating that there 'a lot of apples'. The smallest share in this spectrum is held by dialectic rationalism (5). This is probably the hardest one to circumscribe, because it is precisely the openness and dialectic between phenomenon and noumenon which Bachelard tries to advocate. The details of this

[22] Inertial mass is a quantitative measure of an object's resistance to the change of its speed. Gravitational mass is a measure of magnitude of the gravitational force. Classically, the equivalence of both types of mass is noted but not explicated.
[23] See special and general theory of relativity.
[24] As indicated by its height in the y-axis.
[25] The physical concept of weight refers to a property of matter related but not equal to mass. Weight is the gravitational force acting on an object. Its mass is an intrinsic property of this object independent of gravity.

will become clearer by the end of this chapter. For now a possible example, which was not within the scope of Bachelard's considerations because of its newness, is the role and the search for Higgs boson as a hypothetical massive elementary particle predicted by the Standard Model. The so-called Higgs mechanism describes how elementary particles obtain their mass. We could think of it as a good example of how to envision the relationship between rationalization and realization in the sense of Bachelard. For the simple reason that it is a profoundly rational consideration within the Standard Model which, of course among other motives, triggered the building of the largest machine to this day in order find the origin of mass.[26]

Epistemological Profile of Quantum Entanglement

Bachelard's example of the epistemological profile of the notion of mass seems to be quite emblematic for many of our foundational terms. What would an epistemological profile of quantum entanglement look like? Bachelard does not consider it directly, but in a short passage *(Bachelard 1980, p.121)* he indicates which unusual characteristics a epistemological profile of the Heisenberg uncertainty principle would have. As the uncertainty principle is fundamental for quantum mechanics, we will see that it is apt to take up these specifics mentioned by Bachelard and transfer them into the epistemological profile of quantum entanglement: Namely Bachelard denies that the Heisenberg uncertainty principle has any realistic relevance in everyday life. The same can be said about quantum entanglement, but even more so.

Two other sources are available for constructing the epistemological profile: my personal comprehension of the notion of quantum entanglement and the statements of the interviewees regarding this topic. It is important to recall that Bachelard's epistemological profile is a spectrum of the personal psychological effects of the different (philosophical) schemes operating in conceptualization. Although it is a matter of the individual mind, it is also localized in an intellectual culture of the respective period and community. Hence the epistemological profile of the notion of quantum entanglement which will be devised here is admittedly deduced from my personal understanding. Nevertheless, as a student of physics I am trained in quantum entanglement to a degree that is standard for the people scientifically involved with this topic. Thus I find myself as part of the community at issue in this regard, especially when drawing on the people I interviewed in the course of this thesis. They are the ones conducting opto-mechanical experiments and hence are engaged with the notion of

[26] see *Cern 2011*.

quantum entanglement not only theoretically, but also empirically.

Of course the questions and the answers in the interviews concerning this topic do not have the analytic precision implicated by the instrument of the epistemological profile. They are more about the general nature of quantum mechanics and the difficulties in understanding it properly. However, they strongly hint at what the epistemological profile of quantum entanglement should eventually reproduce. One very representative quote is the following:

> "*I already dealt with the Bell inequality, and so on, in my diploma thesis. That is the 'classical' example within the quantum mechanical context. And yet, to this day, I have to reconsider it from a changing perspective again and again. Yet, you have to understand what is happening there once again. I think that is the fascinating part. Because you can't lay your finger on what quantum physics really is. And how to speak about it properly. Therefore you have to develop so many different models in your mind.*" [27]
>
> – Nikolai Kiesel, *(Interviews 2011c, §32)*

An understanding of this kind and the difficulties in conceptually grasping quantum entanglement are characteristic and can be adequately expressed by the peculiar epistemological profile to follow (see figure 5.3). Not because I am able to assign the exact true weights to the different columns of the spectrum, but because I reconstruct the structure in a reasonable way, i.e. the relation of negative and positive values, of the profile. This is thus where I would locate counter-intuitiveness in this matter; namely in the context of the single notion.

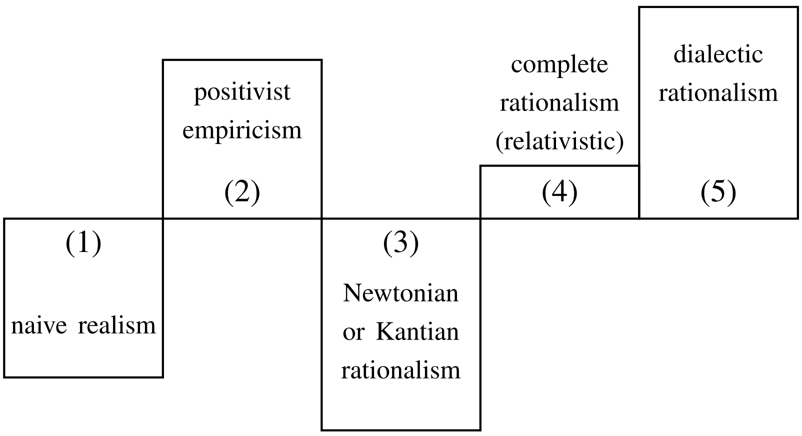

Figure 5.3: Epistemological profile of quantum entanglement.

Like Bachelard with the Heisenberg uncertainty principle, I will draw the naive realistic (1) aspects of the profile with a negative value. There is nothing in everyday life that would bring about an intuitive comprehension of quantum entanglement. Moreover, there is no

[27] Translated by the author.

meaningful usage of the term in everyday life as there is with the notion of mass. At first glance it can be argued that the value should be zero. This would signal that the naive realistic perspective would not matter at all. However it does, because the experience and the thinking common to our daily life also preforms our scientific mind. This is also in line with Bachelard, because for him each 'column' in the spectrum can be regarded as an epistemological obstacle to the others. We have to take this seriously in the case of quantum entanglement. It is not just that there is no everyday life experience of quantum entanglement, but common knowledge about daily life contradicts the findings of the theory and the experiments concerning quantum entanglement. In order to take this into account, a negative value is assigned to naive realism.

The same considerations also apply to Newtonian or Kantian rationalism (3) because, as has been shown throughout this thesis, there is a fundamental contradiction between the classical assumption about realism and/or locality and the fundamentals of quantum mechanics. Owing to the Bell experiments there is also evidence that theories assuming a hidden variable to accommodate for the more intuitive assumptions of reality and locality do not hold true. However, it (psychologically) remains a vital part of the notion of quantum entanglement, but in a negative sense. Again, as with naive realism, Newtonian or Kantian rationalism as the philosophy of classical physics is incompatible with quantum entanglement, and is thus a resistive element in the spectrum, and a negative value is assigned to it.

The positive empirical comprehension (2) concerns the experiments conducted with quantum entanglement, or rather their measurement results. It ranges from the Bell experiments to the more complex set-ups of late, such as in the field of quantum opto-mechanics. A good indication of why this perhaps deserves a rather high value is that quantum entanglement is not only a primary fundamental phenomenon which is being investigated, but also a means exploited in various applications. Examples of this are quantum teleportation, quantum encryption and quantum computing. The experiments realize quantum effects with commonly accessible concepts[28]. It is the results, or let us say the results in the light of the theory, which are non-classical and hence counterintuitive. In general, for quantum entanglement it is a correlation of two observables.[29] In the case of the paradigmatic experiment of quantum opto-mechanics featured here, it concerns the entanglement, i.e. non-classical correlation, of the intensity of the light in the cavity and the deflection of the cantilever.[30] More generally in the words of two of the interviewees:

[28] For example see cantilever, cavity, radiation pressure, and so forth in the paradigmatic experiment of this thesis.
[29] See the definition of quantum entanglement in section *2.2 Schrödinger's Definition of Entanglement*
[30] See section *3.2 The Experiments*

> "*In the moment when you stand in front of the experiment you are indeed always dealing with classical apparatuses.*" [31]
>
> – Nikolai Kiesel, *(Interviews 2011c, §39)*

> "*So I'm doing classical physics [sarcasm]. The hope behind the experiment is to really go into the quantum regime.*"
>
> – Florian Blaser, *(Interviews 2011f, §53)*

From this it appears that we have to consider the status of the positivist empirical perspective twofold. On the one hand, most of the experimental apparatuses involved and the readings of the instruments are classically intelligible. They are not in conflict with naive realism (1) or Newtonian or Kantian rationalism (3). Hence on this level there is no contradictory relationship between those three philosophies [(1), (2) and (3)], and the epistemological profile should tend to look like that of mass (see figure 5.2). That means all three perspectives, naive realism (1), positive empiricism (2) and Newtonian or Kantian rationalism (3), are non-contradictory and hence all positive. However, on the other hand the final outcome of the experiments (i.e. the conclusion of the measurement readings as quantum entanglement, as already shown), contradict the account of naive realism (1) and of Newtonian or Kantian rationalism (3).

In order to somehow incorporate this twofold situation with regard to experiments dealing with quantum effects, the relationship between the three philosophies [(1), (2) and (3)] is devised as shown in figure 5.3. The perspective of positive empiricism (2) is drawn with a high positive value in order to appreciate the positivist concentration on the empirical readings of classical instruments, as is also the case with quantum experiments. However, the contradiction of the experimental outcome to a naive realistic (1) and a Newtonian or Kantian rationalist (3) point of view is expressed by the relation of the positive (2) to the negative (1) and (3). Of course this adds to the previous arguments which already made us assume the naive realistic (1) and the Newtonian or Kantian rationalist (3) perspective to be negative on their own account.

The completely rationalist or relativist perspective (4) is to my mind difficult to properly take into account. On a theoretical level, quantum mechanics has not yet been adequately reconciled with Einstein's general theory of relativity. Apart from that, the Copenhagen interpretation of quantum mechanics has a tendency to introduce relativity at the point of measurement. As the determination of the property value of a particle is a matter of measurement, it can be comprehended as being relative to the measurement itself and the measurement con-

[31] Translated by the author.

text.[32] In sum, this aspect of the epistemological profile of quantum entanglement appears to be neither very tangible nor very conclusive to me. Due to these shortcomings and its rather minor importance for the overall argument, I cautiously assess it to be of low relevance.[33]

On the contrary, dialectic rationalism (5) is considered to be of high value. We do not have to fully comply with Bachelard's understanding of this aspect in the epistemological profile. For a start, we can conceive of it more modestly as the very comprehension which scientists engaged in this field have about quantum entanglement; aside from all the other momenta in the spectrum of the epistemological profile. In concrete terms, this contains for instance the underlying assumption of quantum entanglement that particles do not possess definite property values prior to their measurement. And that the correlation established by quantum entanglement is independent of the distance between the objects involved. Schrödinger's definition of quantum entanglement principally also falls into this category. For now, this is only a quantitative enumeration of statements about what scientists consider quantum entanglement to mean, besides the difficulties involved with the classical understanding.

In order to study some of the qualitative aspects of this dialectic rationalism, it eventually becomes necessary to take a closer look at Bachelard's *Philosophy of the No*. This will also allow us to once again stress the difference between the counter-intuitiveness of quantum entanglement and that of other scientific notions.

Philosophy of the No

Bachelard wrote a short and accessible introduction to his *Philosophy of the No* (*Bachelard 1980, p.155ff*). Generally speaking, it is not an appeal for plain negation as an end in itself. It is a reasonable criticism, i.e. expressing a substantiated *no* against a given understanding of a matter, which is neither an arbitrary negation, nor a negation without evidence, nor rushing a negation out of principle. What it rather implies is a strong synthetic and constructive impetus.

Examples for Bachelard are the panning out of Newtonian mechanics as a special case of non-Newtonian mechanics (i.e. the theory of relativity), the Euclidean within non-Euclidean geometry, and so on. In these cases, the negation of key assumptions of the initial theory did not make them incorrect, but allowed them to be synthetically superposed in a more complete understanding. As Bachelard puts it, there is no automatism which would allow

[32] This is generally referred to as the so-called measurement problem in quantum mechanics.

[33] Nonetheless, this aspect is very underexposed here and would deserve more attention beyond the scope of this thesis.

us to logically reduce the new tenets to the old ones *(Bachelard 1988, p.13f)*. For him they are true irreversible extensions not only to the matter, but also to the scientific mind comprehending it.

Therefore, as a means of generalization and conceptualization, the philosophy of the no retains what it negates. The example Bachelard refers to is the notion of the atom *(Bachelard 1980, p.159f)*. Nowadays the most common intuitive image of the atom, mentally and pictorially, is a simplified version of Bohr's model. It basically resorts to an analogy with the model of the planetary system. The naive realistic picture is that the electrons circle around the nucleus on defined paths due to electrostatic forces, just as the planets orbit the sun due to gravitational forces. This is a nice and intuitively accessible picture, but one we are not entitled to take too literally from a scientific perspective. For instance, according to Heisenberg's uncertainty principle the electrons are not explicitly locatable on their way around the nucleus. This is just one of the many more adaptations to the model needed in order to satisfy other physically relevant tenets. Concerning the notion of the atom, Bohr's model is therefore merely the starting point for an application of critical scientific thinking that dismisses, i.e. says *no* to, an ever growing number of details implicated by the original material. Increasing scientific knowledge about the atom therefore increases the divergence between the initial intuitive image and the current scientific comprehension of the notion of the atom.

The essential insight of Bachelard is that the actual notion of the atom always retains a reference to its relative historical genesis from prior realistic and rational representations. This is exactly what the epistemological profile tries to make explicit. Whatever is abandoned from the comprehension of the notion due to scientific scrutiny still remains inherent to the newly evolved notion. In short, for Bachelard the actual notion of the atom is the sum, and not the result, of the scientific criticism based on its first intuitive images. These *primary imaginings* are very important, because they serve science as an originator which is intended to be eradicated but which one ultimately never succeeds in doing. In this regard Bachelard emphasizes the atom model of Bohr as a very good representative of its kind. Scientifically speaking, almost nothing remained from the original picture, and its dissolution necessitated so many *no's* that scientific knowledge about the atom made huge progress. It is important to note that these initial intuitive images are of course not primary in a strong sense, i.e. metaphysically given or universals. They should only be assumed as being initial in the weak sense that they are only a relative starting point depending on the currently prevailing scientific mind. This already becomes obvious in the example stated here. The Bohr model of the atom is an initial intuitive image bound to a certain era and a certain community. In the past the notion of the atom and hence the epistemological profile has certainly factored in other naive realistic and rationalist images than the Bohr model. Accordingly the notion of the atom will certainly refer to (new) intuitive images due to the progress of science and of the scientific mind in the future.

However, in this day and age the notion of the atom has undergone the very conceptualization depicted so far. This can also easily be seen in how the notion of the atom is taught. The Bohr model is still the earliest starting point for introducing somebody to what is known about atoms. In this regard the educational process is thus a replication of the historical process of conceptualization.

Bachelard has put forward a fairly plausible example regarding the notion of the atom. How about the notion of quantum entanglement? What would the initial intuitive image be in that case? Is it possible to reconstruct it in accordance to the *Philosophy of the No* of Bachelard? What are the difficulties in doing so? And what is the difference compared to the notion of the atom?

From all what has been said so far, it should be easy to identify the initial image that is the starting point of the notion of quantum entanglement. Indeed it is remarkable that it is the absolute starting point for this notion; there was nothing beforehand. Although the naming followed shortly afterwards by Schrödinger *(Schrödinger 1935)*, it has to be remembered that devising the notion was a response to Einstein et al. *(EPR 1935)*. Therefore it is apt to assume the EPR thought experiment as the actual underlying image of the notion of quantum entanglement.

Therefore the first to apply something like a *no* to Einstein's comprehension of the matter was Schrödinger. Besides being the first *no*, it was also the essential one, because it reversed the entire reasoning of the thought experiment. As we already know, Einstein et al. concluded that the theory of quantum mechanics is incomplete on the basis of the fundamental assumption that objects have property values independent of their observation and the impossibility of 'spooky action-at-a-distance'. Schrödinger, however, starts out by assuming that the theory of quantum mechanics is complete and thus concludes that the assumptions embraced by Einstein et al. cannot be upheld.

Based on this, we can certainly identify a major difference compared to the image of Bohr's model in the notion of the atom. As already stated, Bachelard depicts the progressive dismantling of the initial intuitive image by scientific criticism; i.e. saying no to the details the image implies if taken too literally. This is not the case with quantum entanglement. On the contrary, the first step of progression in the conceptualization of quantum entanglement is already the complete reversal of the proposition implied by the starting point. This very situation has been incorporated into the previously devised epistemological profile of the notion of quantum entanglement by assuming negative values for the naive realistic (1) and the classical rationalistic (3) perspective (see figure 5.3).

Consequently a distinction can be drawn on the basis of the relation of the conceptualization towards its initial intuitive image. This difference also characterizes the grade of counter-intuitiveness inherent in the notion. At first sight both scientific notions, that of the atom and that of quantum entanglement, are counter-intuitive in relation to normal everyday life experience. However, taking a closer look shows that they are distinguishable in this matter exactly because of the differing status of their initial images.

The notion of the atom is counterintuitive because the initial intuitive image is refined by a succession of critiques, whereby each of these steps is counterintuitive in relation to the initial intuitive image. This means that in the case of the notion of the atom the counter-intuitiveness is the sum of counterintuitive refinements employed on the initial intuitive image. It is important to note that the relation to the initial intuitive image prevails in a positive way. Although almost completely altered by the criticism, it is possible to back-track and hence reproduce a positive connection to the naive realistic aspects of the notion of the atom.

In contrast, the initial image of the notion of quantum entanglement is somewhat counterintuitive all along. The starting point of the notion is already a radical challenge to physically very intuitive assumptions[34] which are fundamental to our common comprehension of the world. A cue that the counter-intuitiveness of quantum entanglement enters right at the beginning comes from Schrödinger himself. He devised the notion of quantum entanglement, and in the very same paper also the thought experiment of Schrödinger's cat *(Schrödinger 1935, p.812, vol.48).* The latter is the radical upscaling of the consequences of quantum entanglement to human dimensions. Thus Schrödinger vividly expressed the fundamental counter-intuitiveness of his findings right away.

This means that the counter-intuitiveness of quantum entanglement is already constitutive of the initial image of the notion and not so much a matter of its refinements. We could practically speak of an *initial counterintuitive image* as the starting point of the conceptualization of quantum entanglement. It can thus be deemed impossible to reconstruct a positive connection to any naive realistic or classical rationalistic aspects.

The fact that quantum mechanics, and with it quantum entanglement, is backed by numerous experiments is of no great relevance here. For example, the experiments of quantum

[34] E.g. objects are bearers of distinct property values independent of their observation and there is no superluminal influence between distant physical objects.

opto-mechanics try to establish quantum effects at human-size scales. They offer a sort of relationship to the everyday world, because the experiments mostly rely on classical instruments and concepts in order to realize quantum entanglement. We may recall the basic physical concepts put forward earlier in this thesis, such as two opposing mirrors making up a cavity, the radiation pressure of light and so on[35]. None of them are very counterintuitive per se. However, there is a regime where all of this classical set-up realizes data which is only comprehensible in terms of quantum entanglement. This passage seems impossible to comprehend solely by empirical means and without recourse to a positive intuitive image. Of course these considerations were also taken into account in the previously devised epistemological profile of the notion of quantum entanglement (see again (2) in figure 5.3).

Conclusion

We were able to study the specifics of the counter-intuitiveness of the notion of quantum entanglement by employing parts of Bachlard's epistemological framework and examples. Following Bachelard's main thought that the comprehension of a notion is comprised of a spectrum of philosophical perspectives allowed me to generally illustrate the rooting of counter-intuitiveness in the very notion. The specific differences between quantum entanglement and, for instance, the *classical* notion of mass were shown by producing an epistemological profile of quantum entanglement. As a result, the notion of quantum entanglement revealed a repugnancy in its relationship to the naive realistic and classical rationalistic aspects. More specifically, a distinct counter-intuitiveness for the notion of quantum entanglement has been identified by also considering the historical genesis of conceptualization based on Bachelard's *Philosophy of the No*. Namely a counter-intuitiveness that already emerges in the initial image, the originator of a conceptualization. In other words, instead of an initial intuitive image underlying the comprehension of a notion, such as with common notions, an initial *counterintuitive* image is constitutive of the comprehension of the notion of quantum entanglement.

The path which has led us to these conclusions has been pursued in the light of a weak type of Copenhagen interpretation, and we will continue to follow it. As has been repeatedly mentioned, other interpretations such as Bohm's mechanics, Many Worlds and so on, are not within the scope of this thesis. Therefore it must remain open, whether reasoning based on different interpretations would have resulted in widely differing conclusions. In principle it should be equally possible to also employ the same instruments, e.g. devising

[35] See section *3.2 The Experiments*

an epistemological profile, on all other interpretations; with certainly equally exciting results. The circumstance that strongly speaks for the generality of the conclusions drawn here is that the as yet unsuccessful search for a proper interpretation of quantum mechanics parallels the lack of an initial intuitive image for the notion of quantum entanglement. The sought-after interpretation would have to lessen the contradicting aspects of the current comprehension of the matter. In this way it would also automatically supply an initial intuitive image which would dissolve the counter-intuitiveness of our depiction. The other way round, if we can somehow come up with an initial intuitive image of quantum entanglement, it would be rather strange to think that a proper interpretation could not easily be found by straight-forward reasoning.

Of course the hunt for a proper interpretation or an initial intuitive image is one possibility to ease the counter-intuitiveness and the problems in comprehending the subject matter. The alternative, followed up on in the next section, springs from another consideration of Bachelard *(Bachelard 1988, p.11).* He stresses that our scientific mind, i.e. our reasoning and intuition, is mainly instructed by synthetically produced experience. Hence instead of searching for an initial image that fits our scientific mind, it is all about evolving our scientific mind in a direction where the counter-intuitiveness of quantum entanglement becomes *'inconceivable'*.

6 Coping

Until now we have dissected the specifics and highlighted several of the characteristics of the counter-intuitiveness of quantum entanglement. In the course of doing this, I have assumed and shown that counter-intuitiveness can be understood as an indicator of a problematic situation; moreover a prominent one.

That raises the following questions: If it is considerable and undesirable, then how should we cope with it? Can we look forward to resolving the situation and improving comprehension of the matter? What are the conceivable prospects? In principle, several scenarios are imaginable; none of them are really exclusive, but nevertheless distinguishable in a broad outline.

Probably the most wide spread one is the hope for a more viable interpretation of quantum mechanics. One which is not smitten with counter-intuitiveness. Such a fitting interpretation may be found due to some flash of inspiration either based on that which is already known, or led by new discoveries. The following quote is an expression of such an approach:

> "*As long as there are, how shall I put it, phenomenal equivalent interpretations, I mean those which obviously do not produce any contradiction to the observations. As long as there are so many phenomenally equivalent world views, I think our reasoning is still fundamentally wrong. I really think that there can be only one. Now the question is whether we can learn new things by experimenting.*" [1]
>
> – Markus Aspelmeyer, *(Interviews 2011g, §70)*

The last sentence of the quote was rather a rhetorical question when one considers that quantum opto-mechanics, the research field of the experimental group, has the basic intention of realizing quantum effects with larger systems. Namely, they plan to stretch the applicability of quantum entanglement to the limits, other than technical ones, and see what happens there.[2]

[1] Translated by the author.

[2] For instance, one of the challenges of the coming years will be to take a closer experimental look at the relation between quantum physics and gravity *(Interviews 2011g, §73)*.

Another scenario is to contest the importance of the problem of counter-intuitiveness. From a pragmatic point of view, it can be argued that for doing the actual physics it is not important whether the corresponding theory is intuitively comprehensible or not. What is mainly valued with a theory is the power of its mathematical framework and how it enables us to predict and describe the results of the experiments. Quantum mechanics is known to fulfill these pragmatic criteria very well. A specific variant of this scenario is made explicit in the following quote:

> "*What entanglement is as such mainly defines itself by what you can do with it, because I believe nobody really knows what it is. You know a little bit about how to quantify it. How you can tell if you have got a lot of or a little entanglement. And you ... oh well, you can see the effects. Sort of teleportation or transmission of information. Simply a resource.*" [3]
>
> – Jonas Hörsch, *(Interviews 2011e, §110)*

> "*And that is entanglement for me. This operational complex. Having said that I cannot say what it actually is either.*" [4]
>
> – Jonas Hörsch, *(Interviews 2011e, §114)*

However, in my opinion the question remains whether such a 'retreat' into mere mathematical craftsmanship and an operational understanding of the matter is reasonable in the final consequence. With all the opportunities theoretical physics and, more generally, mathematics embodies, well justified by its rise in importance in physics, it must be pointed out that other vital traits of the discipline of physics also have to be kept in mind. Specifically the trait which tries to consistently interrelate the knowledge gained with our realm of experience. Bluntly put, physics, in contrast to mere mathematics, is commonly accepted to yield conceivable explanations – going well beyond operational definitions – about the physical world.[5] Nonetheless, conceiving quantum entanglement as a resource, like energy, is indeed common *(Bub 2010)*.

The third scenario concerns the ability of scientific thinking to progress, adapt and familiarize itself with the matter at hand. This means that we might not just rely on ignoring counter-intuitiveness, awaiting new scientific facts or sudden inspiration, but take into account that our reasoning in that matter is also subject to development and change. The following two

[3] Translated by the author.
[4] Translated by the author.
[5] For instance, the parameters of statistical thermodynamics are made conceptually comprehensible by interrelating them with the intuitive picture of vast quantities of molecules colliding with each other. In the context of the epistemological profile this explanatory effort is connected to utilizing the share of naive realism (see section *5.3.2 Epistemological Profile of Quantum Entanglement*) and stress the historical, pedagogical aspects in order to further comprehension of the matter.

statements of an interviewee indicate the possibility of such a change in thinking and in consequence how the matter is taught:

> "*This battle between realists and local non-realists is quite fascinating. Because right now it is becoming hard to find a guy who believes in local hidden variable theories, or even non-local hidden variable theories. To me personally this looks like people trying to keep the old way of looking at things; not making the step necessary to understand quantum mechanics.*"
>
> – Florian Blaser, *(Interviews 2011f, §51)*

> "*Unless there is a big change to quantum mechanics [...], I think the change that might happen is only at the pedagogical level. People learning differently, having access to more examples.*"
>
> – Florian Blaser, *(Interviews 2011f, §62)*

Particular attention will be paid to the last sentence of this quote, as it motivates the investigation of pedagogics[6] and technology[7] as means of coping with the counter-intuitiveness of quantum entanglement.

For now, it is important to summarize that these scenarios are neither a complete line-up nor exclusive alternatives. In a probable outlook, more or less all of them will play a certain role: It is very understandable to concentrate on the detailed development and experimental application of the theory, when trying to rationally resolve the counter-intuitiveness of the matter on a general level seems so fruitless; as I have tried to illustrate by this thesis. Thus in the practical work done in this field, it is assumed that scientific facts are to be found in the future that if not bluntly suggesting a single valid interpretation, at least exclude some of them from the current plethora of possible interpretations. Of course there is more to science than mere craftsmanship[8]; for instance its conveyance or its history (pedagogics). Subsequently we have to take into account that science can be conceived as a socio-cultural complex, generally disposed to proceed also in its reasoning.[9] This implies that in the process of research, of advancing knowledge and conveying it, not only the comprehension of the matter changes, but in the long run also the intuitions about it. Matters which today seem to be counterintuitive are not necessarily immune to being perceived as intuitive when one has become accustomed to or familiarized with them over time. It is thus conceivable that the issue of the counter-intuitiveness of quantum entanglement discussed in today's context may dissipate and become a non-issue in the (near or distant) future. The reasons for this conjecture will be presented and questioned in the remainder of this chapter.

[6] See section *6.3.1 Pedagogics*.
[7] See section *6.3.2 Technology*.
[8] Cf. the philosophical term *techne*
[9] See section *6.3 Bachelard: Reason Instructed by Fabricated Experience*.

6.1 Aim of Science? Coherent System of Assumptions

Thus far I have established that the counter-intuitiveness of quantum entanglement is problematic in its own right. However, I have not discussed whether this is a relevant matter for the science of physics. In other words, is there a fundamental need for science to get rid of the incoherences in its assumptions – in our more comprehensive diction referred to as counter-intuitiveness – or can the science of physics, or even more precise the physicists, live perfectly well with sets of basically contradictory assumptions?

In order to illustrate what could be meant by this, we will take a look at parts of the interview conducted with Markus Aspelmeyer. In *Interviews 2011g, §50-71* a dialogue unfolded which precisely addresses this topic. The starting point is the widely shared idea[10], here in the words of Aspelmeyer, that the ultimate aim of science is that have all your expectations should be consistent with all your observations. This vindicates the assumption of at least one[11] world view which is totally consistent with all our observations. However, in the light of fundamentally conflicting assumptions visible in the counter-intuitiveness of quantum entanglement, for example, Aspelmeyer is willing to allow for some doubt:

> "*I think, at least in the empirical sciences, there is the implicit assumption that a world view [Weltbild] exists which in the end can be carved out. However, I want to underline that this perhaps must not be the case. So maybe complementarity is something that is also relevant to epistemology. Complementarity is something, also in principle, which is applicable to world views [Weltanschauungen]. That there are different, equivalent descriptions of the world, which are mutually exclusive because they use complementary notions, but refer to the very same nature, the very same being [Sein]. That's a maybe.*" [12] [13]
>
> – Markus Aspelmeyer, *(Interviews 2011g, §53)*

All in all the general aspiration of the science of physics, put forward here, is to find a world view which is maximally consistent. Hence it is apt to claim that counter-intuitiveness in

[10] Certainly this is only one of many possible conceptions of science and its aims. However, it is the one I found with the people interviewed.

[11] Multiple to unlimited equivalent world views are also conceivable and not precluded.

[12] Translated by the author.

[13] As an aside, it is apposite to suggest that complementarity can easily be comprehended in two different ways. First it is all about world views being different, even mutually exclusive, but equally capable of consistently describing the observable data. On the other hand, the second concerns the situation where ultimately all the observable data cannot be consistently apprehended by one world view, but only by a multitude of mutually exclusive world views. This is a much stronger statement as it precludes the possibility of a final coherent system of assumptions.

this field is also an issue for the science of physics in general, as it strives to overcome it in the long run. This is nicely backed by the general tenor that pervaded the interviews. The difficulties in comprehending the matter, i.e. counter-intuitiveness, are not seen as a source of despair but more as a motivation. Almost all of the interviewees stated that they are challenged by the puzzling features of the matter rather than daunted by them. For example see Interviews 2011a, *§45* and Interviews 2011f, *§51.* A more hands-on motive for experimental work is nicely revealed by the following quote:

> "*When standing downstairs [in the lab] and optimizing something, this [question about the comprehension and counter-intuitiveness of quantum mechanics] is of course not relevant. There I couldn't care less. But it is simply my motivation, when I am tinkering around to obtain the last few percent of AOM [acoustic-optical modulator] efficiency [...].*" [14]
>
> – Witlef Wieczorek, *(*Interviews 2011d, *§74)*

At this point it must again be remarked that this specific orientation towards the larger questions about the comprehension of the matter is probably also owing to the fact that research on the foundations of quantum physics is a core theme of the quantum institute here in Vienna. Hence the validity of this observation is first and foremost local.[15]

6.2 New Generations of Scientists

Another general conception we can draw on in studying how the issue is coped with is the following: New findings which maybe hard to grasp and their handling need one, two or more generations of scientists to be taken for granted. Max Planck, a founding father of quantum physics[16], who was himself not very confident with his own findings, mentioned this idea in his *Wissenschaftliche Selbstbiographie, Leipzig 1948*. He wrote that new scientific truths are not established by convincing their opponents, but by them dying out and a new generation which has been raised and acquainted with the truth taking their place. Another and maybe more fitting reference are the following words by Richard Feynman:

> "*We always have had a great deal of difficulty in understanding the world view that quantum mechanics represents. At least I do, because I'm an old enough man that I haven't got to the point that this stuff is obvious to me. Okay, I still get nervous with it. And therefore, some of the younger students ... you know how it always is, every new idea, it takes a generation or two until it becomes obvious that there's no real problem. It has not yet become obvious to me*

[14] Translated by the author.

[15] Cf. section *B Group: Supplementary Notes*

[16] See for instance law of black-body radiation *(*Compendium 2009, *p.39f).*

> *that there's no real problem. I cannot define the real problem, therefore I suspect there's no real problem, but I'm not sure there's no real problem.*"
>
> – Richard Feynman, *(Feynman 1982, p.471)*

This quote is especially telling, because it is eminently vague and hence fertile soil in which to raise the following three issues:

First of all, we will identify what Feynman is circumscribing as a real problem, including doubting its existence, with what in our diction is label with counter-intuitiveness. Indeed it appears to be rash to equate something very specific, such as what I have developed so far, with something so vague as Feynman puts it. However, this reaffirms the picture advocated in this thesis that our study of the counter-intuitiveness of quantum entanglement is one of many possible dedicated instances of the prevalent discomfort with the explanatory inconsistency of the matter. What Feynman vaguely outlined as a real problem can indeed be pinpointed, but only in the light of an already specific understanding.

The second element of vagueness in the quote concerns the meaning of 'generations of scientists' in this context. How long does a generation of physicists last? What is a generation, and especially in the context of quantum physics? Answering these questions adequately certainly exceeds the scope of this thesis. Here I will primarily raise such questions. The dominating concerns are the conflating definitional aspects of the term generation. In general, generations are separable in a cursory manner based on time constraints. However, these time constraints which separate generations only make sense due to other distinguishing features. For instance, a human familial generation can be defined by the average time between a mother's first offspring and her daughter's first offspring. This implies that not only the biological, but also all the social circumstances[17] of procreation are represented in the time tag a generation is labeled with. In the context of generations of scientists, this involves not only the reproduction of knowledge, say education, but also for instance the time it takes new generations of scientists to become influential and efficacious. What are apt criteria for calling the upcoming scientists a new generation? Exaggerating the quote by Feynman illustrates the intricacy of the issue. The general idea is that the comprehension of a matter changes over the course of one or two generations of scientists. In order to distinguish between generations, we need criteria which reveal them to be specifically different from others. A simple criterion such as time which has passed is not sufficient. The most fitting criterion would be that of a fundamental change in the comprehension of the matter

[17] E.g. when is it culturally accepted and common to become pregnant. For an introduction to the topic and as example see *Denham 2011*

at stake.[18] However, with such a definition of generations it is rather circular to state that there is change through successive generations. We can make this even more tangible. Quite some time has passed since the beginnings of quantum physics, and even Feynman's quote is already thirty years old. Have new generations of scientists already emerged in this field of research? In terms of the time scale, we might have to say yes. In terms of generations that have fundamentally changed their comprehension of the matter, we might be inclined to generally tend to say no. As shown in this thesis for example, we are able to call the fundamental questions raised at the beginning of quantum entanglement (EPR, Schrödinger) still valid, relevant and unresolved. Thinking in generations in this matter thus can be very ambiguous if examined in detail, as has just been hinted at.

The third issue which is vague in this quote by Feynman is the mechanism or process in place which makes generations proceed in their thinking. What is it that makes us assume that new generations of scientists will cope differently with the questions raised by older generations? It will not just be time passing by. Hence this is again a vast question to elaborate on and can certainly not be dealt with exhaustively within the scope of this thesis. As a consequence I will just take a look at the two already broached aspects of pedagogics and technology in the following sections.

6.3 Bachelard: Reason Instructed by Fabricated Experience

Again we will first employ an idea stemming from Gaston Bachlard. He tries to show that scientific thinking is essentially oriented towards the realization of the rational *(Bachelard 1988).* Thus Bachelard establishes that this type of realization is the unique feature of today's[19] scientific thinking, which clearly distinguishes it from the preceding ones. This realization has nothing to do with a traditional philosophical realism. It is a second order realism which is a response to a familiar reality and which is in conflict with the immediate. It is a realism based on a realization of reason instructed by produced experience *(Bachelard 1988, p.10f).*

In order to apply this assessment of scientific thinking by Bachelard, we first of all have to assume that it is still viable for today's science. It seems very apt to do so, especially in the case of quantum physics. Bachelard invoked quantum physics as one of the major

[18] In Kuhnean terms we might speak of a change of paradigms.
[19] Bachelard refers to the science of his days, roughly at the beginning of the twentieth century.

examples[20] for this shift towards a new scientific spirit. Furthermore, the fundamentals of quantum physics, which originated at the beginning of the twentieth century, are still generally valid and in place. Hence we can consider Bachelard's reflections appropriate for today. This can also be bolstered by recalling the actual experiments presented in this thesis.

Bachelard calls this second order realism and we can easily obtain an the idea of it in the case of quantum opto-mechanics. In the beginning there is a rational consideration that quantum effects, such as quantum entanglement, are theoretically not bound to the size of the system they are implemented with. This thought is in conflict with the immediate and familiar comprehension of the world; in our diction meaning it is counterintuitive. Hence the immediate reality is not the subject matter of our knowledge any more. Rather it is the produced reality and the experience gathered there which amounts to our knowledge in this case. Therefore experiments have to be conducted in order to create the phenomena. It is important to note that this is done not because it is easier and more reproducible to accomplish an observation in the laboratory, but the phenomenon simply would not exist if it were not produced there. For Bachelard the conditions of the produced experience are determined by the requirements of the experiment *(Bachelard 1988, p.15).* Which, as Bachelard continues, shifts the emphasis to the technical problems that have to be mastered in order to produce the phenomena. In the case of quantum opto-mechanics, as well as most other quantum experiments, it is about excluding environmental influences.[21] For example, such technical measures are the extreme cooling of the apparatus and its placing in a vacuum. Even more specifically, in the case of the experiments introduced in this thesis, the possibility to even come close to a realization of quantum effects strongly depends on the mastery of the production of these tiny high quality mirrors on a cantilever. Nevertheless, everything which is done in order to conduct the experiments is done to produce experience. Experience which again feeds back and instructs reasoning accordingly. Referring to our case of quantum opto-mechanics, the general idea, aim or hope is that by fabricating quantum effects at ever growing size scales, new experiences and hence new knowledge[22] will be gathered.

In order to better apprehend this fabrication of experience, we will take a closer look at two central aspects (pedagogics and technology) of rationally immersing oneself in a manufactured experience especially in the case of quantum opt-mechanics.

[20] See chapter 4 in *Bachelard 1988, p.86-100*

[21] See the concept of decoherence (*Bacciagaluppi 2008*; *Compendium 2009, p.155ff*).

[22] One future scenario is that of reaching a yet unknown border which would hint at a limit to the applicability of quantum mechanics, or maybe something else as yet unforeseen.

6.3.1 Pedagogics

A very important facet in the progression of the comprehension of a matter, such as the mediation of the counter-intuitiveness of quantum entanglement in our case, is its conveyance. The first things that come to mind are the educational means utilized in the rearing of new generations of scientists. However, we should not just confine ourselves to that, because there is also conveyance to those who are not future scientists; that is the ordinary people.

The understanding of pedagogics Bachelard advocates throughout his conception of the scientific mind is rooted in his epistemology *(Bachelard 1980, 1988)*. The intellectual history of the subject matter mainly determines the way its comprehension is imparted. For instance, Bachelard analyzes the passage from Euclidean to non-Euclidean geometry as a rational leap and not a continuous improvement *(Bachelard 1988, p.24ff)*. The dropping of the Euclidean assumption of parallels as lines not intersecting on a plane is not a development of Euclidean geometry itself, but due to a fundamental change of thinking. According to Bachelard *(Bachelard 1988, p.27)* it was not the case that mathematicians deeply doubted the parallel postulate, but that to a greater degree they attained the freedom to generally question the role parallels on a plane play in Euclidean geometry. In retrospect of course, Euclidean geometry is a nicely deducible special case of non-Euclidean geometry. Hence in contrast to its erratic historical genesis, the chronological latter is prior to the former in logical terms. Bachelard also analogously exemplifies the transition from Newtonian to non-Newtonian mechanics *(Bachelard 1988, p.45f)*.

According to Bachelard, the crucial purpose or assignment of the pedagogics in science is rather to replicate its historical sequence and convey the change of paradigms than to directly teach the logical order suggested by analyzing the subject matter in retrospect. This is perfectly backed by taking a look at the curriculum of today. Before we learn non-Euclidean geometry, we start out from Euclidean geometry. First we learn Newtonian mechanics before we engage with the theory of relativity. Many other examples could easily be mentioned here.

That such pedagogics are in place adds up pretty well with the other parts of Bachelard's epistemology mentioned earlier in this thesis. Take for instance his *Philosophy of the No*[23], building on the idea that our comprehension of a matter is the sum of an initial image and the rational criticism applied to it. Therefore it is that which is immediately accessible is the starting point, not only in our conceptualization, but also in our conveyance of the concept to others. For example, in order to explain or teach someone what an atom is, we most probably

[23] See section *5.3.2 Philosophy of the No*

begin by presenting Bohr's model of the atom and then inch along the inadequacies of this starting point. With that said, it is also apparent that concerning the epistemological profile of a notion, the relativistic and rationalistic fraction are formed in distinction to the preceding naive realistic and positive empirical fractions.[24]

The specifics of our actual theme of quantum entanglement with regard to the epistemological profile and its constitution on a counterintuitive instead of an intuitive image has already been explicated in section *5.3.2 Conclusion*. What is left to ask is whether this particularity of comprehending quantum entanglement also manifests itself in the pedagogics of the matter. In essence, Bachelard's pedagogic of reproducing the relevant historical change in thinking is also applicable in this case. Conveying and teaching the subject matter along the lines of a historical shift in reasoning is basically not impeded by its counter-intuitiveness. However, it adds a relevant degree of difficulty to the pedagogical undertaking.

In fact, the intricacy of the matter seems to be so problematic to convey that in actual physics training this Bachelardean approach tends to be rather avoided. The tangible lead which entitles us to adopt this assertion is the educational vita of the interviewees.[25] Across the board it can be discerned that primary access to the knowledge in this research field normally proceeds via the teaching of formalism.[26] Knowledge concerning the EPR thought experiment, for instance, the fundamental considerations of Schrödinger, Bell and so on turns out to be the result of either special personal interest[27] or individual professors committed to this issue[28]. In this regard, the following story of an interviewee is particularly informative, as extracurricular learning (in summer school) of the historical and the experimental core aspects led to personal interest in the matter.

> "*He [Reinhard Werner] had these detectors which somehow clicked subsequently [EPR/Bell experiment]. And then he also told us about Einstein's paper [EPR paper]. It certainly doesn't happen often that: A) it did not get cited very much at the beginning; almost not at all. And B) that it took thirty years until there was a relevant answer [Bell inequality]. You could measure it in an experiment. And that was somehow exciting. The history was exciting, as well as the problem itself.*" [29]
>
> – Witlef Wieczorek, (*Interviews 2011d, §15)*

[24] See section *5.3.2 Epistemological Profile*
[25] Again it is important to recall that the data collected only allows claims with local validity.
[26] For instance see *Interviews 2011d, §16-27.*
[27] E.g. see *Interviews 2011a, §19* and *Interviews 2011f, §6.*
[28] E.g. see *Interviews 2011c, §4* and *Interviews 2011e, §37.*
[29] Translated by the author.

6.3.2 Technology

If we follow Bachelard, merely with his thoughts put forward so far, it becomes clear that technology plays a major role in the realization of phenomena. The necessary deployment of technology determines the actual realization of the phenomena.

The question is how this refers to the overall issue of handling counter-intuitiveness in this matter. I fleshed out that counter-intuitiveness marks the conflict between everyday life experience and the assumptions necessary for comprehending the phenomenon of quantum entanglement. In principle it is indeed imaginable that one day our everyday life experience will be fabricated such as to render familiar the subject matter which is now conceived as counterintuitive. Of course it is impossible to imagine today what this future everyday life experience would actually be like. Nevertheless, following Bachelard, instruments are materialized theories *(Bachelard 1988, p.18);* as in our case quantum entanglement would be. Hence it would be foreseeable that technology derived from experiments made in this field would yield some sort of quantum technology that could find its way into everyday life. It is not for nothing that the prospect of highly capable appliances (e.g. quantum cryptography or quantum computing) is a driving force in this research area; at least to court the funding. Hence what we can hypothetically anticipate is an emergence of technology that materializes the momentarily counterintuitive theories of quantum mechanics.

Besides such a speculative forecast, it is probably more interesting to study the role of technology in the realm of the scientists engaged in the field. Their working environment, their manufactured experience is located in the laboratory. Devising and conducting experiments is their job. As a consequence it is obvious to assume that if they are engaged with quantum entanglement, they are immersed in all the devices and knowledge applicable to the field. Put differently, if we were to look for a place which would maximally confront us with the puzzling phenomenal experience of quantum mechanics, like quantum entanglement, we would have to visit their laboratories.

Nevertheless, immersion in a technological environment where quantum effects are produced does not self-evidently yield a better comprehension of the matter, less struck by counter-intuitiveness. Let us again make this issue more tangible by referring to the interviews with the experimenters of the Aspelmeyer group. One of the major questions posed in all the interviews was whether hands-on experimenting helps in becoming accustomed to or appeased with the counter-intuitiveness of the subject matter.

When looking at quantum opto-mechanics we come upon the situation that they are on the brink of manufacturing quantum phenomena. However, even when fabricating quantum phenomena, they are basically confronted with classical devices in the laboratory.

> "*At the moment when you stand in front of the experiment you are indeed always dealing with classical apparatuses.*" [30]
>
> – Nikolai Kiesel, *(Interviews 2011c, §39)*

As we have seen in the description of the experiment[31], it consists of parts which are very intelligible in terms of classical physics. The Fabry-Pèrot cavity for example, radiation pressure, mirrors on a cantilever and so on. Unfortunately, we also have to bear in mind that the functioning of some parts of the set-up are only properly conceivable on the basis of settled quantum physics.[32] The lasers deployed or the method of side-band cooling are examples of such elements. In sum, the experimenters are dealing with an experimental environment consisting of instruments which are materialized theories (following Bachelard) of classical physics and quantum physics. The point, however, is that the targeted counterintuitive phenomenon of quantum entanglement is not part of the apparatuses, but rather the result of bringing them into a distinct state. That means that when the phenomenon has eventually been produced, it will be cognizable by a readout that is classically perceptible, albeit only interpretable along the lines of quantum mechanics. We need to recall that in essence quantum entanglement is a non-classical correlation of classical measurement results.[33] The same idea also applies in the quantum opto-mechanical set-up at hand.

For this reason it would seem rather odd to assert that the experimenters are very immersed in a technological environment which actually renders the counter-intuitiveness of the phenomena. Hence we should not expect too much familiarization or acquaintance with counter-intuitiveness by means of the present implementation in the experiments. Rather it is apt to think that the manufacturing of experience is still at an early stage. In addition, although strongly emphasized in this thesis, we should now take a step back from the laboratory and a specific implementation of the phenomenon, and move to the level of the scientific community engaged in this subject matter. There, a growing plethora of varying experimental set-ups has already been devised to prepare quantum entanglement. On this level it is palpable that experience of the phenomenon is manufactured by many diverging instances of it. We have to keep in mind here, recalling Bachelard, that it is not merely about producing the phenomenon, but about reason being instructed by the experience of the fabricated phenomenon. A concrete hint on how we might make this intelligible is given by the ex-

[30] Translated by the author.
[31] See section *3.2 The Experiments*.
[32] I.e. quantum physics which is not counterintuitive in the sense put forward in this thesis. For example the functioning of lasers is well understood in terms of quantum physics and undisputed in its comprehension.
[33] See section *2.1 Einstein, Podolsky and Rosen*.

perimenters themselves. It is not so much the specific technological realization which is helpful in comprehending the subject matter, it is rather the intellectual exchange about the realization of the phenomenon with colleagues and the community which furthers the understanding and the acquaintance with quantum entanglement. For instance, when asked whether experimenting helps in understanding the matter, Blaser nicely summarizes with his answer the subtle attitude I encountered among the experimenters interviewed :

> "*So with this current experiment, no. From the theory I read, the theory papers I read, I get a bit. I guess I still increase my understanding of the things through interactions with other people from the quantum group.*"
>
> – Florian Blaser, *(Interviews 2011f, §58)*

7 Conclusion

In sum, this thesis, motivated by a common dictum that quantum mechanics is counterintuitive and based on a field study of an experimental group, aimed to raise questions about the counter-intuitiveness of quantum entanglement, a key phenomenon in quantum mechanics. The notion of counter-intuitiveness put forward here plausibly describes the situation regarding a common comprehension of quantum entanglement. However, this thesis is just a starting point and is far from covering the topic exhaustively. Moreover, it is dependent on the presumed mainstream interpretation of quantum mechanics. Nonetheless, the notion of counter-intuitiveness is apt to generally signify and specify the intricacies of comprehending quantum entanglement.

The following basic properties of the notion of counter-intuitiveness have been demonstrated:

- Per definition, labeling something as counterintuitive expresses that the matter is not in agreement with the immediate expectations. In the case of the counter-intuitiveness of quantum entanglement, this conflict touches upon fundamental expectations about the world we 'classically' live in. For example, recall the classical assumption about the property values of objects being determined prior to their measurement, or of the locality of events. This high degree of contradiction is well captured by the *counter* in counter-intuitiveness. It is not that people concerned with the issue do not have intuitions about quantum entanglement (= being non-intuitive).[1] It is rather the case that the phenomenon of quantum entanglement, already by its definition[2], contradicts our classical expectations manifested in our everyday lives. This has been specifically made visible by reference to the actual experiments of the Aspelmeyer group.[3]
- Besides defining the term counter-intuitiveness, it is also appropriate to analyze some of the more apparent characteristics of the counter-intuitiveness of quantum entanglement. This has been accomplished in two steps. First, by comparison with the inevitabil-

[1] See section *5.1 General Definition*
[2] See section *2.2 Schrödinger's Definition of Entanglement*
[3] See section *5.2 Specifics*

ity of perceptual intuitions (Müller-Lyer illusion) and with the counter-intuitiveness of deeply classical-physics matters, such as free fall.[4] The former indicated that the counter-intuitiveness of quantum entanglement can be described as prevailing despite countervailing beliefs, such as perceptual intuitions. The latter illustrated that the counter-intuitiveness of quantum entanglement is more fundamental and less reconcilable with common assumptions held about the world than classical – and nevertheless also – counterintuitive concepts. Second, this account of the fundamental counter-intuitiveness of quantum entanglement has been refined by locating the counter-intuitiveness in the comprehension of the very term quantum entanglement. I devised an epistemological profile of quantum entanglement in order to demonstrate the intricacy at the level of conceptualization[5]. In order to reflect the counter-intuitiveness within the epistemological profile, I contrived the contribution of a naive realistic and of a Newtonian or Kantian rationalistic understanding of quantum entanglement to be negative. With regard to the naive realism, it is assumed negative because there is nothing in daily life which brings about an intuitive comprehension of quantum entanglement. In the case of the Newtonian or Kantian rationalism, the negative value is owing to the elementary contradiction between classical assumptions of physics, for instance depicted by Einstein's et al. understanding of the EPR thought experiment and the fundamentals of quantum entanglement.[6] Furthermore, I exemplified this difference in conceptualization between the notion of quantum entanglement and other scientific notions[7] by utilizing Bachelard's *Philosophy of the No*. As a result, quantum entanglement, in contrast to other scientific notions, is outlined by the lack of an intuitive initial image upon which refining criticism (saying a justified no to the initial image) could be based. The conceptualization of quantum entanglement could be apprehended as resting on an initial image which is already counterintuitive and hence locates the counter-intuitiveness of quantum entanglement at this very fundamental level of comprehension.

In virtue of this, admittedly non-exhaustive, account of counter-intuitiveness and its characteristics with regard to quantum entanglement, it is apposite to actually call quantum entanglement counterintuitive. With that said, the second issue of interest was just around the corner, namely analyzing the coping of this counter-intuitiveness. The starting point was the question whether the counterintuitive understanding of quantum entanglement is eased by hands-on experimenting. The answers given by the interviewees backed the following

[4] See section *5.3.1 By Comparison*
[5] See figure 5.3
[6] See section *2.3 Interim Conclusion 1*
[7] Cf. figure 5.2 and figure 5.3

assertions:

- Before studying how the counter-intuitiveness of quantum entanglement is coped with, I established that this is a relevant issue. Namely, under the assumption that empirical science aims at the consistency of all our expectations with all our observations (i.e. classical and quantum), it is apt to claim that there is a basic aspiration to overcome as presented here.[8]
- In order to lead to the question at hand, I differentiated three possible attitudes towards the handling of counter-intuitiveness. None of them is actually exclusive, but nonetheless distinguishable. The first is the longing for a conclusive interpretation of quantum mechanics which is not burdened with a counter-intuitiveness which is as fundamental as propagated in this thesis. The means to accomplish this task are flashes of inspiration concerning the already known or new discoveries. Secondly, one can also adopt a more agnostic attitude with respect to the severity of the counter-intuitiveness; for instance a strictly operational definition of quantum entanglement.[9] The third and pivotal consideration linked to the initial question is based on the idea that reason is able to progress, adapt and familiarize itself with the matter at issue. Hence subject matters which are counter-intuitive today might become more intuitive in the future due to familiarization. How this applies and which issues could be raised with regard to quantum entanglement has been shown by the following:
- A central figure of thought in the concept of getting used to initially counterintuitive matters is often associated with the succession of generations of scientists. I gave no detailed analysis in this regard, but addressed an essential question or issue. If we ascribe upcoming generations with a more casual, or let us say intuitive comprehension of matters which have puzzled older generations, we need to come up with criteria for this change in comprehension other than time passing by.[10] The obvious one of making new discoveries has already been mentioned (see last point). The one I pursued in detail is rests upon Bachelard's rationalism that reason can be instructed by fabricated experience.[11]
- This second order realism according to Bachelard, i.e. actively producing the phenomena to be experienced and thus instructing reason, has been revealed to be a good representation of the situation of experimental research in this field. Quantum entanglement is far from being passively observable and is actually only realized by the experiment.

[8] See section *6.1 Aim of Science? Coherent System of Assumptions*
[9] Cf. quantum entanglement as resource. *(Bub 2010)*
[10] See section *6.2 New Generations of Scientists*
[11] See section *6.3 Bachelard: Reason Instructed by Fabricated Experience*

Therefore at first glance it seemed that quantum entanglement is a candidate suited to instructing reason by experimenting with the phenomenon. However, having had a look at two tangible means of experience which bring about the instruction of reason, namely pedagogics and technology, there is a catch to it in the case of quantum entanglement:

- Again I followed Bachelard and conceived pedagogics as being analogue to the intellectual history of the subject matter. In other words, pedagogics in science tends to replicate the historical sequence and conveys the corresponding changes in reason rather than establishing a sequence of learning which is logical to the subject matter. For instance, Euclidean geometry is usually taught before non-Euclidean geometry, although the former is just a special case of the latter. The reason being that Euclidean geometry is more initial, more immediate relatable to the world we live in. In this regard, pedagogics is also associated with the *Philosophy of the No*. In this concept of Bachelard, an initial image of the matter, which conceivability is the prime criteria, is the starting point for a critical differentiation of the comprehension of the matter. Concerning quantum entanglement, the catch is that we cannot make out such an initial intuitive image, but are straight away confronted with the counter-intuitiveness of the matter.[12] Hence the pedagogics of quantum entanglement deviates from the given examples and might demand specific deliberations. Elaborating on those was not within the scope of this thesis, which humbly restricted itself to raising the issue.[13]
- The second means of experience which can be deemed instructive for reason is immersion into a technological environment which realizes and applies the phenomenon. The people the most in touch with the realization of quantum entanglement are scientist conducting quantum experiments, like the Aspelmeyer group. Nonetheless, based on statements by the interviewees and the counterintuitive character of quantum entanglement as described, it turned out that intricacies can also be found here. As has been presented, experiments realizing quantum effects comprise of apparatuses which are comprehensible in terms of classical physics or settled[14] quantum physics. Consequently the apparatuses do not constitute a *quantum world* you could immerse yourself to. Quantum entanglement is cognizable by a readout that is classically perceptible, albeit only interpretable along the lines of quantum mechanics. This of course corrupts the idea of significantly instructing reason in relation to quantum entanglement

[12] See section *5.3.2 Philosophy of the No*
[13] See section *6.3.1 Pedagogics*
[14] I.e. quantum physics which is not counterintuitive in the sense put forward in this thesis. For instance, a laser is well understood in terms of quantum physics and undisputed in its comprehension.

by dealing with the technology realizing the phenomenon.[15]

Although major impediments to two central facets of instructing reason by experience have been identified in the case of the comprehension of the phenomenon of quantum entanglement, the thesis finishes with an optimistic outlook. A general hint deducible from the interviews is that intellectual exchange with colleagues and the community about the realization of the phenomenon is a furthering factor concerning the understanding of and the acquaintance with quantum entanglement.[16]

In conclusion, this thesis has accomplished its goal of starting off a comprehensive notion of quantum entanglement which illustrates its counter-intuitiveness along the line of three accounts which have been discerned but not separated. The introduction of the theoretical and experimental foundations, drawing on the interviews with researchers in the field and the instrumentalization of key concepts of Bachelard's philosophy of science, facilitated a hopefully stimulating analysis of the dictum of quantum entanglement being counterintuitive. The hope for stimulation is certainly plausible, as the thesis raises more issues than it settles.

[15] See section *6.3.2 Technology*

[16] This is certainly an interesting aspect worthy of detailed elaborations.

Bibliography

Aspelmeyer Group

2011 *Quantum Foundations and Quantum Information on the Nano- and Microscale*, Faculty of Physics, University of Vienna, http://aspelmeyer.quantum.at/ (visited on 11/05/2011).

Aspelmeyer, Markus

2010 "Quantum mechanics: The surf is up", in *Nature*, 2010/04/01/print, pp. 685–686, http://dx.doi.org/10.1038/464685a.

Bacciagaluppi, Guido

2008 "The Role of Decoherence in Quantum Mechanics", in *The Stanford Encyclopedia of Philosophy*, ed. by Edward N. Zalta, Fall 2008, http://plato.stanford.edu/archives/fall2008/entries/qm-decoherence/.

Bachelard, Gaston

1980 *Die Philosophie des Nein. Versuch einer Philosophie des neuen wissenschaftlichen Geistes.* ('La philosophie du non', 1940), Suhrkamp(stw325), Frankfurt/Main.

1988 *Der neue wissenschaftliche Geist*, ('Le nouvel esprit scientifique', 1934), Suhrkamp, Frankfurt/Main.

Bell, John S.

1964 "On the Einstein Podolsky Rosen Paradox", in *Physics*, vol. 1, pp.195–200.

Bokulich, Alisa and Gregg Jaegger

2010 *Philosophy of quantum information and entanglement*, Cambridge Univ. Press, Cambridge, XXX, 277 S.–.

Brown, James Robert and Yiftach Fehige

2011 "Thought Experiments", in *The Stanford Encyclopedia of Philosophy*, ed. by Edward N. Zalta, Fall 2011, http://plato.stanford.edu/archives/fall2011/entries/thought-experiment/.

Bub, Jeffrey

2010 "Quantum Entanglement and Information", in *The Stanford Encyclopedia of Philosophy*, ed. by Edward N. Zalta, Winter 2010, http://plato.stanford.edu/archives/win2010/entries/qt-entangle/.

Cern - European Organisation for Nuclear Research

2011 *Why the LHC?*, http://user.web.cern.ch/public/en/LHC/WhyLHC-en.html (visited on 11/21/2011).

Compendium of Quantum Physics: Concepts Experiments, History and Philosophy

2009 , ed. by D.M. Greenberger, K. Hentschel, and F. Weinert, Springer.

Denham, Woodrow W

2011 *Familial Generations Tutorial*, http://www.escholarship.org/uc/item/5m51s6k6 (visited on 01/14/2012).

DePaul, Michael R. and William Ramsey

1998 *Rethinking Intuition: The Psychology of Intuition and Its Role in Philosophical Inquiry*, Rowman & Littlefield, Savage, Md. [u.a.], XVI, 335 S.–.

Einstein, Albert, Boris Podolsky, and Nathan Rosen

1935 "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?", in *Phys. Rev.*, 47, 10 (May 1935), pp. 777–780, DOI: 10.1103/PhysRev.47.777.

Encyclopædia Britannica

2011 "Intuition", in *Encyclopædia Britannica. Encyclopædia Britannica Online Academic Edition*, ed. by Encyclopædia Britannica Inc., http://www.britannica.com/EBchecked/topic/292162/intuition (visited on 11/29/2011).

Enzyklopädie Philosophie und Wissenschaftstheorie (EnzyklPhilWiss)

2010 "Intuition", in *Ins - Loc: Enzyklopädie Philosophie und Wissenschaftstheorie*, ed. by Jürgen Mittelstraß and Gottfried Gabriel, Metzler, Stuttgart [u.a.], pp. 59–61.

Feynman, Richard

1982 "Simulating physics with computers", in *International Journal of Theoretical Physics*, 21 (6 1982), pp. 467–488, ISSN: 0020-7748, http://dx.doi.org/10.1007/BF02650179.

FoQuS - Foundations and Applications of Quantum Science

2011 , University of Innsbruck, http://www.uibk.ac.at/foqus/ (visited on 09/20/2011).

Gerlich, Stefan *et al.*

2011 “Quantum interference of large organic molecules”, in *Nat Commun*, 2 (Apr. 2011), pp. 263–, http://dx.doi.org/10.1038/ncomms1263.

Gröblacher, Simon

2010 *Quantum opto-mechanics with micromirrors: combining nano-mechanics with quantum optics*, PhD thesis, Universität Wien, http://homepage.univie.ac.at/simon.groeblacher/SGroeblacher_Dissertation.pdf.

Gröblacher, Simon *et al.*

2007 “An experimental test of non-local realism”, in *Nature*, 446, (Apr. 2007), pp. 871–875, http://arxiv.org/abs/0704.2529.

Illusionism.org

2008 *Müller-Lyer Illusion*, Illusionism.org, http://www.illusionism.org/shape-distortion/m%FCller-lyer+illusion/ (visited on 10/11/2011).

Interviews

2011a *Interview with Dilek Demir*, ed. by Reinhard Stanzl, Transcription (see Appendix, p.100: Dilek_110524).

2011b *Interview with Dr. Garrett Cole*, ed. by Reinhard Stanzl, Transcription (see Appendix, p.105: Garrett_110610).

2011c *Interview with Dr. Nikolai Kiesel*, ed. by Reinhard Stanzl, Transcription (see Appendix, p.111: Nikolai_110525).

2011d *Interview with Dr. Witlef Wieczorek*, ed. by Reinhard Stanzl, Transcription (see Appendix, p.115: Witlef_110510).

2011e *Interview with Jonas Hörsch*, ed. by Reinhard Stanzl, Transcription (see Appendix, p.121: Jonas_110622).

2011f *Interview with Mag. Florian Blaser*, ed. by Reinhard Stanzl, Transcription (see Appendix, p.127: Florian_110525).

2011g *Interview with Prof. Dr. Markus Aspelmeyer*, ed. by Reinhard Stanzl, Transcription (see Appendix, p.131: Markus_110706).

IQOQI - Institute of Quantum Optics and Quantum Information

2011 , Austrian Academy of Sciences, http://iqoqi.at/ (visited on 09/20/2011).

JAXA Japan Aerospace Exploration Agency

2011 *IKAROS Project*, http://www.jspec.jaxa.jp/e/activity/ikaros.html (visited on 02/08/2011).

Kippenberg, T. J. and K. J. Vahala

2008 “Cavity Optomechanics: Back-Action at the Mesoscale”, in *Science*, 321, 5893, pp. 1172–1176, http://www.sciencemag.org/content/321/5893/1172.full.pdf.

Lebedew, P.

1901 “Untersuchungen über die Druckkräfte des Lichtes”, in *Annalen der Physik*, 311, pp. 433–458, http://dx.doi.org/10.1002/andp.19013111102.

LIGO - Laser Interferometer Gravitational-Wave Observatory

2011 , http://www.ligo.caltech.edu/ (visited on 03/18/2011).

Mermin, David N.

1985 “Is the moon there when nobody looks? Reality and the quantum theory.”, in *Physics Today* (Apr. 1985), pp. 38–47, http://dx.doi.org/10.1063/1.880968.

Merriam-Webster

2011a “counterintuitive”, in *Merriam-Webster Learner’s Dictionary*, ed. by Merriam-Webster, http://www.learnersdictionary.com/search/counterintuitive (visited on 12/16/2011).

2011b “intuition”, in *Merriam-Webster Learner’s Dictionary*, ed. by Merriam-Webster, http://www.learnersdictionary.com/search/intuition (visited on 12/16/2011).

Nichols, E. F. and G. F. Hull

1903 “The Pressure Due to Radiation. (Second Paper.)”, in *Phys. Rev. (Series I)*, 17 (1 July 1903), pp. 26–50, http://link.aps.org/doi/10.1103/PhysRevSeriesI.17.26.

Nickles, Thomas

2011 “Scientific Revolutions”, in *The Stanford Encyclopedia of Philosophy*, ed. by Edward N. Zalta, Spring 2011.

O’Connor, J.J. and Robertson, E.F.

2009 *Giovanni Battista Benedetti*, http://www-history.mcs.st-andrews.ac.uk/Biographies/Benedetti.html (visited on 03/09/2012).

Quantum Optics, Quantum Nanophysics, Quantum Information

2007 *Entanglement based quantum communication over 144 km*, Quantum Optics, Quantum Nanophysics, Quantum Information, http://www.quantum.at/research/quantum-teleportation-communication-entanglement/entangled-photons-over-144-km.html (visited on 10/15/2011).

2011a , http://quantum.at/ (visited on 09/20/2011).

2011b *Research: Quantum Teleportation & Communication & Entanglement*, Faculty of Physics, University of Vienna, http://www.quantum.at/research/quantum-teleportation-communication-entanglement.html (visited on 10/05/2011).

2011c *Research: Wave–particle duality of C60 molecules*, http://www.quantum.at/research/molecule-interferometry-foundations/wave-particle-duality-of-c60.html (visited on 03/29/2011).

Redner, S.

2005 "Citation Statistics from 110 Years of Physical Review", in *Physics Today*, vol. 58, p. 49, http://arxiv.org/abs/physics/0506056v2.

Rorty, Richard

1967 "Intuition", in *Encyclopedia of Philosophy*, ed. by Donald M. Borchert, 2nd ed., 2006, Macmillan Reference, Detroit, Mich. [u.a.], vol. 4, pp. 722–732.

Rowe, M. A. *et al.*

2001 "Experimental violation of a Bell's inequality with efficient detection", in *Nature*, 409, 6822 (Feb. 2001), pp. 791–794, ISSN: 0028-0836, http://dx.doi.org/10.1038/35057215.

Scheidl, Thomas

2009 *A fundamental test and an application of quantum entanglement*, PhD thesis, Universität Wien. Fakultät für Physik, http://othes.univie.ac.at/4739/.

Schrödinger, Erwin

1935 "Die gegenwärtige Situation in der Quantenmechanik", in *Naturwissenschaften*, 48,49,50, pp. 807–812, 823–828, 844–849, http://dx.doi.org/10.1007/BF01491987.

Skulls in the Stars

2008 *Fabry, Perot, and their wonderful interferometer (1897, 1899)*, http://skullsinthestars.com/2008/10/16/fabry-perot-and-their-wonderful-interferometer-1897-1899/ (visited on 03/11/2011).

Vanner, M. R. *et al.*

2011 "Pulsed quantum optomechanics", in *Proceedings of the National Academy of Sciences*, vol. 108, no. 39, pp. 16182–16187, http://www.pnas.org/content/108/39/16182.full.

VCQ - Vienna Center for Quantum Science and Technology

2011 , http://vcq.quantum.at/ (visited on 09/20/2011).

Vitali, D. *et al.*

2007 "Optomechanical entanglement between a movable mirror and a cavity field", in *Phys. Rev. Lett.*, 98, http://arxiv.org/abs/quant-ph/0609197.

Weihs, Gregor *et al.*

1998 "Violation of Bell's inequality under strict Einstein locality conditions", in *Phys.Rev.Lett.*, 81, pp. 5039–5043, http://arxiv.org/abs/quant-ph/9810080v1.

Appendices

A Acknowledgment

First of all I would like to thank the people of the Aspelmeyer group. The openness with which they shared their thoughts with me in the course of the interviews was a stimulating experience. Their useful statements motivated and structured the issues raised in the thesis and provided it with actual relevance. Moreover, they were really talkative, and thus for me, a total novice at conducting interviews, the perfect counterparts.

I also wish to thank my supervisor Martin Kusch for his continuous support from the first draft of the idea to the final thesis. After all, its formation spread over a year and in this time he constantly assisted me with very proficient and productive feedback which provided guidance without being patronizing. The most salient assessment to make of our cooperation is the circumstance that I not only learned a whole lot, but that I was able to also provide Martin Kusch with some insights; admittedly mostly concerning physics.

In addition, I also want to mention my fellow students who were, like me, among the last to complete the expiring diploma programme in philosophy here in Vienna. The last of a dying breed confronted with a shared deadline. These aggravations motivated me to start off an initiative to support one another by practical means and ease some of the (self-)proclaimed maverick attitude of philosophers. Again, this was something I did for the first time and which has turned out to be a horn of plenty for new exciting experiences. I hope it has not only been a big help for me but also for others. Thanks to those that became engaged.

Finally, I want to thank all the others who had also a share, however small, in the realization of this thesis. All those who spared a word of encouragement, took interest in the overall topic and supported me, of course not only intellectually but also in any other ways. I will not name anyone – I am really bad with names – you know who I mean, so please feel thanked.

B Group: Supplementary Notes

Besides the information already stated, the interviews also contain interesting issues and trivia which are not directly linked to the subject of the thesis. Even so, they are worth mentioning, at least to convey a more detailed picture of the group.

For people working together, whether in science or any other working environment, an important facility for 'socializing' is the break room or kitchen. It is common source and space for not only satisfying the elementary needs for food and drink, but also for communication and coordination. Moreover, it is also a place to celebrate accomplishments[1] and discuss everyday business and, likely after long working hours and adequate beverages, the more fundamental questions. In the case of the Aspelmeyer group, the kitchen is steeped in history because it is located in the former office of Erwin Schrödinger. Schrödinger's desk, in the corner of the kitchen, is not treated like an exhibit, but still serves its designated use from time to time.

Although it might seem obvious, it is important to note that the Aspelmeyer group is part of a larger quantum community in Austria and linked up with research groups around the globe. It is not a task of this thesis to unravel the entire structure of the Austrian quantum community[2]. It is more relevant to remark that the 'Viennese community' has a more or less homogeneous point of view in terms of the interpretation of quantum mechanics; vaguely describable as a Copenhagen-type attitude with an emphasis on information as the determining entity. This can be ascribed to two aspects. First, maintaining diversity on the fundamental issues, like in this case the interpretation of quantum mechanics, within a team does not foster collaboration on day-to-day details. As a second aspect, the quantum community in Austria is largely influenced and shaped by Zeilinger[3] and his scientific successors. These circumstances are neither unique nor astonishing for a research community,

[1] My very first contact with the group was a spontaneous invitation to the appreciation of Demir reaching a significant milestone in her project.

[2] For a starting point see *FoQuS 2011*; *IQOQI 2011*; *Quantum 2011a*; *VCQ 2011*.

[3] This is just to name one of the publicly known contemporary contributors to quantum physics in Austria. Certainly there are many others to name who have had their share in taking the Austrian quantum community to a high stage.

but worth bearing in mind.

Another interesting detail which was mentioned in the interviews was the difference between the physicists working theoretically and those doing experiments. Wieczorek and Hörsch remarked that there is quite some gap between the theoretical and the experimental mind-set, or relationship to the object of research. Unsurprisingly they noted that quite some translation work is required in the course of collaboration (see *Interviews 2011e*, *§57* and *Interviews 2011d*, *§78*).

The next remark tackles the interconnection of different research fields by the implementation of equal fundamental physical tenets. Shortly before I conducted the interviews, some of the group members attended a presentation about the Laser Interferometer Gravitational-Wave Observatory *(LIGO 2011)*. In principle they also deploy a Fabry-Pèrot cavity[4], in their case on a very large scale to measure very minuscule length variations presumably caused by gravitational waves. The mutual fascination relies on the common demand for highly reflective mirrors, although those of LIGO are several centimeters in diameter and the ones in opto-mechanics just a few micrometers.

A further circumstance to note is that interpretations and their equivalence in describing the empirical phenomenon of quantum entanglement were not part of the standard curriculum of many of the interviewees. This reflects the impression that in general academic training[5] there is a mainstream concept of quantum mechanics which utilizes a minimum set of assumptions of a Copenhagen-type interpretation, enough to bolster formalism, but not so much as to remain agnostic about the more fundamental, philosophical inferences of the assumptions. Interpretations which further a different formalism, e.g. Bohmian mechanics, are a minority program. This is only an impression about academic education in this field and not about the actual, personal standpoints of the long-serving physicists driving the quantum community.

[4] See section *3.2 The Experiments* for details.

[5] I am well aware that my personal experience and the handful of statements about the academic training of two to three universities, mostly located in German-speaking countries, do not allow for such a general assertion. However, it is apt to assume that a scientific community that is strongly interconnected around the globe will arrive at a minimum standard of formalism for practical collaboration; granted local color. Hence standard academic training is geared towards conveying a mainstream understanding of quantum mechanics, especially as natural sciences generally tend to carve out one valid school of thought. Examining one implementation of academic training can therefore be sufficient to make more general assertions.

C Transcription of Interviews

The following are transcriptions of the interviews with the members of the Aspelmeyer group. They have been transcribed in the language they were conducted (German or English). Translations have only been made in the course of citations within in the thesis.

Dilek_110524

Interview mit Dilek Demir vom 24.05.2011
Transcribed by yotta, version 1 of 110525

Anfang, persönliche Daten, Ausbildung

(no speaker)
1. Small talk

Reinhard
2. Gut. Ich will am Anfang nur so Formalien wissen.

Dilek
3. Das heisst?

Reinhard
4. Ja. Wie alt du bist?

Dilek
5. Warte, wie alt ich bin? Ich bin 22.

Reinhard
6. Nur einfach... Ich weiß es eigentlich eh auch alles, dass du gerade Diplomarbeit schreibst usw. Aber dein akademischer Grad ist halt gerade vor dem Magister. Was du ja hoffst zu werden.

Dilek
7. Irgendwann einmal.

Diplomarbeit

Reinhard
8. Aber das heisst du schreibst ja hier die Diplomarbeit.

Dilek
9. Ja. Sagen wir einmal so eigentlich bin ich schon am Schreiben. Aber ich muss noch was nachmessen praktisch. Also ist es so eine Übergangsphase wo man halt noch nicht Diplomand ist und auch nicht mehr Student ist, aber auch nicht schon weiter ist, sondern irgendwo dazwischen noch herumeiert und darauf hofft, dass es endlich einmal zu Ende ist.

Reinhard
10. Das Thema genau der Diplomarbeit ist...?

Dilek
11. Es ist "Radiation Pressure Effects on Macroscopic Systems". Also eigentlich mehr Mechanik und Optik. Also basics. Und das einzig quantenmechanische an dem Ganzen ist eher dann der Strahlungsdruckeffekt selber. Die Idee der Diplomarbeit ist einfach nur ein simples, einfaches Experiment zu haben, bei dem man Strahlungsdruck demonstriert.

Reinhard
12. Also das heißt es aufzubauen...?

Dilek
13. Es hat so Berechnungen gegeben und dann hat sich halt herausgestellt, das müsste eigentlich funktionieren. Und meine Aufgabe lag dann mehr oder minder darin, dass ich da ein Experiment selbst - am Anfang mit Hilfe natürlich -, aber dann auch selber designt, aufgebaut und gemessen habe. Und jetzt kommt halt dann: gegen Ende müssen wir das Ganze auch dann noch interpretieren und herausfinden ob dann auch der vorhergesagte Effekt [Strahlungsdruck] auch wirklich genutzt worden ist.

Reinhard
14. Und das ist jetzt dann sozusagen der aktuelle Stress das hinzubekommen?

Dilek
15. Genau, weil in Luft haben wir es mal ausprobiert und da hat es ziemlich gut gepasst. Und nur eine Messung, da waren wir ein bisserl daneben und wir wissen nicht warum das so ist. Jetzt sind wir halt im Vakuum. Das wird nochmal überprüft und dann schauen wir was passiert.

Studium und Zugang zur QM

Reinhard
16. Wie bist du eigentlich... Also wie ist dein Hintergrund vom Studium her?

Dilek
17. Aber was genau meinst du mit Hintergrund vom Studium?

Reinhard
18. Ja also wir kennen uns ja teilweise vom gemeinsamen Studium. Also nehme ich an, dass du hier in Wien studiert hast. Du hast also hier begonnen?

Dilek
19. Ja mit Null Wissen an die Physik herangemacht. Also ich habe gar kein Wissen gehabt, was ja normal bei den Physikern nicht so ist. Denn alle andern die beginnen sind irgendwie schon von Anfang an Olympioniken [z.B. Physik-Olympiade] und was weiß ich nicht noch alles. Das war halt bei mir nicht der Fall. Das heißt ich habe noch nie in meinem Leben zuvor Quantenmechanik gehört. Und wie ich dann zur Quantemechanik gekommen bin war dann weil es mich einfach interessiert hat. Das war so ein paper, dass ich gelesen habe und da kam EPR, EPR?, vor und dann habe ich mich gefragt na was ist denn das. Und dann habe ich halt verschiedene Bücher darüber gelesen. Ja, deswegen.

Reinhard
20. Ok. Aber das war dann sozusagen im Zuge vom Studium?

Dilek
21. Es war eher Freizeit. Es war dann ein paar Semester lang sogar so, dass ich meine Sachen die ich eigentlich machen musste zurückgestaucht habe und dann mehr Freizeit, unter Anführungszeichen, genommen habe und dann quantenmechanische Sachen gelesen habe. Auch wenn sie halt zu hoch waren.

Reinhard
22. Und wann war das ungefähr? Zeitlich jetzt im Studium? Wenn man jetzt sagt, dass die T2 Vorlesung [Vorlesung über die Theorie der Quantenmechanik, viertes Semester im Diplomstudienplan] das Erste ist wo es quantenmechanisch losgeht.

Dilek
23. So richtig theoretisch ist es natürlich bei der Quantenmechanikvorlesung losgegangen. Aber vorher habe ich auch schon versucht was mir selbst beizubringen. Auch wenn es noch nicht ganz theoretisch gewesen ist. Das war so ab dem zweiten Semester. Also ab der Prinzipien-Vorlesung [Prinzipien der Modernen Physik (Spezielle Relativitätstheorie und Elementare Quantenmechanik), grobe Überblicksvorlesung, zweites Semester im Diplomstudienplan] eigentlich. Davor habe ich den Arndt [Markus Arndt, leitet die Forschungsgruppe der Materiewellen (Welle-Teilchen Dualismus)] in der Optik [Vorlesung] besucht und der hat dann immer gesagt gehen sie halt zu den Vorträgen. Und dann war es dann eher so, dass ich die langweilige Prinzipien-Vorlesung - die hat der Baumgartner [Bernhard Baumgartner] ziemlich langweilig

gehalten - gelassen habe und zu diesen Montags-Vorlesungen immer gegangen bin. Ab und zu halt. Und das hat zirka ab dem zweiten Semester eigentlich begonnen.

Reinhard

24. Und das hat dich zur Quantenmechanik und zu den Leuten gebracht?

Dilek

25. Ja. Witzigerweise wenn ich mich so zurück erinnere, waren die Leute die dann in diesen Montagsvorlesungen gewesen sind, die sind jetzt alle da in der Gruppe. Also der Markus [Markus Aspelmeyer] war dann oftmals der, der dann vorne gestanden ist und irgendwas geredet hat. Also ich bin da im nachhinein dann daraufgekommen, dass er die organisiert hat. Ein paar halt von der Gruppe sind auch dringesessen, aber ich habe die natürlich damals noch nicht gekannt.

Perspektive

Reinhard

26. Stellst du dir vor dann in dem Feld zu bleiben, oder? So eine Perspektive nach der Diplomarbeit?

Dilek

27. Ah, das. Ja, ich weiß nicht, ich finde es recht interessant. Ich glaube auch, dass in kommender Zukunft wird das halt ein... Also man kann sicher Quantenmechanik auch irgendwann einmal so verwenden, dass das jeder zuhause stehen hat und was völlig normales ist.

Reinhard

28. Ja, ja. Man hat das Gefühl, dass es nicht so ein totes Feld der Physik ist. Falls es überhaupt so etwas gibt.

Dilek

29. Nein, eigentlich überhaupt nicht. Ich glaube es gerade das Problem, dass man da noch viel machen muss. Tot glaube ich ist es nicht. Also es ist alles andere als tot.

Reinhard

30. Von anderen Bereichen der Physik, hat man andere Vorstellungen, was man dort machen kann.

Dilek

31. Du meinst auch richtig Anwendungen? Bei meiner Diplomarbeit, da ist nur sehr wenig Quantemechanik eigentlich dabei, bzw. fast gar keine, aber mein System könnte man locker verwenden als Sensor. Oder keine Ahnung, als Powermessgerät. Man müsste es ein wenig ummodelieren, oder als Detektor. Man kann es schon verwenden.

Aufgabe im Experiment / Rolle in der Gruppe

Reinhard

32. Das bringt mich dann eigentlich eh dazu nach deiner Rolle in der Gruppe oder im Experiment [zu fragen]. Weil du sagst, dass ist ja nur eher so am Rande quantenmechanisch. Trotzdem ist es vom Prinzip her Teil der ja bei den anderen Experimenten verwendet wird.

Dilek

33. Ja, das stimmt. Weil eigentlich verwendet zum Beispiel der Witlef [Witlef Wieczorek, Beispielexperiment meiner Diplomarbeit] ja auch cantilevers und der verwendet das als cavity. Und er könnte eigentlich, und sogar dann auch der Nikolai [Nikolai Kiesel] und der Florian [Florian Blaser][beide beim Experiment über die superpositionierten Nanokügelchen], die könnten auch ihre Systeme als hochempfindliche Sensoren benutzen.

Reinhard

34. Das wäre dann, wo du eher so die "Tisch"-anwendung machst. Es ist die Frage ob deines so ein Demonstrationssystem ist?

Dilek

35. Also primär ist es als Demonstrationsexperiment gedacht. Das war auch der Grund warum wir es überhaupt gestartet haben. Naja, eigentlich gab es da eine challenge von den Opto-Mechanikern und da wollte der Markus [Markus Aspelmeyer] unbedingt was haben. Und das war eigentlich nur ein Sommerprojekt und hätte niemals soweit kommen dürfen oder sollen. Und es war natürlich als Demonstrationsprojekt gedacht. Es gab schon im Jahre 1901 Experimente dazu.

Reinhard

36. Aber es ist halt die Frage wie aufwendig oder wie einfach die Dinger dann sind.

Dilek

37. Genau. Aber vor allem, ich betone das auch gern, weil das habe ich letztens beim DPG-Meeting [Deutsche Physikalische Gesellschaft?] erlebt, wo dann die Leute zu mir gekommen sind und gesagt haben: "Jö, schau ein Schülerexperiment". Das hat so wehgetan. Das hat so wehgetan. Weil eigentlich kann man auch eben zum Beispiel für AFM-Cantilever, also das ist Atomic Force Microscopy, da ist ja das Prinzip, dass du so einen cantilever hast und vorne eine Spitze. Und dann fährst du über die Probe drüber und misst die Auslenkung. Und eigentlich ist es das selbe und könntest es mit dem auch machen. Oder halt noch senistiver, in dem du das System ein bisschen ummodelierst. Natürlich musst du Arbeit hineinstecken, aber es wäre möglich.

Reinhard

38. Aber es ist halt schon sehr gemein es als Schülerexperiment zu bezeichen.

Dilek

39. Aber es gab auch Leute, die zu mir gesagt haben: "Wow schön, Schülerexperiment. Damit könnten sie viel Geld machen. Gründen sie doch ein Unternehmen". Das habe ich eben auch gehört.

Reinhard

40. Es ist halt ein Unterschied, dass eben auch zu zeigen; wenn ich sage ich stelle ein ganzes Labor voll oder ich habe genau das gleiche gezeigt mit viel weniger.

Dilek

41. Genau. Wir haben es sogar Schülern gezeigt. Die fanden das auch recht interessant. Es wäre eben halt ein bisschen anstrengend wenn man sie gleich vor einen Gryostaten ["Kühlschrank" in dem das System runtergekühlt wird um den Grundzustand des Systems in dem Quanteneffekte auftreten zu erreichen] stellt und sagt, da machen wir Quantenmechanik, da kühlen wir runter. Als wie dieses kleine Kompakte und [wo man leicht zeigen kann], da haben wir den Cantilever, und da haben wir den Laserstrahl und so weiter.

Reinhard

42. Es ist dann eh die Sache, wie du dann auch die Sachen irgendwie darstellst oder verständlich machst. Weil du kannst zwar den Gryostaten zeigen und die ganzen Kisten, aber es ist halt schon ein Unterschied ob ich das nachvollziehen kann.

Dilek

43. Zugegeben. Feynman, der hat sich auch mit ganz komplizierten Dingen beschäftigt, hat aber auch immer wieder geschaut, wirklich die basics [zu machen]. Es also runterzuschrauben und dann auch wirklich es verständlich zu machen.

Faszination an der Quantenmechanik

Reinhard

44. Obwohl dein Experiment nur am Rande mit Quantenmechanik zutun hat, was würdest du sagen ist es was dich irgendwie an der Quantenmechanik anzieht? Oder warum es interessant ist für dich Quantenmechanik zu machen? Was dich halt fasziniert daran?

Dilek

45. Also theoretisch finde ich Quantenmechanik ziemlich cool, weil irgendwie läuft das bei mir etwas intuitiv ab. Also nicht das ich, keine Ahnung, der Beste in Quantemechanik oder so wäre. Weil ich glaube so einen gibt es einerseits nicht, weil niemand es so richtig versteht, andererseits aber... Was wollte ich jetzt sagen? Genau. Es sind halt viele Fragezeichen in der Quantenmechanik. Und theoretisch gesehen ist es insofern interessant, weil einfach Sachen, die normal klar sind dann nicht mehr klar sind. Also man muss sich eigentlich, zum Beipiel das EPR-Experiment, das paper muss man sich glaube ich zwanzigtausend mal durchlesen und man versteht es immer noch nicht. Weil immer wieder was drin ist, was man vorher nicht gesehen hat. Und das ist eigentlich ziemlich interessant, finde ich, in der Theorie, dass man irgendwas findet, was man immer wieder versteht. Es ist irgendwo dieser Widerspruch: So sollte es eigentlich sein, aber die Quantenmechanik sagt es anders. Warum wohl? Und dann kann man darüber grübeln. Das finde ich ziemlich cool.
46. Und experimentell sind halt im Moment die Experimente, die ich so im Kopf habe - also wir beschäftigen uns ja mit cavities und mit Spiegeln - das ist eigentlich voll schräg, weil meine cantilevers zum Beispiel, die sind schon richtig makroskopisch. Und die anderen sind auch recht groß. Und wenn man sich jetzt überlegt, es gibt dies LIGO Leute [Laser Interferometer Gravitational-Wave Observatory] am MIT[Massachusetts Institute of Technology], die dann so richtig massive Spiegel verwenden. Also letztens, das war eh gestern, waren wir bei so einer Konferenz, bei so einer Austellung. Und da haben sie eben diese Spiegel ausgestellt und die waren so groß [zeigt mit den Händen eine Abstand von ~50cm] und so dick [zeigt mit den Händen eine Dick von ~15cm]. Also das waren kilogramm-schwere Spiegel. Und jetzt muss man mal verstehen die Theorie, die man eigentlich nicht so richtig gut versteht, wird umgesetzt auf eine Experiment und das noch dazu so groß. Ich finde das cool.

Reinhard

47. Ja, weil es dann schon massiver wird. Das sind ja dann schon angreifbare Dinge.

Dilek

48. Das finde ich eben ziemlich interessant. Und die Experimente sind halt sehr, sehr interessant, was die [die LIGO Leute] machen.

Interpretationen

Reinhard

49. Und weil du das vorher bei der Theorie gesagt hast. Eben, dass man sich nicht sicher sein kann. Oder eben wie du vorher gemeint hast, dass man sich immer hinterfragen muss und immer neu sich das überlegen muss, je nach Situation. Ist da irgendwie relevant die Interpretationen? Also wenn man jetzt die nimmt die es gibt, sozusagen im Studium zumindest einmal hingestellt bekommen hat?

Dilek

50. Naja, im Studium glaube ich kriegt man ja nicht alles aufgetischt. Einiges wird einem nicht erklärt. Andere Sachen, da muss man glaube ich dreimal irgendwo hingehen damit man einmal ansatzweise erklärt bekommt was es zu bedeuten hat oder mal versteht.

Reinhard

51. Und das ist halt die Frage ob du sozusagen da extra nachfragen hast müssen. Oder Dinge halt nicht aus dem Studium so eindeutig [genannt] worden sind. Was wären das für Sachen, die du vorher gemeint hast?

Dilek

52. Zum Beispiel gibt es ja die Kopenhagener Deutung, die wird ja einem eigentlich, obwohl die hat auch wieder Formen, aber eigentlich das Allgemeinste ist ja die Kopenhagener Deutung.

Reinhard

53. Die minimalste Variante [der Kopnehagener Deutung] die notwendig ist um...

Dilek

54. Die wird ja einem beigebracht. Aber zum Beispiel ist ja nicht klar wie das mit der Bohm'schen Mechanik ist. Und da war ich sogar bei einem Seminar wo sie das so genau durchgenommen haben. Da hat man auch schon schräge Sachen gehört. Da war es halt dann schwierig, dass was man gelernt hat mit dem anderen zu vergleichen und dann in Verbindung zu bringen. Und dann richtig herauszudeuten, was ist jetzt falsch, was ist nicht falsch. Wie haben es die Einen betrachtet, wie haben es die Anderen betrachtet. Und das hat dann für ziemlich viel Diskussionsstoff gesorgt, während dem Seminar.

Interpretationen / Theorie / Experiment

Reinhard

55. Und wie würdest du das verbinden mit dem was du jetzt hier brauchst? Was sozusagen hier relevant ist?

Dilek

56. Ich muss zugeben ich bin ja, wie am Anfang gesagt, ziemlich am Anfang. Und weil ich am Anfang bin und weil das Studium selber ziemlich theoretisch ist, muss man einmal experimentell einiges aufholen. Also ich glaube ich habe vier Semester lang Theorie gehabt, weil ich ja noch im Diplomstudium bin. Und experimentell waren halt nur so das Anfängerpraktikum und dann habe ich noch das Quantenoptikpraktikum gemacht, und auch da lernt man nicht wirklich was. Und um ehrlich zu sein, das was ich während dem Studium gelernt habe über Quantenmechanik, das wende ich jetzt sehr wenig bis eigentlich gar nicht an.
57. Nur halt wenn es darum geht bei anderen Experimenten, wo es mehr um Quantenmechanik geht und wo dann diskutiert wird, da kriegt man schon einiges mit und es gibt auch wieder neue Sachen. Aber ich kann nicht wirklich etwas im Moment anweden, muss ich zugeben. Ich muss mich eher damit rumschlagen, welcher Detektor am besten passt und wie ich das am gescheitesten justiere und so was. Das ist dann wieder... Theoretisch gesehen kann ich so gut wie garnichts anwenden. Und experimentell bietet sich gerade bei meinem Experiment das nicht so gescheit an. Ich glaube wenn man wirklich das Stadium erreicht, wo man das anwenden kann, was man vor Jahren in der Quantenmechanikvorlesung gelernt hat, dann vergehen einmal so einige Jahre. Es muss einmal auch ein Experiment sein, das schon soweit ist, und dann erst. Aber vorher kannst du es vergessen, das kannst du spaßhalber machen.

Reinhard

58. Und Interpretationen, wie du gesagt hast vorher bei dem Seminar, sind ja dann noch weiter weg? Für das eigentliche Experiment dann vielleicht noch weniger relevant?

Dilek

59. Ja, ich glaube schon.

Reinhard

60. Aber du würdest schon sagen, dass das zumindest als Diskussion schon stattfindet? Also Interpretationssachen oder diese Theoriegeschichten?

Dilek

61. Doch schon, weil es gibt ja im Moment ein Experiment - bald hoffentlich soweit ist - und da wird es dann, sobald man Ergebnisse hat, wieder aktuell werden. Also im Sinne von: da wird man sich nochmal überlegen müssen, wie man das überträgt auf das Experiment. Also wenn man die ganze Sache mit dem, keine Ahnung, Teleportieren oder mit dem EPR darauf überträgt. Da bin ich mir sicher wird sehr viel diskutiert werden. [Sie spricht hier von der Anwendung opto-mechanischer Quantensysteme, wie sie in der Gruppe erforscht werden, für die Quanteninformationstechnik]

Verstehen durch Experimente?

Reinhard

62. Wie siehst du das in Bezug auf das Verstehen? Helfen dir sozusagen die Experimente - nachzuvollziehen oder zu vestehen -, hilft dir das auch bei den größeren Sachen?

Dilek

63. Was meinst du mit größeren Sachen?

Reinhard

64. Ja, wie jetzt Interpretationen oder die theoretischen Sachen oder die EPR Geschichten. Würde es helfen wenn du siehst was in der Gruppe passiert jetzt mit den cantilever Sachen und den Verschänkungs Sachen. Und wenn du dann zurückgehen würdest und dir die EPR Sachen anschaust, hilft es dann?

Dilek

65. Das man es besser versteht? Ich glaube wenn man das Experiment selber aufbaut, dann hat man schon irgendwie einen Bezug zu dem und versteht es auch viel besser, als wie wenn es ein Kollege macht und sagt ja ich habe das und das Resultat. Da muss man dann sicher länger darüber diskutieren als wenn man es selber gemacht hat. Und ob es dann hilft die Theorie besser zu verstehen? [Pause] Ich meine, ich habe eine Quelle, es geht in die andere Richtung, up oder down,... Ich habe es zumindest gemessen. D.h., dass mein Resultat der Theorie entspricht.

Reinhard

66. Ja, aber wird es zumindest etwas realer? Wenn man nur die Theorie hat, ist es vielleicht ein bisserl wunderlicher, gerade wenn man so Konzepte hat wie Verschränkung oder so?

Dilek

67. Nein, ich glaube nicht. Ich glaube es wird immer noch ein bisschen geben, wo man sich denkt: Warum ist es denn so. Warum gerade so und nicht anders. Und warum passt gerade die Theorie zum Experiment. Ich glaube die Frage wird es immer geben.

Reinhard

68. Also da scheint das Experiment nicht so arg weiter zu helfen?

Dilek

69. Doch schon, weil du machst Messungen und du kannst damit was machen. Aber...

Reinhard

70. Vom Verständnis her wird es immer noch komisch, merkwürdig oder wie immer man das nennen will? Also das ist die Frage, wenn man rückblickend auf die Sachen, die papers die du gelesen hast usw., [schaut], und jetzt zum Unterschied experimentell selbst mehr in der Hand hat. Ob der Umgang jetzt etwas leichter ist?

Dilek

71. Wenn ich an mein Experiment denke, dann ist es bei meine Experiment schon so: Es gibt eine Theorie, ich habe es gemessen, es passt genau mit der Theorie überein. Und d.h. ja dann muss es halt so sein. Aber bei den richtigen Quantemechanikexperimenten sind es ja viel gößere Experimente mit viel, viel mehr Parametern und da muss man wirklich sorgfältig sein. Wenn man aber sorgfältig gewesen ist und das richtig gemacht hat, müssten eigentlich keine Fragen offen bleiben. Aber ich muss zugeben ich habe so ein Experiment noch nicht gehabt. Ich hatte noch nicht die Möglichkeit sowas zu überprüfen, deswegen glaube ich wäre jede Aussage die ich jetzt treffe nicht ganz der Wahrheit entsprechend.

Reinhard

72. Ja, das ist klar.

Dilek

73. Also zu Beginn habe ich bei meinem auch niemals daran gedacht, dass ein makroskopischer Spiegel durch Photonen bewegt wird und immer noch ist die Frage offen ob es wirklich so ist. Im Moment ist es so, aber es kann sich jede Minute ändern.

Reinhard

74. D.h. aber mehr zu experimentieren würde dann helfen,zumindest mit den Sachen, wenn man so will, herumzuspielen?

Dilek

75. Nein, das eigentlich auch nicht. Weil irgendwann einmal ist es halt so. Man kann fünftausend mal noch messen, dass ist dann einfach so.

Reinhard

76. Ja, aber das du zumindest in einer anderen Variante die Dinge nochmal [überprüfst].

Dilek

77. Also wenn das Ergebnis immer noch das selbe ist und die Parameter immer noch gleich sind, oder annäherend gleich, dann wird man, glaube ich, nicht noch mehr dran spielen, weil es einfach so ist. Weil eben die Theorie dann mit dem Experiment nicht übereinstimmt, und vielleicht findet man da einen Widerspruch. Und zeigt dann sogar, dass die ganzen hundert Jahre die die Physiker darauf aufgewendet haben, nur Schwachsinn gewesen sind. Recht schwierige Frage eigentlich. Ich habe auch selber mir nie selbst diese Frage gestellt.

Reinhard

78. Es ist auch die Frage ob so etwas für einen selbst relevant ist. Oder eigentlich egal ist, weil es für das Konkrete nichts aussagt oder nicht hilft.

Dilek

79. Also im Moment halt nicht.

Technischer Fortschritt

Reinhard

80. Hat jetzt eigentlich bei deinem Experiment der technische Fortschritt geholfen hat? Oder sind es eigentlich Sachen die es schon länger gibt?

Dilek

81. Naja. Die Spiegel die jetzt gebaut worden sind, da ist es schon die zweite Generation an Spiegel die wir verwenden. So gesehen...

Reinhard

82. Ja, weil du brauchst ziemlich gut reflektierende Spiegel.

Dilek

83. Genau. Sehr, sehr, sehr, sehr gute Spiegel mit geringer Absorption. Obwohl ich mich wundere, ich habe immer noch mehr Absorbtion, als diese fetten LIGO [Laser Interferometer Gravitational-Wave Observatory] Spiegel. Das war unfassbar, die sind so groß und so dick und, keine Ahnung, 25 Kilogramm schwer. Und meins ist nur nanogramm-schwer. Aber die haben immer noch weniger Absorption.
84. Und es gehört glaube ich schon auch ein bisschen Wissen und eben eine Art von Fertigkeit dazu diese Spiegel auch bauen zu können. Und eigentlich haben es die früher 1901 mit ganz simplen, also auch mit großen Spiegeln gemacht, also auch so Mikroskopspiegeln, und sich eine ganz verrückte Aufhängung überlegt. Und dann haben sie es halt gemacht. Wir haben halt die kleinen Spiegeln. Ja, ich glaube wenn man diese dielektrischen Spiegel, so wie sie gebaut werden... Hätte es die nicht gegeben, hätte es das Experiment auch nicht gegegeben. Die Detektoren die ich verwende sind eigentlich, also im Vergleich zu 1901...

Reinhard

85. Ja, ok. Aber es sind schon Dinger, die man einfach bekommen kann. Bis auf die Spiegel, die muss man extra herstellen, da muss man Aufwand reinstecken, den Rest nimmt man sozusagen vom Regal.

Dilek

86. Ja, das stimmt. Es hat ja auch vorher die Spiegel gegeben und dann ist die Idee gekommen. Sowie Henne oder ist das Ei vorher dagewesen.

Reinhard

87. D.h. aber [zuerst] die technische Möglichkeit den Spiegel zu haben und dann schaue ich mir an, dass ich das damit machen kann.

Dilek

88. Genau. Und normalerweise werden bei unseren Experimenten, bis auf beim Michael [Michael Vanner], verwenden alle anderen eh nur... also Witlef [Witlef Wieczorek] zum Beispiel, sein Spiegel ist nur auf der einen Seite hochreflektiv, aber auf der Rückseite nicht. Und das musste eben bei mir sein. Weil ich von der einen Seite Auslese und das von der anderen Seite auslenke. Dafür hat Garrett [Garrett Cole] ziemlich viel Arbeit schon reingesteckt, damit er einmal herausfindet wie man auf beiden Seiten das edged.

Ende

Reinhard

89. [Pause] Also meine Fragen wären damit erschöpft.

Dilek

90. Prüfung bestanden?

Reinhard

91. Es gibt keine Prüfung. Also wenn, dann bin ich der Prüfling in dieser Situation.
92. Wenn du noch Fragen hast?

(no speaker)

93. Kurzes Gespräch, was so der Philosoph macht. Danksagung und ausklingender small talk.

Garrett_110610

Interview mit Dr. Garrett Cole vom 10.06.2011
Transcribed by yotta, version 5 of 110617

Anfang, persönliche Daten, Ausbildung

(no speaker)

1. [intro small talk]

Reinhard

2. Just for a start, could you tell me your age?

Garrett

3. I just turned 32 in May 31st.

Reinhard

4. Then, what is your educational background?

Garrett

5. Bachelors degree in materials engineering. So I'm orignally from San Francisco area. Then I went to this school in, you never heard of, California Polytechnic State University. It's like a small polytechnic school. They had a materials engineering for bachelors. And then I went to Santa Barbara, UC Santa Barbara, for, it's just called 'Materials' there, but it's materials science and engineering. But it's also in the college of engineering there. So it is considered an engineering department. Materials is a very broad field. So I actually did electronic and photonic materials. So it's more applied condensed matter stuff; applied solid state. And there I did my PhD in 2005. And then I worked in industry for a year. I worked at Lawrence Livermore, it's a National Laboratory in the US, for two years. And then here. Livermore is a big... So there is Los Alamos and Livermore. So Los Alamos was first... Livermore was build to develop the hydrogen bomb. So it's to build thermonuclear wepons. So it's a weapons lab. But now it's just a general scientific research lab.

Werdegang

Reinhard

6. How did you kind of transfer from the material engineering part to something like here, the physics department?

Garrett

7. So my background is in micro-nano fabrication. I have a really weird background. So even though by degree, the degree material science, most of the work I've done has been just applied device design and fabrication. For my dissertation research I made diode lasers. So these mechanically tuneable diode lasers. They are these funny, very specific types of surface amending lasers. So how to do surface legit. Then I made a small moving mirror that would change the cavity length. And you could tune the center of wavelength with this device. If you look, this is where the connections come in. I made moving mirrors! But much more complex, cause you had a full diode laser structure that you had to build with this moving mirror. A suspended mirror that you electrostatically moved. And then I did that continuously afterwards. So in industry there is a company that actually licenced a patent for some of the work that we did. They still develop these devices. And at Livermore I just did sensor development. These things are really fast tuneable lasers; narrow linewidth, very fast tuning. So for gas sensing or displacement sensing. Then I saw this opto-mechanics work came up. Actually in my structures, if you had high enough intra cavity power, you could see static displacements of the mirror; through radiation pressure forces. Cause the cavity length was two microns, so you get massive displacements.

Reinhard

8. Although you don't want them.

Garrett

9. You don't want them! They are actually bad. They hurt the stability of the laser. But it was always an interesting sort of aside. Nothing we would ever publish on it, but we used it just to play around. You could change the centre of wavelength of the laser by putting enough power in it. And then on 2005 there is these first papers coming up, like parametric oscillation in these devices; in opto-mechanical devices. So I always kind of watched it. When I was at Livermore the position was really nice. Half of the time you had to do work for the laboratory and half the time you could do anything you wanted; which was awesome. I ended up... So I started trying to get money internally to do the work like with some other people in the laboratory and it never got accepted. I mean it was an engineering department and the always wanted applications and use. So it was always shutdown. And then at one point I was actually just wrote in [???] to people to work. And I was bored and so I just typed a message to Markus [Aspelmeyer], who I'd never met. And just said: Ok this is very interesting and I can do micro fab. Here are some ideas. And sent it to him.

Reinhard

10. And how you get to [know] Markus?

Garrett

11. I saw the papers. Yes out of the papers. And I contacted them and Markus [Aspelmeyer] wrote me back. And then for about a year from Livermore I worked with Markus [Aspelmeyer] like for very small side projects. Fabricate samples, ship them to Vienna, they would test them, send me the results, make new devices and ship them back. So that went on for a year. And then unfortunately the laboratory had some major financial problems. So that's a whole long story. So they layed off lots of people. I was except from the layoff. I could not get fired, but it was very depressing.

Reinhard

12. That's a point to jump off and do something different?

Garrett

13. It look really bad and I didn't like the way things were going. I had a talk to Markus [Aspelmeyer] about it and he asked if I wanted to come to Vienna; fulltime. So it's a very long and complex connection.

Reinhard

14. Yeah, but it is kind of extraordinary story, not very common story to tell.

Garrett

15. It's a weird one.

physik-theoretischer Hintergrund

Reinhard

16. So that is your background also in kind of physics? The theory stuff?

Garrett

17. That's very weak. So coming from an engineering background, like for my bachelors degree, I took a number of solid state courses and a lots of material science courses. But I took one intro... It wasn't even quantum mechanics, it was

modern physics. So it had like relativity and some intro to quantum mechanics. And when I started graduate school, I guess I just took two quantum mechanics courses. So I took again something like an intro, but for quantum mechanics. And then I took some, I don't even remember the name,... now this is ten years ago. Some mixed level quantum mechanics course. I started to take another quantum mechanics course, actually through the physics department. And I was already doing research and it was just too much, so I stopped. That was it. But most everything was much more applied. And because I was in this like electronic materials program... So you sort of basically got the quantum issues, but most of it was applied to like confined electronic structures.

Reinhard

18. Handled as just a side effect, which you probably don't want to have?

Faszination an der Quantenmechanik

Garrett

19. Yeah. So that was interesting. I mean it was always interesting to me. Like the 'modern physics' course I took for my bachelors. I didn't get any credit for that class. It wasn't part of my curriculum, I just added it because I thought it was interesting.

(no speaker)

20. [little interruption]

Garrett

21. So I always had an interest in basic physics. That's one of the reasons why I would come here. It would be hard to justify coming here, but didn't like the more fundamental stuff.

Reinhard

22. That is the question whether you can pinpoint to somewhere where you got started to be interested?

Garrett

23. No, it was just sort of always there. I can go back and say some whole thing like when I was younger. I liked astronomy and I had some [???] book that described modern scientific stuff and it had a little description about things like quantum mechanics. So it is always interesting. I'm sure everybody says the same thing, but just the counter-intuitiveness was interesting to some degree; right. Cause there is something you don't expect or don't see.

Reinhard

24. So that is one of the attraction points, especially in the beginning. When they come up with statements that are hard to believe, or hard to get.

Garrett

25. Exactly. It was fun just to learn the concepts.

Aufgabe im Experiment / Rolle in der Gruppe

Reinhard

26. So what is your current role in the group? What are you doing?

Garrett

27. So I've been here two and half years now. I had this Marie-Currie fellowship, which was kind of nice. So mainly for the group I do like design the resonators, micro fabrication of the resonators at the technical university [Technische Universität Wien]. And then characterization of the resonators. So we build a small test setup... Cause the final experiment is in this dilution fridge that takes days to cool down and it's complex. The first goal was to build a quick turn around testing system. So it wasn't the full experiment, but was enough to characterize the mechanics. So I build this cryogenic-enabled Fabry-Perot interferometer system, where we could load chips in, measure the mechanical response of the devices [cantilevers on the chip].
28. It wasn't intially the plan, but at one point we started getting... All these things are limited by the quality factor of the resonance, so the mechanical damping of the resonance. Which is the biggest roadblock to all these opto-mechanical experiments. So we started looking into ways of quantifing and understanding the mechanical damping in the systems.

Reinhard

29. To improve then on the mechanics.

Garrett

30. So then I took, that was like two years almost, like a year and a half just focusing on this. Ultimately we also got some nice paper. So it's basically design, fab, characterization of the resonators. And then there is always lots of little side things that pop up. But my main role would be the guy who works in the clean room.

Reinhard

31. Making all this resonators. And the others then spoil them.

Garrett

32. Adapt them! There is Dilek [Demir], this diploma student does the radiation pressure test with these cantilevers that I make for her. I made some devices for Michael [Vanner]. There is a group at MIT that uses some of the devices that I made here. We have the resonators that we use for the cooling experiment. Making new really short cavity resonators for some other experiments. There is always something. And anytime stuff needs to be done, like really high precison, like microscopy. Like the beat exeperiment, they want to see the size of their beat [???]. Anything that goes on outside of the lab that we currently have. So anything that needs to be done in like a clean room.

Reinhard

33. So you do this alone? Or is there somebody else?

Garrett

34. Simon [Gröblacher] for a while was going to Cornell [University]. Simon Gröblacher? I never say his last name properly ever. He would go to Cornell and do the fabrication. He is also capable of doing the fabrication; in a more limited sense. He can make those mechanical resonators, but not as like... I mean I have done macrofab since 1999 or 2000. So it's just much more like variety, which I'm still very good at. But I think he is also better. I mean his focus is at the cooling experiment. So it's better for him to not have to got to the fab, that's nice. So it's predominantly then me. But I would say: me 90%, Simon 10%.

Reinhard

35. Ok. So although not working here, he is giving some input.

Zukunftsaussicht

Reinhard

36. Do have any plans or prospects what you are going to do futurewise?

Garrett

37. I don't know, I don't know. That's actually been a pain, it has been though. Cause I haven't really put a lot of effort into it. And I don't really know, what I wanna do. I worked for the industry, then I was at Livermore, then here and then... I was going

back and forth thinking about academic positions. But it doesn't... Right now it's sort of leaning away from that. I don't know what I wanna do.

Reinhard

38. So it's just... Leave it open and see what is going to come. And wait for that.

Faszination an der Quantenmechanik

Reinhard

39. I mean we already talked about it, but could you tell what fascinates you about like quantum mechanics? Or more [explicit], the stuff that is done here, basically in the experiments?

Garrett

40. I just like the concept of like... Just explaining the concept of the work to somebody is crazy to think about. Cause the size scales are very different. Isn't that trival? Say, if you make a single photon superposition, or do something like optical entanglement experiment. But to take it to a fairly macroscopic mechanical system. I mean I go to the clean room, I start do some things with my hands and in the end you have a little resonator; right. And people say you can see with your eye, almost. It's amazing to think that you could then do, say in the long run, have some -- now we couldn't do -- but some massive superpostion, where you have this thing both static and displacing. So some zero-point motion of the thing and then some vibration amplitude of the thing simultaniously. I think this is really cool. A cool concept. It is just intriguing to the point that people are looking at this. And there is all kinds of funky... I used to do this studies of these non-linear resonances, classical non-linear resonances. They can be really funny stuff. So these things have this hysteresis. But if you had a quantum resonator that was capable of doing that, it would just lead to, I don't know if you even call this tunneling. But it could hop between those two states...

Reinhard

41. ...with nothing in between...

Garrett

42. Yeah. So it's fascinating to think about things like that. I think it's more of the size scale. Because a lot of these concepts have been done. You know.

Reinhard

43. So are they settled for you? Or are they still kind of intriguing?

Garrett

44. So I would say, in my mind everything just seems to be a technical hurdle. Like it is physically possible. Not to infinity, but to a very large scale. I don't see any roadblocks there. It's just a technical challenge isolating this thing properly. That's the way I see it.

Reinhard

45. So the concept is there. The theory says it works, so...?

Garrett

46. That's true. I mean theory [???] works for, right now, up to something like these sort of resonators, we are looking at. Something that's only in the order of some hundreds of nanograms. That's feasable. If you wanna go much larger than that, no. At the same time you see results like from LIGO [Laser Interferometer Gravitational Wave Observatory], the gravitational wave type thing. And they have multi kilogram mirrors and they are getting down to few hundred phonons [quasiparticle, which represents an excited state of the modes of vibrations of elastic structures of interacting particles. The smaller the number of phonons, the closer you are at the ground state of the system and to a quantum regime.]. So honestly seeing that, it makes me think it wouldn't be that much harder to keep pushing that. That's humongous.

Reinhard

47. So this is also an interesting way just to go there, push technically the limits and see what the outcome is? Be surprised, or not.

Helfen Experimente dem Verständnis?

Reinhard

48. Do you see these experiments as something that might help in understanding, like the intriguing parts?

Garrett

49. I think so. The thing that always comes up and for me it's more like -- what's the right word -- parading or [???]... Because theoretical my background is not nearly that strong.

(no speaker)

50. [little interruption]

Garrett

51. Ok. What was the last question? We have to rewind and see.

Reinhard

52. Oh, if like doing the experiments could help in understanding the intriguing things. Or just getting settled about it.

Garrett

53. I come from a totally different background, such as weird that the way I think about it might be differently. Which is interesting, I understand. When people talking about all this quantum classical transition: Is there like a boundary in between these things? Mine is: I don't see that they are any different. But one is just some extreme form of the other. So I think it would be nice to show that you can take something massive and see quantum effects in it. I don't really know how many people in this field or in this area, would every think there is some sudden change when you go from one side of physics to the other. I think anybody doing this, it'd be surprising if they thought that way. I'd actually be surprised, if there is any [???] that actually also thinks that way. But it'd be nice to proof, that you can take something that massive and show some quantum effects in it.
54. I think the most interesting, like technical, thing to study, is to see what causes it to appear, to be completely... What causes it to be classical, I guess. So in that sense, in that direction you need to study the decoherence mechanisms that work. That would kill those quantum effects in these big systems. So there's lots of neat proposals, like this Penrose model and these other ones I don't know the details of and the names of. It'd be a [???] to see like say: We can prepare, fist some nano mechanical resonators and larger micromechanical resonators, and eventually those LIGO scale, like kilogram structure. And then prepare it in some state and then let it sit and evolve, and just die back to some boring, dumb [classical state]. How fast is that time scale happening on. What does the theory show it happens on. And then compare this and see what's it like.
55. It sort of goes back to what I said earlier, but in the end everything is just... If you take anything and properly isolate at least one degree of freedom or one thing that you can get some characteristic of. Have the measurement has to be some point were you can see quantization, you can see some quantum effects in that state. If you properly removed it's connections from everything. Which becomes just more technically challenging as you you move up in scale. So it's just kind of neat to think about that. That's maybe not the most exciting outcome, to me it would be neat to see.

Reinhard

56. So the experiments, at least try...

Garrett

57. Short term all these experiments first have to get there; towards repeatable... So if you go back and look at like the ion trapping or atom cooling. And people worked for a long time and now it's, I wouldn't call it routine, but it's fairly routine to prepare these states. And now you can do like very beautiful physics with these systems. So we are at the point were we're developing the background steps to get there. It's really challenging, but there will be a point like years from now, when people look back and say: Now it's done, now we can buy a model and press a button. And you do it, right. So we are at the more difficult stage of just preparing, just laying the ground worth to get to the quantum regime with the devices; right. Once they are there, then you can start looking at what sort of physics can you do with these systems. Prepare some entangled state or superposition state of the mechanics. Let them evolve in time and do these measurements.
58. I mean it's already here. Because the Cleland group at Santa Barbara [http://www.physics.ucsb.edu/~clelandgroup/] had this demonstration last year. This thing was rapidly decaying, but neat electromechanical resonator. Just because it's so high frequency they can cool it to the ground state. It was coupled to this two level qubit. They could write single phonons onto it. Read it out. They could put single phonon superposition states in it. This thing was a large structure. This is also a micron-scale device.

Reinhard

59. Nice!

Garrett

60. We are basically there. We are on the brink where it's like being able to realize this. And then what you do next? So then you prepare, just for sort of glory, these fanzy quantum states, even though they may not last for any sort of time. But it's just to show that we can do this. And then when it becomes more reproducable to create these things, study how they survive. And then you can do all the same sort of experiments you did within optical domain [but] with these large mechanical systems. Do they behave the same?
61. It's neat to see, coming out of like... We started at IQOQI [Institut fuer Quantenoptik und Quanteninformation, Akademie der Wissenschaften], so in Anton Zeilingers institute there. So he started way back with the neutron experiments, optical experiments. And then the extension to larger stuff, like Markus Arendts work. And so then you keep walking up the size scale. Now we have full microfabricated devices. It's neat to see the progression. It's really cool that they [Markus Arendt group] are doing this basic, archetypal double slit experiment. First with the C60 [fullerene] and now it's like proteins and crazy stuff.

Reinhard

62. On paper, in principle, it is quite nice and easy, and not complicated at all. You just [have to implement it][sarcsm]

Garrett

63. The basic physics obviously have interference occur. It's the same. Be it single photon, be it bucky ball [C60, fullerene]; you know. Just the bucky ball has lots more degrees of freedom. So they can see some neat things. Even though these are launched out of an oven, with something like internal temperatures of hundreds of Celcius at least. And that these things don't just instanteniously decohere. They just even can still see effects. That is very impressive. But the same arguments can be made of like... This is something some persons put in the lab, made with their hands, brought out, welded into a machine. You know, if you make the conditions right you can cool to the ground state and then see these effects. I think it's exciting.
64. I don't know if it makes it more tangible to the general public, but it's... Ok, when you have a single electron, or give a neutron or those things. People would know the words, but they have no idea what that thing is. Right? At next we are moving up to say a molecule, like a bucky ball [C60, fullerene]. That is starting to get a little more... You can show pictures of a soccer ball, that's what it looks like. It's becoming more tangible to the normal person. And then as you progress up in the size of clusters and different organic molecules. Then it becomes more relevant. And the same thing, I think for us. Now we are starting to make some mechanical resonators, the extreme again is this LIGO mirror, that is massive, like just a giant fat diner plate. Something you could actually go see that. You could tell them what it was doing. Then it becomes much, much more tangible to the general public.

Reinhard

65. At least increasing some kind of relevance.

Garrett

66. Yeah. Even if it's just size gain. Or something someone can see. Or something that you are familiar with. You can always turn to describe our devices like it's a mirror, a tunig fork. It's something more that they can imagine as a little resonator. Right? Versus like I have a neutron. [laughs] To some degree the physics aren't very different, but just another platform to display. And there are obviously new things that come into play.

Interpretationen

Reinhard

67. Are you somehow into the discussion about interpretation of quantum mechanics?

Garrett

68. The problem is... That's getting to far out for me sometimes. I mean just because... That's one thing I'm actually slightly disappointed with myself here so far. I think you just get caught up in the work that you have to do. When I first got here I promised myself: Ok, I really sit down and study like basic quantum mechanics to more thoroughly participate in the conversations. But at some point you have to stop, cause you have your day-to-day stuff that you need to do. Unfortunately no. I'm actually really bad with that.

Reinhard

69. But you see that there is some kind of discussion going on?

Garrett

70. I see those discussions. I feel like here... Honestly that is purely my interpretation, but it seems like because to some degree everybody branches out from Anton [Zeilinger]. There is not a huge diversity in sort of mind set. Like everyone sort of aggrees. Many tiny details that people disaggree with, but it's... There is one team here. There is like one single interpretation that will be followed here. But that's just what I would guess.

Reinhard

71. Plausible.

Garrett

72. Yeah. I see examples when visitors will come and there will be discussions with the visitors. They then disagree with what maybe sort of a norm here. But it seems like the discussion within the greater, like university, IQOQI, and the groups that interact with IQOQI from the university. Everybody seems to be on the same train of thought. This is our interpretation and that is how things are.

Reinhard

73. I see. So you are also in this set of interpretation.

Garrett

74. Kind of. I think I haven't been exposed to anything else.

Reinhard

75. The question is whether it is of any relevance? Propably not for the day-to-day work, because...?

Garrett

76. I don't know if this is true, but... Obviously the people who come here, to some degree agree with what's going on. So follow that interpretation. And then also it would be harder if you came with a completly contradictory view to sell yourself to come into the department like that. As I said for me, I have only been exposed to this honestly.

technischer Fortschritt

Reinhard

77. How do you see, that is kind of an obvious question,... How do you see the influence of the technical enhancements that were going on. Propably those experiment wouldn't be possible if one could not engineer those things.

Garrett

78. This is on all fronts though. I mean the thing is you have to, at least for our experiments specifically, have very high performance, like low damping, high reflectivity, very precise geometry mechanical resonators, right. That relies fully on micro-nano fabrication technologies, like have their root in integrated circuits. So like from the fifties. And every time that advances, then we can build off those advancements, right. But everything in the lab... I think it's true of all science to some degree that like these effects have been there.
79. It takes someone to come up with a theory to look for it in the first place or you accidentally discover it, which is also possible. But then to experimentally measure any of these things there has to be advancements in the tools to do the measurement. All the basic electronics, just stuff like the oscilloscope, spectrum analyzers, whatever it may be. As they become more sensitive, then it's easier to sort of find out these tiny funny things. Most of the obvious effects are kind of gone. Unless you come up with an entirely new physical fact that was somehow overlooked or under some conditions something pops up. That's rare. So you are really looking for higher order things that people did not anticipate, didn't expect or couldn't measure just before; right.
80. I mean for us it's... You know we are dealing with radiation pressure. So we sort of... amplifiy is not the correct technical term, but we make this visible. Because we have this cavity and because we are modifying the dynamic, the response of the mechanical resonator. We also have an experiment out, which is kind of fun, where we just have these large cantilevers. Large?! I call them large, because they are three millimeters. But they are 3 millimeters by 6 microns by 5 microns. So they are like little hairs. We use radiation pressure just to deflect those, I mean just to drive them into resonance.
81. And the nice thing is, we can fully do this on a table top. That's because I had a very nice laser source. It took advancements to make this like nice little laser. It's a green narrow line diode laser, I can microfabricate this thing [the cantilever]. Because the materials available nowadays are in all very nice; sort of high quality material. The microfabrication has gotten to the point where I can make this complex structure. And then I have some read out system with this split photo diode, where I can measure the displacement of this little beam. On the table I can now build this set up that I can show you the momentum transfer with photons reflecting of the surface, making a mechanical system move. Which is already... There is not like fundamental quantum effects there unless you start get single photons.
82. I mean this is physics, that in principle should have always been there, but it's just so hard to see. So the original experiments in that area were in 1901, where this guy Lebedev, then Nichols/Hull [Ernest Fox Nichols and Gordon Ferrie Hull], these american guys. They had... If you look at pictures of their experiments, they basically have some massive light source, these lenses, these silvered mirrors need huge [???] archs. These things take up a whole room. And they are measuring teeny, teeny, tiny forces and tiny displacements. And they are using just either their eye and a small guide to see a deflection. So it's amazing just what you can see. Now we can routinely... Markus [Aspelmeyer] when he gave his Antrittsvor....

Reinhard

83. Die Antrittsvorlesung.

Garrett

84. I stopped cause I thought that was really wrong. So we made like a little demo. Did you go to that?

Reinhard

85. Yeah, I have seen that.

Garrett

86. So that was this experiment actually I just described. Into the point where we could build it and roll it into the auditorium and show it. And if you'd show it someone like Lebedev or Nichols/Hull, it's a hundred and ten years later. So there is a lot of advancements in technology; on all fronts. Like from just the vibration isolating optical table to this diode laser, to these electronics that do the read out. Everything we do relies on advancements in these tools. The extreme case of that is measuring quantum effects. If we are going to measure some... At some point we have to be able to measure the resolution better than the zero point motion of this mechanical resonator; right. And just the precision that's necessary to measure that is absurd. It's amazingly that you can even get there. So go back ten, twenty, thirty years, it's just not possible to do. These experiments could have been proposed, but they would never happen until the technology caught up.

Reinhard

87. Do you see... this things driving the technology the other way. Say because there is need for the experiments to have such a precision engineering, that also the engineering profits from it.

Garrett

88. I think our field is extremely new, so it's hard to see directly the impact. But again given things like LIGO. The gravitational wave people are essentially...they are not looking for quantum effects. But their requirements are very similar to ours. They are very parallel to what we do. I mean these guys have pushed the limit of like these optical coatings to make these high reflecting mirrors, which you can now get... All the optics we use are coated with stuff based on technology developed for... driven by that experiment.
89. Same thing for us now, where we really have... Like the one example, cause this is also very recent, it's tied to stuff I also used to do. So we need to amplify very, very, very low light levels now. We have this optical cavity, we send in very, very, very weak light and we wanna read out the state of light coming out of this. And that's actually really tough to do. To take this very, very...this tiny signal out of the noise and amplify it. And so we ordered... It was actually a company I used to work for. So we just bought this amplifier from them, which did not exist up until they start offering it a year ago. And now it looks like... We'll see, if it worked. But in

principle that can enable us to really drop the power. It makes a lot of things experimentally nicer.

90. For the past year plus, I've been pushing them. I had worked on these devices before and we had a need for something like that. And I said: We need this, we need this, we need this, we need this. So really pushing them. Cause they were making devices like for proof of principle stuff. In the US a lot of is driven by defence related stuff. They were making devices for these defence contracts, but really not to be applied in anything. It was more just advance the state of the art and then maybe find a use. Then I have to email or call them, pester these guys and say: I know you can meet these specs, if you keep trying. And if you say we will buy them and we will use it. And if we show, we get good press for this and other people want to buy it. It opens a little market. It's small right now in our specific field. But there's lots of measurement technology that can benefit from measuring these extremely low light levels, weak light levels. So it does go back and forth. I definitely think it feeds back.
91. And so one more thing just cause we... The other one was, another concrete example, these positioning systems. This very like esoteric. Very specific stuff we have to do techically. We have to work at very low temperatures and we have to move a little chip [The chip with the cantilevers on it] around. And there is a german company, called [???], that makes these systems. And then they... One thing that was always annoying before, you never knew where you were locally. You could move, but I can never ask the system, where did you move to. It wouldn't know. So it would move, move, move, move. Maybe I knew where I started, but I have no idea where I ended up for sure.
92. So then we talked to them and they said that they were developing an encoded system, that can record where the thing was and we can read that out. We showed some interest and we said yes. And now there is a lot of groups, not just us, but there's tons of applications for that to have it. But we pushed them. We thought it was a finished commercial device, but it turned out it was more of a prototype. Because we had an automated system, some software to read out were this thing was. But that didn't work at all. I don't agree with it, because we spent tons of time developing this software, essentially for them, to make it work. And then feed back to them. Hopefully they now have a more robust product.

Ende

(no speaker)

93. [Thanks for the interview]

Nikolai_110525

Interview mit Dr. Nikolai Kiesel vom 25.05.2011
Transcribed by yotta, version 1 of 110526

Anfang, persönliche Daten, Ausbildung

Reinhard

1. Zu Beginn will ich eigentlich eh nur allgemeine Fragen stellen. Wie alt bist du?

Nikolai

2. 34.

Reinhard

3. Kannst du kurz schildern: dein Studium, deinen Werdegang. Wo du studiert hast?

Nikolai

4. Ich bin zum studieren nach München gegangen. Ich komme aus Nordbayern, aus Franken. In der Schule war eigentlich nicht klar ob ich jetzt Chemie, Physik oder Mathe studiere. Und dann habe ich Mathe und Physik angefangen und bin bei der Physik hängengeblieben. Nach den Lectures von Feynman, also nach dem Buch. Dann habe ich in München Physik studiert. Und habe eigentlich erst gegen Ende dann in einem Seminar mitgekriegt von den experimentellen Sachen zur Quantenphysik; von Harald Weinfurter dort. Der auch beim Anton Zeilinger war. Das war ganz spannend und dann habe ich mir das angeschaut. Und eher noch so theoretische Sachen zur Superstringtheorie. Ich habe mit in den Urlaub genommen, die papers. Fand ich dann die Experimente der Quantenphysik doch spannender. Dann war ich dort zur Diplomarbeit und dann nach einem halben Jahr Pause, dann auch zur Doktorarbeit.

Reinhard

5. Über was die Diplomarbeit?

Nikolai

6. Das war Drei-Photonen Verschränkung. Ich hatte einen experimentellen Aufbau zu einer bestimmten Art von Drei-Photonen Verschränkung. Also W-State, im Gegensatz zu dem GHZ-Zustand [Greenberger, Horne und Zeilinger] der da [in Wien] schon gemacht war. Dann war ich ein halbes Jahr weg und bin dann auch wieder in Multi-Photonen Verschränkung. Also dann vier Photonen.

Reinhard

7. Ja, man muss sich steigern.

Nikolai

8. Genau, genau. Auch einige mehrere Zustände. Dann zur Doktorarbeit geblieben und dann noch ein Jahr als Post-Doc. Und dann bin ich hierher gegangen zum Markus [Markus Aspelmeyer].

Reinhard

9. Das war jetzt vor zwei Jahren, oder?

Nikolai

10. Das war vor zweieinhalb Jahren. Weil dann war es mal Zeit irgendwie thematisch leicht zu wechseln. Also es ist immer noch natürlich experimentelle Quantenphysik, zumindest wünschen wir uns das jetzt hier. Aber halt doch ein bisserl ein anderes System, und andere Herangehensweise, neue Methoden.

Reinhard

11. Also auch die Motivation wieder etwas neues zu machen?
12. Und wie bist du dann auf hier gekommen?

Nikolai

13. Ich habe mich so ein bisschen umgeschaut. Es war klar das es Quantenphysik sein soll. Es war klar das es zumindest ein bisschen Grundlagen sein sollen. Ich wollte nach Möglichkeit irgendwie mit meinem Wissen um grundlegende Sachen... Also mit Photonen kann man halt alles mögliche schon machen, weil sie so einfach zu handle'n sind. Was man nicht so richtig lernt sind natürlich die ganzen Methoden die an komplizierteren Experimenten stattfinden. Und ich wollte halt das irgenwie kombinieren. Das ich die anderen Methoden lerne, aber da mein Wissen einbringe. Weil viele Gruppen - das wird jetzt immer weniger - hatten nicht so Ahnung vor einiger Zeit noch. Wenn man jetzt Qubits [Zweizustands-Quantensystem, analog zum klassichen Bit in der Informatik] hat, was man da machen kann; außer Quanteninformation.

Reinhard

14. Also das es da auf dem Level stehengeblieben ist, oder?

Nikolai

15. Ja. Das kam halt meistens von der Sache her, jetzt zum Beispiel Superconducting Qubits. Das kam halt meistens von der Sache her: Ja, jetzt hat man ein System. Quanteninformation ist irgendwie cool und deswegen ist Qubits toll. Und jetzt macht man so Qubits und natürlich will man viele. Und man will das integriert für einen Quantencomputer. Aber das es jetzt da eine ganze Welt - also vielleicht unterstelle ich das auch nur - von Theorie zur Verschränkung gibt und das man nicht immer nur eine Bell Ungleichung messen muss, wenn man Verschränkung nachweisen will; zum Beispiel. Das waren Sachen die jetzt erst so mit der Zeit so richtig bekannt werden; glaube ich.

Aufgabe im Experiment / Rolle in der Gruppe

Reinhard

16. Was ist da so deine Rolle in Gruppe? Ich weiß, dass du das Experiment mit den "Kugerln", oder...

Nikolai

17. Mit den Nanokugeln.

Reinhard

18. Klingt ein bisschen professioneller.

Nikolai

19. Nano-Kugeln ist auch nicht so professionell. Ja, als ich vor zweieinhalb Jahren kam in die Gruppe, da habe ich eigentlich noch so ein bisschen mitgearbeitet am Experiment, an dem jetzt auch Witlef [Witlef Wieczorek] ist, mit den cantilevern. Habe mich hauptsächlich... Also ich bin ja im Rahmen von einem Humboldt-Stipendiat hier. Das ging im wesentlich um Einzel-Photonen Quanten-Optomechanik und Verschränkung. Wie so oft in solchen Sachen zieht sich das halt länger hin. Und so zur halben Zeit, oder sowas, kam dann dieses... Also vor eineinhalb Jahren fast jetzt, kam dann diese Sache auf mit den Nanokugeln. Und da bin ich dann aufgesprungen. Als ich kam war die Gruppe noch nicht so riesig. Da waren wir irgendwie zu fünft; glaube ich. In der Zwischenzeit, durch den Ruf vom Markus [Markus Aspelmeyer], sind wird jetzt halt noch zwei mehr Post-Docs und noch ein paar Leute. Ich bleibe auch noch länger da.

Reinhard

20. Eine größere Planung? Also schon weiter geplant, was du machen willst?

Nikolai

21. Genau. Also das Experiment werde ich jetzt weiter mit ausbauen. Und bin ich natürlich auch bei den ganzen Nicht-experimentellen Sachen so mitbeteiligt. Was

halt immer damit zu tun hat? Was man halt so mit der Zeit auch macht.

Reinhard

22. Und das wäre?

Nikolai

23. Naja. Das sind halt so Sachen, wie wenn es um irgendwelche Verantstaltungen geht. Also was halt mit der Zeit auf einen zukommt, wenn man dann mal irgendwann selber soweit ist, wie der Markus [Markus Aspelmeyer]. Dann kommt man eh nicht mehr ins Labor. Im Moment bin ich noch viel im Labor; das ist gut.

Reinhard

24. Wie ist denn ungefähr der Status im Experiment?

Nikolai

25. Der Status im Experiment [Lachen]. Der ändert sich täglich. Das Experiment sah am Anfang wie immer ganz einfach aus. Da war es auch so, dass es... Es ist immer noch was ganz neues. Es hat in dieser Form bis jetzt noch keiner levitierte Nano-Kugeln in Cavity-Opto-Mechanik verwendet. Dadurch sollte das ja auch schnell gehen, damit es niemand anders vor uns macht; ganz klar. Aber es ist ganz klar, dass die Motivation von dem Experiment natürlich ist, irgendwann gute Quantenphysik zu machen. Weil levitierte Kugeln super geeignet sind.
26. Der Status im Experiment ist der: Mit der Zeit findet man dann raus wo es hakt. Und wir hatten dann im wesentlichen alles dastehen. Nur unsere Kugeln die brauchen wir ja bei tiefem Vakuum. Und eine Sache die nicht klar ist, warum wir nicht ins tiefe Vakuum können. Weil die Kugeln gehen vorher verloren. Die bleiben nicht in der Falle. Bei ein bisschen unter einem Millibar verschwinden die. Das ist eine Sache, die jetzt so ist. Ja, gar nicht quantenmechanisch, nur anstrengend. Auf der anderen Seite ist es so, dass wir natürlich die Cavity-Opto-Mechanik sehen wollen und da ist es in letzter Zeit ziemlich gut gegangen. Wir sehen jetzt ein Signal in der cavity und damit können wir jetzt die ersten Methoden zeigen. Und zeigen, proof-of-principle, dass wenn man denn mal zu einem niedrigerem Druck kommt, dass man dann auch ein Ground-State-Cooling [d.h. das System in den Grundzustand=Quantenzustand zu bringen] und so machen kann. Insofern ist das ein guter Zeitpunkt die Frage zu stellen.

Reinhard

27. Die beste Zeit ist wahrscheinlich, wenn man das volle Ergebnis hat und schon alle papers raus. Das ist der beste Status vom Experiment.

Nikolai

28. Ich glaube der beste Status ist in dem Moment wo man weiß was man jetzt aufschreiben kann. Weil wenn die paper... dann wird es schon wieder anstrengend.

Reinhard

29. Und bei dem Experiment warst du von Anfang an dabei? D.h. auch in der Konzipierung und theoretischen Entwicklung?

Nikolai

30. Ja, das habe ich aufgezogen. Es gab ein Theorie-Paper davor; also von anderen Gruppen. Und da arbeiten wir auch mit einer zusammen; mit der Ignacio Cirac [Gruppe] in München. Aber alles was das Experimentelle betrifft und wie wir es aufbauen, habe ich dann angefangen. Und dann kam ein Dplomand dazu und dann später noch Florian [Florian Blaser] als Doktorand. Jetzt machen wir das so miteinander.

Faszination an der Quantenmechanik

Reinhard

31. Jetzt zu etwas anderem. Was würdest du als faszinierenstes Feature sehen, jetzt von der Quantenmechanik? Was dich begeistert in diesem Feld? Was einen motiviert?

Nikolai

32. Das hat viele Aspekte. Ein Hauptaspekt ist der, dass diese Aha-Erlebnisse nicht aufhören. Also ich habe jetzt... Wir haben letztens die Diskussion gehabt. Ich habe in meiner Diplomarbeit eben auch mit Bell Ungleichungen und so schon zu tun gehabt. Also das "klassische" Beispiel im quantenmechanischen Kontext. Und trotzdem muss man es immer noch mal von einer anderen Seite anschauen. Und trotzdem muss man nochmal verstehen was da passiert. Ich glaube das ist das Faszinierende. Dadurch das man es nicht direkt greifen kann, was denn jetzt die Quantenphysik ausmacht. Und wie man es jetzt richtig sagt. Dadurch muss man so viele verschiedene Modelle im Kopf entwickeln. Also ich weiß bei mir persönlich, dass was mir am meisten Spaß macht - überhaupt an der Physik - immer die Sichtweise zun ändern. Ich glaube, dass das eher ein allgemeines Phänomen ist.
33. Andererseits, es klingt komisch, aber was natürlich irgendwie toll war, gerade in der Zeit der Diplomarbeit - das ist jetzt mit den Experimenten die wir jetzt machen ein bisschen anders -... Diese Qubit Rechnerei ist ja relativ einfach zugänglich. Das war ein Gebiet in dem man relativ schnell einsteigen konnte Sachen zu machen, die jetzt sich noch niemand so überlegt hatte. Oder man neue Ideen haben konnte, ohne das man wirklich ein riesiges Fundament von Wissen gebraucht hätte. Das ist natürlich mit den Experimenten wie es jetzt hier ist, oder was wir auch planen wirklich Quantenphysik damit zu machen, nicht mehr ganz so einfach.

Reinhard

34. Aber scheint halt mit der Zeit mehr zu werden. Es wird ja immer mehr Technik reingesteckt. Oder Dinge die du dann zusätzlich brauchst. Wie du schon gesagt hast, nicht mehr so einfach wie die Bell Experimente sind.

Nikolai

35. Es wird auch konzeptionell schwieriger. Wenn man jetzt gerade sieht hier bei uns mit massiven Objekten geht natürlich in einen Bereich wo es an Gravitation stösst. Da wollen wir ja auch hin. Das verlangt natürlich auch, dass man sich das zusätzliche Wissen aneignet. Was ja Sinn und Zweck der Übung ist. Also, in a nutshell: Das Faszinierendste für mich ist das... Man kann es nicht direkt begreifen, deswegen muss man so viele Perspektiven finden aus denen man es beschreiben kann.

Interpretation / Theorie / Experiment

Reinhard

36. Aber das treibt das Ding auch irgendwie weiter. Das macht ja dann auch die Motivation für Experimente aus. Wenn man eben nicht ganz sicher ist auf was das hinausläuft. Ob das Experiment so jetzt funktioniert, oder ob man nicht auf neues stößt?

Nikolai

37. Einerseits überhaupt auf ganz neues stößt. Andererseits - das klingt fast abwertend zum Experiment ist aber gar nicht so gemeint, im Gegenteil - ist es natürlich eine Art sich damit zu beschäftigen, die einen zwingt Sachen dann halt richtig zu sehen. Dann denkt man darüber nach und denkt das müsste so und so sein. Ist es dann eben jetzt nicht so, nicht weil die Theorie irgendwie geändert werden müsste, sondern einfach weil man noch einen Knoten im Hirn hat. Es ist eine Art damit zu spielen. Wenn man recht nett ist, eine andere Art damit zu spielen.

Reinhard

38. Wie würdest du dann die Beziehung so von Theorie und Experiment sehen? Weil es

ja schwierig ist. Theorie und Experiment geht ja dann noch, aber wenn man dann so an Interpretationen denkt. Die spielen dann im Experiment dann kaum eine Rolle?

Nikolai

39. In dem Moment wo man am Experiment steht hat man ja immer mit klassichen Geräten zu tun. Da wo es aber schon auf eine Art, manchmal, selten reinkommt ist natürlich wenn man dann... Man muss ja nicht nur überlegen jetzt: Ich weiß jetzt wie ich das mache und dann sehe ich das am Schluß, oder was sehe ich dann am Schluß. Sondern jetzt ist das alles nicht so wie ich es will, kann ich trotzdem einen Effekt sehen. Und in dem Moment muss man natürlich wieder darüber nachdenken. Und sieht vielleicht was neues, was einem nicht vorher klar war, dass da ist. Aber das ist tatsächlich, glaube ich, das Einzige wo das Experiment... Wenn man nicht die richtigen Bilder im Kopf hat, dann hat man auch nicht die richtige Idee wie man das macht.

Reinhard

40. Verstehe. Und ist es irgendwie persönlich interessant für dich diese Sachen... Sind die relevant, Interpretaionen, die es da, wenn man will auch "klassisch" nennen [könnte], gibt? Falls man sie überhaupt mitbekommt? D.h. was man im Studium lernt, bzw. was du gelernt hast?

Nikolai

41. Nochmal? Ich habe das nicht ganz verstanden.

Reinhard

42. Nein, ob so prinzipielle Fragen, wie jetzt eine Interpretation wie die Kopenhagener Deutung oder Bohmsche Mechanik, Viel-Welten Theorien und was da so herumschwirrt. Einerseits ob man das überhaupt im Studium irgendwie mitbekommt. Und ob das überhaupt eine Rolle spielt?

Nikolai

43. Im Studium mitbekommt? Ja. Also ich habe im Studium schon ein bisschen was mitbekommen. Was zum Teil daran lag, dass es halt, zum Beispiel, so einen Bohm'ianer an der LMU [Ludwig-Maximilians-Universität München] gibt. Der hatte eine Mathe Vorlesung, die eine versteckte Bohm Vorlesung war.

Reinhard

44. Musste er sich verstecken?

Nikolai

45. Ja, es ist schon... Ich glaube der hat einen harten Stand da. Also das ist alles sehr konservatives Umfeld. Wenn man so will, quantenmechanisch konservatives Umfeld.

Reinhard

46. Da ist es eben die Frage, was da noch durchscheint? Oder ob du nur den normalen quantenmechanischen Lehrplan hast? Der eh ziemlich gleich ist überall.

Nikolai

47. Nein, in der Form wie ich es jetzt gesagt habe, hat man das schon mitgekriegt. Ob ich es jetzt halt noch so sehen würde, ob das so ist oder ob das nur so vermittelt [wurde], weiß ich nicht. Aber mir kam das damals so vor: Ja, der hat jetzt diese andere Interpretation. Der hat das auch mit Feuereifer versucht klar zu machen, dass das die bessere Sichtweise ist. Und das er da angeeckt ist, das war auch allseits bekannt. Insofern war das auch interessant. Also ich war, das hängt ja immer viel davon ab, mit vielen Leuten mit denen man dann über diese Sachen geredet hat beieinander. Auch Bell und so weiter. Was bedeutet es und wie kann man es verstehen. Relevant? Ja, es ist für mich hauptsächlich relevant, weil es eine von den Sachen ist, die mich am meisten interessieren. Ich glaube ich könnte, dass was ich jetzt mache genauso machen, wenn ich das jetzt nicht so wüsste alles. Aber gerade wenn einen das interessiert ist hier das richtige Umfeld, glaube ich.

Reinhard

48. Die Frage ist auch ob inwieweit einen sowas zumindest hilft besser zu verstehen? Oder zumindest, wenn man mehrere Sichtweisen hat, zum Beispiel die Bohm'sche so daneben stellt, im Vergleich ein besseres Gefühl bekommt? Wie die Sache liegt, oder was die eine erklärt, was die andere schwieriger erklärt?

Nikolai

49. Ich muss dazu sagen jetzt... Es ist ein extrem unterschiedliches Level auf dem ich diese Sachen unterschiedlich kenne. Bei Bohm jetzt zum Beispiel kann ich nicht viel dazu sagen, da gibt es nur zwei, drei Bilder im Kopf. Auf einem Verständnis-Level hilft es. Also auf einem einfach theoretischen Level hilft es einfach dehalb, weil wenn man was auch anderes verstehen kann, dann muss man sich fragen warum man es so und nicht anders meint. Auf dem Level, ja. Wie gesagt für die konkrete Arbeit, nein. Also ich glaube, dass... Konkrete Arbeit meine ich jetzt Laborarbeit, aber natürlich ist es Teil der Arbeit. Denn wir diskutieren ja hier ständig über solche Sachen.

Reinhard

50. Aber das scheint auch eine Möglichkeit zu sein, zumindest in der Beschäftigung damit, das Verständnis zu steigern. Das will man ja zumindest, dass man Dinge besser versteht. Und das ist auch für dich ein Mittel das besser zu verstehen?

Nikolai

51. Ja, ja. Auf jeden Fall.

technischer Fortschritt

Reinhard

52. Eine Frage ist noch inwieweit würdest du das einschätzen, wie sich durch technische Möglichkeiten eben die Möglichkeiten im Bereich der experimentellen Quantenmechanik auswirken? Weil es scheint ja doch ein, muss man schon sagen ein paar Jahre oder man kann schon bald Jahrzehnte sagen... dass es da doch einen ziemlichen Anschub gibt, wenn man vielleicht die vorherigen Perioden vergleicht.

Nikolai

53. Ja, da ist plötzlich viel passiert in kurzer Zeit. Speziell der technische Aspekt ist gerade jetzt mit der Opto-Mechanik so, dass einfach vor zehn Jahren die Technologie nicht da war um die Experimente zu machen. Das kann man schlicht und ergreifend so sagen. Da gab es natürlich die Ideen das zu machen und auch Leute, die das angefangen haben. Aber die Technologie das so zu machen ist jetzt erst da. Viele Systeme werden natürlich erst so entwickelt, aber die Methoden sind erst da. Von daher hat es einen riesigen Einfluß. Das gilt jetzt hauptsächlich für die Experimente [hier in dieser Gruppe]. Wenn man die Photonenexperimente anschaut ist mir nicht ganz klar warum das an einer Stelle so einen Schub gab. Weil das hätte man auch vorher, wenn man es gepusht hätte, vielleicht früher... Aber da brauchts halt dann noch die Leute, die das machen einfach.

Reinhard

54. Es hat sich sicher auch Motivationslage geändert. Irgendwie gibt es ja den Wunsch mit dem was anzufangen. Anwendungen zu haben. Also wenn ich die Schlagwörter sage: Quantencomputer, Kryptographie und Informationstechnik...

Nikolai

55. Sicher gibt es Leute, die genau die Vision haben. Wobei genau die Applikationsschlagworte natürlich schon stark getrieben sind, weil man sie auch finanzieren muss. Also ich glaube, dass, jetzt weniger, aber vor allem in der Zeit wo das geboomt hat am Anfang. Das ist vor meiner wissenschaftlich sehr aktiven

Zeit, deswegen kann ich das nur raten. Aber die aller meisten Leute, die was gemacht haben, erstmal gar nicht daran interessiert waren Anwendungen zu machen. Und das halt nur eine Finanzierungssache war. Jetzt wo die Technologien weit genug sind, gibt es da einige die da wirklich aktiv und erfolgreich daran arbeiten. Aber das ist mehr so, das ist jetzt böse gesagt, aber wenn einem was besseres einfallen würde was Grundlagenphysik betrifft, dann würden die Allermeisten das lieber machen. Als jetzt hier bessere Laser zu bauen, die dann einen Quantencomputer ermöglichen. Der Boom ist erstaunlich, der dann irgendwann kam. Das interessant. Hängt natürlich auch mit dem zusammen, dass dann Geld da war für Quantencomputer.

Reinhard

56. Das ist es ja auch, dass man hier Wachstum sieht. Auch experimentell. In gewisser Weise scheinen die Theorien, zumindest der mathematische Korpus, gegeben. Die Grundlagen auf jeden Fall. Für die Multi-Photonen Verschränkung braucht man vielleicht auch mathematisch mehr. Experimentell gibt es noch mehr Unentdecktes.

Nikolai

57. Ja, es gibt zumindest viel zu tun. Es gibt halt viel zu tun, weil wenn man an Applikationen denkt auch der Transitor noch nicht erfunden ist [Anspielung, dass man gerne ein Quantenanalogon zum klassichen Transistor finden würde] in keiner von den ganzen Systemen.

Ausblick / mögliche Lösung?

Reinhard

58. Siehst du eigentlich eine Möglichkeit, dass was du vorher gesagt hast, dass da noch etwas unbestimmt ist oder dass man sich Dinge immer noch einmal anschauen muss um sicher zu gehen, dass man sich auch wirklich im Bereich der Quanten befindet, dass man das irgendwie auflösen kann? Oder das sich da irgend etwas ergibt? Oder, dass man eine Art Hoffnung hat, dass irgendwann jemand mit einer Theorie kommt die einem das plausibler macht oder direkt zugänglicher? Oder muss es immer offen, im Wechselspiel, bleiben?

Nikolai

59. Ich denke, dass man sich stark daran anpassen wird. Vieles was einem jetzt komisch vorkommt... Das ist jetzt eine sehr subjektive Meinung. Aber es ist ja irgendwie nur eine Gewohnheit. Wir hatten kürzlich die Diskussion, um ein konkretes Beispiel zu sagen: Messproblem und jetzt sagt man irgendwo muss ja diese Wellenfunktion dann doch kolabieren. Ja, warum eigentlich. Das könnte man sich ja vorstellen: Wir sind halt Teil dieser großen Wellenfunktion. Und wie wir halt gerade dasitzen ist nur so eine Realisierung. Dafür braucht man auch nicht Viele-Welten, weil Superposition. Passt schon. Wo ist eigentlich das Problem? Es ist lustig, weil es sind... Jeder mit dem ich hier rede hat sich ausgiebigst mit Quantenmechanik auseinandergesetzt. Und viele, ich glaube die alten Hasen würden eher eine kritischere Antwort darauf geben können, aber viele sagen: Wo ist eigentlich das Problem?
60. Ich glaube, dass man sich an Sachen gewöhnt. Und manche davon sind falsch und manche sind richtig. Und zu sagen, wo ist da eigentlich das Problem ist schon ein Hinweis darauf. Für mich fühlt sich das nicht falsch an es zu sagen. Ich habe meine Modelle wie ich mir vorstellen kann wie das sein soll. Und das war es. Kann natürlich sein, dass es da ein gutes Argument gibt, das es nicht so sein sollte. Und dann muss man eben wieder einen Paradigmenwechsel irgendwie schaffen. Deswegen glaube ich nicht, dass es eine grundlegende Änderung in dem Verständnis der Quantenmechanik geben wird. Eher... Wir schärfen unsere Bilder und irgendwann fühlt sich das alles recht richtig an.

Reinhard

61. Und sind da die Experimente so eine Art Instrument um den Umgang besser zu schulen? Weil man hier ja die Hände darauf legen kann?

Nikolai

62. Bis zu einem gewissen Grad glaube ich ja. Aber ich weiß nicht ob es daran liegt, dass man Hand anlegen kann. Also ein Experiment ist immer die letzte Entscheidung. Man kann sich halt da nichts vormachen. Und zwar schon im Kleinen. Ich meine das jetzt gar nicht nur wenn man eine große Theorie widerlegt, sondern schon im Kleinen, wenn man ein falsches Bild im Kopf hat. Und es ist ja immer wieder erstaunlich: Da reden wir mit jemanden, mit dem man seit zwei Jahren arbeitet, und plötzlich bei der fundamentalsten Sache merkt man, dass man eigentlich ein komplett unterschiedliches Bild im Kopf hat. Und dann wettet man meistens ein Bier darauf. Dafür, schon im Kleinen die Bilder im Kopf zu prägen.

Reinhard

63. Ja, es gibt halt Sicherheit. Das Experiment ist da und dies ist schon ein sehr starker Hinweis.

Nikolai

64. Ich habe jetzt letztes mal etwas nicht mehr ausgerechnet, weil ich mir gedacht habe, jetzt lohnt es sich nicht mehr, jetzt sehen wir es eh gleich im Experiment. Es wäre falsch gewesen was ich dachte das [bei der Rechnung] rauskommt. Insofern war es die richtige Entscheidung. Von daher glaube ich, dass die Experimente auf jeden Fall helfen. Und dann natürlich, wie gesagt, es gibt ein paar Sachen wo man halt sich vielleicht an Sachen gewöhnen kann, die auch nicht richtig sind. Die muss man dann an einer bestimmten Stelle dann widerlegen. Das finde ich gerade das spannende hier in der Gruppe. In einer besonders ausgeprägten Weise halt geschaut wird wo kann ich jetzt Sachen testen, die wirklich an eine Stelle gehen, wo ich mir wirklich unklar bin was rauskommt. Wo ich nicht sage, da müsste das jetzt rauskommen, aber schauen wir mal nach. Sondern wo es wirklich einfach nicht klar ist jetzt. Das ist spannnend. Es ist natürlich die Frage in welchem Zeitrahmen es passiert, ob ich dann immer noch das selbe mache?

Ende

Reinhard

65. Von meiner Seite aus wäre es das. Wenn du noch etwas sagen willst?

(no speaker)

66. Gespräch über den Inhalt und Motivation meiner Diplomarbeit. Und inwieweit das Philosophie ist. Danksagung und ausklingender small talk.

Witlef_110510

Interview mit Witlef Wieczorek vom 10.05.2011
Transcribed by yotta, version 4 of 110830

Anfang, persönliche Daten, Ausbildung

Reinhard + Witlef

1. **1:** ipod? Wie lange kann man aufnehmen?
   2: ja, externes Mikro. So lang Batterie oder Platz reicht.
2. **1:** Also du hast es (DA-ExposeIV_RST.pdf) gelesen? D.h. du weißt ungefähr um was es geht. Die Fragen werden, dann eh nicht so speziell sein.
   2: Ja, ich hab es gelesen.

Reinhard

3. Am Anfang will ich eigentlich nur sehr generelle Sachen wissen. Z.B. dein Alter?

Witlef

4. 32. Post-Doc. Seit einem Jahr hier. Davor in München gewesen. Da war ich vier Jahre Doktorand. Multiphotonenverschränkung gemacht. Und davor die Diplomarbeit in Berlin. Da habe ich gar nicht Verschränkung gemacht, da waren es eher Quantenpunkte.

Reinhard

5. D.h. aber sonst bist du eigentlich ziemlich in dem Feld jetzt drinnen?

Witlef

6. Ja, schon wirklich jetzt längere Zeit. So fünf, sechs Jahre.

Motivation

Reinhard

7. Gründe warum du das machst? Falls man sowas überhaupt angeben kann.

Witlef

8. Also genau jetzt Optomechanik oder an sich Physik, Quanteninformation,...?

Reinhard

9. Fangen wir mit dem Allgemeinsten an, Physik überhaupt? Warum tut man sich das an?

Witlef

10. Ich bin ein bisschen vorgeprägt durch meinen Vater wahrscheinlich, weil der ist selbst Physiker. Und hat auch als Physiker gearbeitet, auch als Experimentator. Aber einfach nur von zuhause. Da waren irgend wie immer nur irgendwelche Geräte zuhause. Irgendwas zum löten und so ; und hab das halt gemacht.
11. Aber als angefangen hab zu studieren wußte ich gar nicht, dass ich Physik machen wollte. Also ich wollte schon was naturwissenschaftliches machen, weil das auch in der Schule total viel Spaß gemacht hat. In der Schule wars gar nicht mal eigentlich Physik was richtig, richtig viel Spaß gemacht hat. Da war es eher Chemie, aber das lag ein bisschen am Lehrer. Dann wollte so ein Kreuzfach studieren, so wie Biophysik oder physikalische Chemie. Aber das gab es nicht so richtig in Berlin. Ich hab auch nicht weiter gekuckt. Ich weiß auch nicht mehr warum. Jetzt würde ich es machen, aber damals halt nicht.
12. Und dann habe ich halt Physik studiert, weil irgendwie haben mich Experimente dahin gebracht. Weil dort an der TU Berlin gabs sowas wie ein Praktikum, Projektlabor hieß das, wo man halt in der Gruppe gleich zusammen anfängt zu arbeiten und nicht schon die Experimente aufgebaut sind. Man musste sich halt selbst eins überlegen, planen, aufbauen und auswerten. Also das war total genial.
13. Und Quanteninformation? Dahin bin ich eigentlich erst, also bin ich während des Studiums gekommen, weil ich auch of so einer Sommerschule war, die halt über Quanteninformation war. Und da war der Reinhard Werner und der Jens Eisert, und ich glaube die sind ein bisschen bekannt. Beides Theoretiker und gerade der Reinhard Werner konnte mich total dafür begeistern. Denn er hat auch sozusagen gesagt, ja da gibts halt Probleme mit Bell'scher Ungleichung. Und irgendwie seitdem hat mich das eigentlich interessiert.

Reinhard

14. Also das fängt eigentlich schon an mit der Problemstellung sozusagen. Also wenn du da sagst, dass du genau dort..., aufzuzeigen, der erste Kontakt, und das es eben nicht so einfach ist.

Witlef

15. Ja, das war auch so ein bisschen der Vortrag wie er ihn gemacht hat. Er [Reinhard Werner] ist ein Mensch der den Laptop nicht nur als Beamerprojektor nimmt, sondern auch den Sound. Er hat halt so Detektoren gehabt, die dann so geklickt haben [EPR/BELL Experiment]. Und dann hat er auch gesagt das Einstein das Paper [EPR Artikel] rausgebracht hat. Und es passiert ja nicht so oft : A) Dass es nicht so zitiert wird, gleich am Anfang ; also es wurde ja gar nicht zitiert am Anfang. Und, dass erst dreißig Jahr gedauert hat bis dann eine Antwort kam. Das man es experimentell messen kann. Und das war dann irgendwie spannend. Die Geschichte halt war spannend, und dann das Problem halt auch.

Ausbildung

Reinhard

16. Fast ein klassicher Einstieg, ich wüsste jetzt nicht wie dies so...

Witlef

17. Weil im Studium war das gar nicht, also kam das gar nicht vor bei uns.

Reinhard

18. Im Studium selbst nicht?

Witlef

19. Ja das hängt von der Universität ab.

Reinhard

20. Wie war da der Zugang für jetzt Quantenmechanik? Rein nur...

Witlef

21. Kastenpotential, Wasserstoffatom, dann Störungsrechnung, Diracformalismus. Aber nie irgendwie dieses Problem angesprochen. Aber das hängt von der Uni ab.

Reinhard

22. Aber wie haben die das dann experimentell verbunden, oder hat es das dann nicht gegeben?

Witlef

23. Sozusagen in der Uni, in den Vorlesungen? Ne gar nicht. Also halt die haben nie erwähnt das es Bell'sche Ungleichungen gibt. Oder das es Experimente dazu gibt. Oder das es halt ein Problem gibt. Und bei der Interpretation null.
24. Aber ich glaube das hängt halt wirklich davon ab wo die auch selbst gelernt haben. Und ob sie es halt reinbringen wollen. Ich mein man hätte es auch bei statistischer Physik machen können, da wär es auch gegangen. Irgendwo, Dichtematrix, Quantenformalismus hätte man es einfach machen können, haben sie aber nicht.

Reinhard

25. D.h. es ist fast rein beim Formalismus geblieben und...

Witlef

26. Genau, es ist einfach Formalismus ohne Interpretation. Oder ohne Folgen.

Reinhard

27. Ohne groß motiviert [zu werden]. Es geht zwar über Wasserstoff, das Kastenpotential, usw. Aber es nicht so...

Aufgabe im Experiment

Reinhard

28. Ja, jetzt bist du da in der Gruppe und hast das Experiment über.

Witlef

29. Über? Also das ich es nicht mehr mag ?

Reinhard

30. Nein, also dass du der Hauptzuständige bist.

Witlef

31. Ah ! Zur Zeit ja. Also weil der Simon [Gröblacher]. Simon hat ja praktisch an dem Experiment seine Doktorarbeit dran geschrieben. Er hat das aufgebaucht. Und er ist jetzt halt als Post-Doc am CalTech [California Institute of Technology]. Teilweise dort, teilweise hier. Und ich manage praktisch das Experiment ; baue da auf. Und wir sind ja gerade am Umziehen. "Über" ist lustig. Bei uns würde das heißen, dass du es nicht mehr magst. Hast du das Experiment jetzt schon über!?
32. Ne, also von daher bin jetzt praktisch Hauptverantwortlicher. Aber zur Zeit steht ich halt praktisch nur im Labor.

Reinhard

33. Ja ist klar, jetzt mit dem Umzug.

Witlef

34. Ich beschäftige mich im Moment nicht so viel mit Theorie. Das ist ein bisschen Schade, weil ich finde gerade als Post-Doc wäre das gerade eine Aufgabe und sich auch überlegen was man für zukünftige Experimente machen kann. Und weil es halt wichtig ist, in dem Feld ansich, welche Fragestellungen man beantworten will. Aber dafür habe ich gar keine Zeit.

Reinhard

35. Also das wäre der zukünftige Ablauf ?

Witlef

36. Ja hoffe ich mal !

Reinhard

37. Also so stellt du es dir vor. Also so hättest du es gerne. Wenn der Umzug abgeschlossen ist, dass du dann auch arbeitstechnisch zukünftige Sachen, experimentelle... aber auf der Basis von dem vorhandenen.

Witlef

38. Unsere Basis zur Zeit ist, rein experimentell, unser Delution Fridge. Wir haben halt die Möglichkeit auf tiefe Temperaturen zu gehen und damit mechanische Systeme entweder direkt in den Grundzustand zu kühlen. Also wenn sie halt eine hohe Frequenz gleich von sich aus haben. Oder halt zusätzlich, haben wir eine niedrige Badtemperatur, und dann zusätzlich das Seitenband kühlen um in den Grundzustand zu gehen. D.h. das ist unsere Möglichkeit die wir haben und jetzt, sagen wir so, warten wir einfach auf die richtigen Proben, Samples, die entweder das eine machen oder das andere, oder beides. Und dann gehts von den Experimenten ausgehend weiter.

Reinhard

39. Also, dass man das so als Basis oder Ausgangsexperiment hat und dann schließen sich...

Witlef

40. Genau, und dann schließen sich die Sachen die wir eigentlich machen wollen an.

Reinhard

41. Es ist ja so und so nie ein Experiment, dass du aufbaust und dann ein Ergbnis hast und dann wieder abreisst.

Witlef

42. Passiert auch, aber bei uns halt nicht.

Einteilung der Experimente

Reinhard

43. Eine nächste Frage wäre dann wie die Gruppe aufgebaut ist? Wenn du jetzt, wie immer man das nennt, Hauptverantwortlicher bist bei dem Experiment ; denn es gibt ja mehrere parallel. Es sind ja noch die gepulsten Sachen...

Witlef

44. Fangen von den Nanoteilchen, und noch Strahlungsdruck ganz einfach gibts noch, und der Jonas [Schmöle] hatte, aber der macht jetzt sozusagen bei uns mit. Er hatte davor halt magnetisch levitierte Sachen ; Graphit und sowas.

Reinhard

45. Das sind also die Teile die parallel laufen?

Witlef

46. Genau, also praktisch das große Thema in der Arbeitgruppe, an sich der Aufhänger, wofür sich halt Markus [Aspelmeyer] interessiert und damit wir auch, sind einfach makroskopische Systeme. Systeme also die Masse haben in Quantenzustände zu bringen. Und da gibts jetzt verschiedene Herangehensweisen. Entweder so wie wir. Wir kühlen halt irgendwelche Oszillatoren. Hat den Nachteil, die haben halt immer irgendwie eine Verbindung zur Außenwelt.

Reinhard

47. Ja, du musst schauen, dass du die Umwelteinflüsse sozusagen wegkriegst. Temperatur in dem Sinn ?

Witlef

48. Temperatur, genau. Oder Verbindungen. Das Andere was halt Nikolai [Kiesel] macht mit diesen Nanoteilchen, die haben halt gar keine Verbindung mehr zur Umwelt. Die sind halt nur limitiert durch Druck von außen, oder Absorbtion. Und der Jonas [Schmöle] hat halt was anderes versucht, magnetisch zu levitieren. Das sind einfach verschiedene Herangehensweisen um irgendwie so Quantenzustände bei diesen Systemen hinzubekommen.
49. Und sagen wir mal die Struktur von unserer Gruppe ist eigentlich, relative lose. In dem Sinne, dass es jetzt nicht ein gigantisches Projekt gibt, woran alle daran arbeiten. Sondern es gibt halt diese verschiedenen...

Reinhard

50. Das Prinzip, oder das Konzept dahinter ist eben diese opto-mechanische... Verkopplung.

Witlef

51. Genau. Aber um ehrlich zu sein ich glaube wenn man jetzt nur an makroskopischen Quantenzuständen interessiert ist oder irgendwie massive Objekte dahin zu bringen, dann ist es eigentlich egal was man nehmen würde. Aber sozusagen die Optomechanik ist halt gerade so weit, dass sie kurz davor ist das zu erreichen.

Reinhard

52. Das ist ja das Schöne, dass die Realisierung von Quantenzuständen ziemlich offen ist. Also es ist ja nicht eine Bindung an irgendein System, sondern es sind technische Fragen. Wenn ich mit der Minitutrisierung im Mechanischen, weil ich das halbwegs im Griff habe, die meachanischen Komponenten hinzukriegen. Wenn das halt so funktioniert kann man das damit Anstreben.
53. In dem Sinn gibt es ja keine Abhängigkeit von der Realisierung. Also wie ich diese Sachen versuche zu realiseren.

Gruppe

Witlef

54. Wir sind halt relativ Post-Doc lastig. Unsere Arbeitsgruppe ist jetzt nicht so typisch. Ich würde schon eher sagen, dass es meistens so ist : Es gibt ein paar Post-Docs, die jeweils für so ein Experiment verantwortlich sind. Und dann gibts zwei bis drei Doktoranden pro Experiment. Und bei uns ist es halt nicht so. Wir haben mehr Post-Docs, oder genausoviel Post-Docs wie Doktoranden oder knapp weniger Doktoranden und wenig Masterstudenten. Also schon nicht so typisch. Aber das kommt vielleicht auch einfach daher das Markus [Aspelmeyer] eben noch nicht solange hier ist. Und das es sich hier erst rumsprechen muss, dass es die Experimente gibt und den Nachwuchs anzulernen.

Reinhard

55. Ja das dauert bis du die Leute reinkriegst. Weil beginnen wirst du so und so mit erfahreneren Leuten. Also fängst du mit Post-Docs an, damit das einmal läuft. Überhaupt wenn es neu ist, dann wirst du dir nicht noch am Anfang Einarbeitungszeit [aufhalsen].

Faszination an der Quantemmechanik

Reinhard

56. Eine Frage im theoretischen Bereich. Oder wir haben darüber eh schon mal gesprochen.Was würdest du als faszinierenstes Feature sehen, von der Quantenmechanik. Eigentlich bis du ja eh in dem Bereich der dich interessiert.

Witlef

57. Zur Zeit ja. Wechselt. Also ich finde sehr spannend wirklich was wir machen, also das Ziel von uns. Das man wirklich versucht mit Systemen, die halt viel Masse haben, also im Vergleich halt zu Atomen, Ionen, oder Atomwolken, Quantenzustände zu erzeugen. Und dann halt auch am Idealsten natürlich zwei massive Sachen miteinander zu verschränken. Finde ich schon total spannend. Und immer mehr kommt dazu, aber da kenne ich mich leider noch zuwenig aus, inwieweit Gravitation eine Rolle spielt. Also die verschiedenen Dekohärenzmodelle. Kenne ich mich leider zuwenig aus, aber es wird ein Seminar geben. Und da bin ich ziemlich froh drüber, dass wir das machen. Denn ist nocheinmal ein ganz anderer Aspekt mit dem ich halt nie in Berührung gekommen bin.
58. Verschränkung an sich ist auch spannend. Also, man kann sich halt immer wieder Fragen, wie interpretiert man dies nun ; mit unserer klassichen Welt.Ich finde nur ein bisschen wird es zu viel betont. Ich fand es ein bisschen so wie du es geschrieben hast in deiner Einleitung, dass man vielleicht ein bisschen überstrapaziert um halt irgendwie das Besondere immer wieder herauszukehren

Reinhard

59. Das ist eben die Frage ob man das jetzt nur...

Witlef

60. Ist Ansichtssache, ist ein persönlicher Geschmack. Jeder würde da sicher etwas anderes sagen, aber nichtsdestotrotz ist es halt wirklich eine Problem. Weil man halt bestimmte Annahmen macht wie Lokalität, Realismus und das Quantenmechanik eine komplette Theorie ist, dann sieht man zur Zeit ist es einfach nicht so und dann hat man wirklich ein Problem. Was ich halt ein bisschen Schade finde, dass es verschiedene Meinungen gibt, das ist ja ok, gibts ja immer, aber, dass dann mit den Leuten nicht mehr diskutieren kann. Es gibt halt so Schulen, die sind halt so, die anderen so und das wars. Eine Diskussion kann man dann vergessen. Das ist halt Schade, dann wird halt etwas aufgedrückt, ist man passiver Zuhörer und es ist die Frage ob man da was lernt.

Reinhard

61. Ja, die Frage ist von wo sozusagen die Interpretation herkommen. Für mich scheint es von der Theorie her zu kommen ; die stehen am Scheideweg. Die Frage ist wie dies experimentell relevant ist. Wenn man es ganz runterbricht auf ganz einfache Arbeiten im Labor ist ja das alles irrelevant.

Witlef

62. Völlig klar. Da ist es erstmal Wurst. Es ist halt Inspiration.

Reinhard

63. Ja, Ja. Es geht dann eher in Richtung der Sachen, die das Experiment motivieren. Warum will ich eigentlich eine Verschränkung mit massiveren Teilen?

Witlef

64. Ich glaube das ist eben, finde ich, zum erstenmal wirklich für mich auch eine richtige Motivation an Verschränkung weiterzuarbeiten, weil man sich halt wirklich eine konkrete Fragestellung stellen kann, in dem Sinne, welche Rolle spielt Gravitation. Also gehts bei massiven Objekten oder kann man wirklich so Dekohärenzmodelle sehen. Und das finde ich wieder gut, weil es hat für mich was konkreteres als zu sagen....Ich meine, dass weiß ich jetzt schon, dass ist halt wie mit Lokalität - Realismus, das geht halt nich zusammen. Aber da gibts halt zur Zeit keine Antwort drauf. Da kann man die Bell Ungleichung zehntausendmal verletzen. Die wurde einfach verletzt, das reicht.

Reinhard

65. Es scheint so, musst du sagen ob du auch so denkst, dass du von der Seite [hier ist Theorie gemeint] kaum eine Antwort oder Neues erwarten kannst. Die Bell Ungleichungen sind theoretisch aufgestellt, die Experimente dazu gibts und man wird noch sehr viele machen können, aber im Endeffekt...

Witlef

66. Man braucht halt irgendwie eine neue Theorie, die einem das halt erklärt oder man testet mal in eine andere Richtung.

Reinhard

67. Aber selbst so etwas wie eine neue Theorie wurde auch wieder etwas experimetelles vielleicht nachsichziehen. So wäre es so wie du schon gesagt hast nebenbei wieder eine neue Meinung oder Interpretation.

Witlef

68. Ich meine es gibt halt viele Verfeinerungen zur Bell'schen Ungleichung. Eben das Leggett-Modell [Nobelpreisträger Sir Anthony James Leggett], dass er halt annimmt, einen Teil Nicht-Lokalität reinbringt, dass das wieder ausgeschlossen werden kann. Das ist halt für mich nur ein kleiner neuer Aspekt. Das löst für mich auch nicht das Problem. Oder das man halt fragt wieviel Lokalität muss so eine Theorie haben und das kann man halt fast auf Null reduzieren. Ja, aber man fragt sich wie schnell diese Information hin und her fliegt, mit wieviel Mal Überlichtgeschwindigkeit. Aber mir persönlich gibt dies keine Antwort. Ist aber halt auch Geschmackssache.

Reinhard

69. Ja, aber immerhin gibt es Gründe warum man experimentell veranlagt ist oder warum man in experimentelle Sachen geht. Da sieht man halt einen Mehrwert im Experiment. Es gibt ja einen Grund warum man als Experimentator nicht Theoretiker geworden ist, weil...

Witlef

70. Aber ich habe mich das noch nie gefragt um ehrlich zu sein. Also es macht schon Spass im Labor zu sein und rumzuschrauben. Und halt sozusagen die theoretischen Sachen wirklich umzusetzen, und da kommen dann nochmal andere Fragen auf. Wenn man sowas wie eine Fromel hingeschrieben hat, eine Gleichung oder hier wie eine Pulssequenz, wie implementiere ich das? Ja, ich kann mir aber auch vorstellen schon theoretisch zu Arbeiten. Ich weiß nicht inwieweit ich das Labor vermissen würde. Ich würde es schon vermissen, aber ob es soweit geht, dass ich nicht theoretisch arbeiten könnte? Ich habe halt einfach nicht die Ausbildung.

Reinhard

71. Ich tue mich immer schwer mit dieser Trennung, weil für die ganzen Experimente brauchts du so und so einen ziemlichen Teil von Theorie. Die ganzen kontinuierlichen Varibalen Verschränkung [theoretische Voraussetzung für das in der Diplomarbeit behandelte opto-mech. Experiment] und so weiter. Es ist ja nicht so leicht, denn es ist ein ziemlicher Block der voraus[gesetzt ist].

Witlef

72. Oder den Hamiltonian um den Oszillator zu beschreiben, Dekohärenzmodelle und so weiter. Das ist alles Theorie.

Reinhard

73. Es ist ja nicht so, dass es voraussetzunglos wäre. Also, dass du nur ins Labor gehst und da herumdrehst. Aber das ist für mich das Interessante, inwieweit die Fragen überhaupt dann noch relevant sind.

Witlef

74. Also, wenn ich jetzt konkret unten stehe und irgendetwas optimiere, dann ist das natürlich überhaupt nicht relevant. Da ist es mir völlig egal. Aber es ist halt wirklich die Motivation. Wenn ich mich da um jedes Prozent AOM [Akustooptischer Modulator] Effizienz da hinfriemel, dann sage ich mir ok, dass muss ich jetzt machen. Das kostet jetzt vielleicht einen Tag, damit dann unser Experiment dann vielleicht in einem Monat richtig gut funktioniert, weil ich mich dann einfach darauf verlassen kann. Und wenn das Experiment funktioniert kann ich das und das machen und vielleicht die Frage beantworten. Es ist einfach wirklich Motivation und was einen eigentlich interessiert. Also mich interessiert nicht, dass die AOM Effizienz 46 oder 47 Prozent erreicht. Es ist halt besser wenn es 47 Prozent sind.

Reinhard

75. Das sind die Erfordernisse.

Witlef

76. Also konkret, wenn ich da unten über Verschränkung nachdenken würde oder über Dekohärenzmodelle oder mir eine Lösung überlegen würde, könnte ich nicht justieren. Also ich nicht. Ich glaube es wäre auch etwas traurig, oder? Wenn man sich da unten [das Labor ist im Keller] einfach hinstellt, rumjustiert, rummacht und jetzt nicht weiß wofür oder warum. Man hätte jetzt nicht ein Ziel. Da kannst du jeden da unten hinstellen. Es wäre völlig Wurst. Es ist ja nur einfach Handwerkszeug was man halt lernen muss.

Reinhard

77. Also für mich das Spannende am Experimentieren ist, dass du die Pallette von theoretischen Notwendigkeiten und...

Witlef

78. Das gibts bei Theoretikern auch. Markus [Aspelmeyer] meint es gibt zwei Sorten von Theoretikern. Die Einen die einen Hamiltonian [Hamiltonoperator : Zeit- und Energieentwicklung eines Systems] hinschreiben, nicht darüber nachdenken. Und die Anderen die halt darüber nachdenken. Wenn mal halt nicht darüber nachdenkt, ist es das glaube ich nicht. Du schreibst es hin und überlegst dir was bedeutet das jetzt. Also eben so wie Verschränkung, wenn ich hier einen nicht seperablen Zustand hinschreibe [allg. Definition von Verschränkung], aber was heißt das jetzt, auf was referenziert es. Und das macht halt auch einen guten Theoretiker aus und wahrscheinlich ist es bei einem guten Experimentator genau das Gleiche. Wenn er da drin steht und herumjustiert, überlegt er sich wie kann ich das verbessern oder wenn das ist was kann ich damit machen oder ergibt das was neues.

Reinhard

79. Im Endeffekt sehe ich das als Voraussetzung für die Physik, weil fast bei jedem mathematischen Anschreiben oder so was, du irgendwann zu einem Punkt kommen musst, wo du dann nach Bedeutung, oder was es nun wirklich heißen soll fragen musst. Das muss man nicht herunterbrechen bis zu einem Experiment. Aber die Frage ist was der Hamiltonian nun jetzt wirklich meinen soll.

Entwicklung

Reinhard

80. Die Frage ist auch wie die Geschichte weitergeht. Also es scheint klar zu sein wie die Entwicklung in [diesem Bereich, opt-mech. Systeme] weitergeht?

Witlef

81. Also ich kann jetzt erstmal konkret bei uns bleiben. Ich hoffe das wir es erstmal schaffen die Mechanik mit Licht zu verschränken. Also ich denke das geht definitiv. Es wird halt wahrscheinlich knapp sein, einfach aus technischen Gründen. Und dann hoffe ich, dass bei Nikolai's [Kiesel] Experiment mit den Nano-Sphähren, dass die halt weiterkommen als wir. Dass die halt schaffen so eine Nanosphäre in eine Superposition von zwei Orten zu bringen und dann wirklich so eine Art Doppelspaltexperiment zu machen. Und dann wird es, glaube ich, einfach schwierig in diese Regimes zu kommen, wo man halt genau solche Dekohärenzmodelle testen kann. Inwieweit eben Gravitation auf Superpositionen oder so eine Kohärenz zwischen den verschiedenen Zuständen einwirkt. Es ist total schwer zu sagen. Zur Zeit kann man es vergessen. Das hat der Rainer [Kaltenbaek] ausgerechnet. D.h. er hat sich ein Experiment überlegt was man im Weltraum machen kann, weil da halt das Vakuum besser ist, weil es besser isoliert ist. Und da kommen Zahlen raus die gehen heutzutage noch nicht. Und das ist halt schade, aber es heißt ja nicht das es überhaupt nicht geht.

Reinhard

82. Aber es gibt zumindest die Richtung vor.

Witlef

83. Wenn man sich eben mit diesen Sachen beschäftigt, zum Beispiel mit so einer experimentellen Fragestellung wie ich das umsetzen kann, und dann gehts halt einmal nicht. Dann kriegt man aber eine andere Idee was man vielleicht anders testen kann oder ob es anderes Experiment gibt in die Richtung. Und ich denke schon, dass man irgendwie in so einen Bereich kommt, vielleicht in den nächsten zehn Jahren, wo man es halt wirklich schafft solche Modelle zu testen. Also das wäre glaube ich wirklich ein Ziel. Ich meine das trägt jetzt auch nicht zum... Ich meine Verschränkung wird man nie verstehen können, würde ich mal sagen. Wie du schreibst, wenn man damit aufwächst, mit Lokalität und Realismus. Ein Baby so erzieht, dass halt alles immer da ist auch wenn ich nicht hingucke und ja wenn ich halt hier was tun kann, dass dort nicht sofort beeinflusst wird, natürlich dann

kann man das nicht verstehen ; nie. Es ist halt auch so, wenn man irgendwann durch ein STM [Rastertunnelmikroskop, scanning tunneling microscope] durchschaut oder eine Oberfläche atomauflöst, das kann man auch nicht vorstellen. Das sieht man halt und glaubt, dass das so aussieht.

Reinhard

84. Ja, aber das Problem ist. Man sieht gerade diese Kugerln oder Halbkugeln und man kommt nie umhin die als eben solche Kugerln [solide Sphären] zu sehen. Schaut man sich an wie diese STM und die anderen Sachen funktionieren, so sind es in dem Sinn nur Energieaufzeichnungen [Messungen von Energie eines best. Schwellenwertes].

Witlef

85. Aber, da würde ich antworten. Ok, das schafft man sicherlich auch, in fünf bis zehn Jahren, dass man eine Verschränkungquelle baut, die aus mehreren Photonen besteht, dass man halt wirklich mit seinen eigenen Augen die Messung macht. Das man sich, was weiß ich, Polarisationsfilter davor macht. Hier ein Klick, da ein Klick, klick klick klick. Das man es halt mit sich selbst macht so ein Experiment. Und dann eine Strichliste und sieht [die Verschränkung].

Reinhard

86. Diese Verschränkungsexperimente die es gibt, die es auch in der Ausbildung usw. gibt, die haben schon eine erschreckende Einfachheit und, für mich zumindest, [Überzeugungskraft]. Es ist halt immer nur dieser Übergang schwer zu begründen, bzw. schwer zu behaupten, weil er gegen etwas spricht was man immer annimmt. [Nämlich], dass es mit lokalrealistischen Sachen eben nicht geht. Also, dass die Korrelation und Verschänkung da ist, das kann man eigentlich ziemlich überzeugend darstellen. Aber, dass es damit nicht erklärbar ist. Und da ist für mich immer auch der Sprung wo man sich halt immer selbst dazu bringen muss. Das man sagt ok, ich bin jetzt üerzeugt worden von Bell usw., dass es lokalrealistisch nicht läuft und als rationalles Konstrukt, oder wie immer man sagen will, sehe davon ab für alle meine weiteren Dinge die ich in dem Bereich mache, d.h. für die ganzen Experimente usw. Es ist aber die Frage wie weit das "natürlich" sein kann, oder selbstverständlich.

Witlef

87. Aber, das weißt du wahrscheinlich viel besser was man natürlich und selbstverständlich heißt. Ist das nicht eine Frage der Erziehung, also eine Frage der Ausbildung. Oder eine Frage, dass es gar nicht geht, weil man aufwächst mit greifen, anfassen und so?

Reinhard

88. Aber du bist ja jetzt länger in dem Feld wie ich auf jeden Fall. Es gibt schon eine gewisse Selbstverständlichkeit im Umgang mit den Dingen.

Witlef

89. Ja klar mit Verschränkung, Definitionen und so. Eine Erklärung habe ich trotzdem nicht. Ich kanns auch nur so erklären, dass lokaler Realismus einfach nicht damit einhergeht.

Reinhard

90. Diese Problematik schiebt sich dann etwas raus, weil im täglichen Geschäft... Oder würdest du das nicht...?

Witlef

91. Also im täglichen Geschäft brauche ich es halt nicht, aber die Problematik ist ja trotzdem da. Die geht nicht verloren. Die ist da. D.h. jetzt nicht das ich aufhören würde zu arbeiten, weil ich das erstmal lösen will. Sondern sie ist einfach da und ungelöst. Wie gesagt, es geht nur durch eine neue Theorie, das irgendwie aufzulösen.[Pause] Wenn es auflösbar ist. Wenn man es nicht einfach akzeptieren muss.

Reinhard

92. Ja das ist die Frage. Es gibt genug Leute, auch Physiker usw., die [Letzteres meinen]. Die stellen auch die Frage wie relevant dann auch solche Diskussionen sind. Das will ich sowieso nur anstossen.

Witlef

93. Es ist ein bisschen schwierig, weil es halt ein Thema ist, dass seit jünfzig Jahren, seit Bell, in bestimmten Kreisen diskutiert wird. Seit zwanzig Jahren ist es wahrscheinlich so, da ist am Besten den Anton [Zeilinger] mal zu fragen oder den Markus [Aspelmeyer] der weiß das sicherlich auch, dass es auch wenn man sich darüber unterhält nicht der Tod seiner Karriere ist. Weil es nicht etwas ist, was esoterisch ist. Es wird ja als Problem erkannt und auch als wichtig. Und seit zehn Jahren, vielleicht ein bisschen mehr, ist durch die Quanteninformation ein völlig anderer Aspekt nochmal dazugekommen. Das nicht nur esoterisch ist oder halt nur ein Problem der Physik, sondern, dass man damit auch etwas machen kann. Und wahrscheinlich hat es dem, seit man mit der Verschränkung was machen kann, auch wahnsinnig geholfen. Dass man auch nicht nur jetzt damit was machen kann, sondern auch mal wieder fragen verstehe ich vielleicht eine Erklärung oder finde einen anderen Zugang.

Reinhard

94. Die Möglichkeiten, experimentell, haben sich sehr geweitet. Da ist es klar das auch die Frage wieder akut werden kann.

Witlef

95. Es ist halt einfach ein ungelöstes Problem, für mich. Man weiß sozusagen, dass lokaler Realismus und vollständige Quantenmechanik geht nicht mit Verschränkung einher. Und es gibt keine Lösungsmöglichkeiten. Was halt spannend wäre irgendwie mal,... ok letztendlich sind es halt solche Ungleichungen. Dass man sich überlegt, das und das aufgebe, da gibt es ganze Bücher dazu, gibt es eine experimentelle Konsequenz daraus die ich halt überprüfen kann. Aber wahrscheinlich sind es die ganzen Ungleichungen die da rumgeistern. Es wär mal spanned irgendwie was anderes zu haben als eine Ungleichung immer zu messen. Dass man mal eine physikalische Konsequenz hat. Wenn ich halt Lokalität,... Das Problem ist ja auch, es wäre ja nicht so eine Lokalität die man aufgibt, dass man auf einmal mit Überlichtgeschwindigkeit Signale übertragen kann.

Reinhard

96. Dies Würde dann wieder eine Lokalität, oder Begriff bedeuten, der...

Witlef

97. Kausalität in dem Sinne muss man nicht aufgeben. Sagen wir es mal, dass man irgendwie noch was anderes... einen physikalischen Effekt den man testen kann. Aber da kenne ich mich auch zu schlecht aus.
98. Was ich vorher noch sagen wollte, weil du gemeint hast von wegen spanned. Was auch noch total spannend finde, was auch bei Verschränkung implizit drin ist, aber jetzt nicht unbedingt so hervortritt. Also sagen wir es wird nicht thematisiert, dass einfach wenn ein Festkörper, zum Beispiel in jüngster Zeit irgendwie alles irgendwie verschränkt. Eben gerade die Experimente mit optischen Gittern, wo die Atome so einzeln plaziert sind. Die haben es geschafft einzelene Atome zu addressieren und dass man damit halt Festkörpersysteme möglichst simulieren kann. Und vielleicht es auch schafft die Supraleitung, Hochtemperatur-Supraleitung, zu erklären. Oder einfach irgendwelche Phänomene, die man im Festkörper dreckig hinkriegt, halt wahnsinning sauber hinzukriegen. Das find ich total spannend. Da ist Verschränkung implizit einfach da. Es wird eben in dem Sinne nicht philosophisch thematisiert, sondern es wird einfach ausgenutzt, untersucht.

Reinhard

99. Aber das wäre dann sozusagen der Übergang dann von der quantenmechanischen Seite zu einer klassichen Sache, oder zu größeren Systemen. Wenn du sagst Supraleitung oder größere Festkörper,...

Witlef

100. Ja klar. Letztendlich ist Supraleitung auch ein makroskopischer Quanteneffekt. Wo du halt auch eine Wellenfunktion hinschreibst die verschränkt ist. Also will einfach nur sagen, Vielteilcheneffekte sind auch wahnsinnig spannend.

Reinhard

101. Weil du dann diesen Übergang besser, der scheint irgendwie theoretisch nur postuliert zu sein, [verstehen wirst können]. Das dies vorhanden ist kann man irgenwie machen...

(no speaker)

102. [kurze Unterbrechung durch Kollegen]

Offene Fragen?

Reinhard

103. Im Endeffekt wäre es das [gewesen]. Die Frage ist ob du noch Fragen hättest, wenn du schon vorbereitet bist [d.h. mein Expose gelesen hast]? [Danksagung und kurzes persönliches Gespräch.]

Jonas_110622

Interview mit Jonas Hörsch vom 22.06.2011
Transcribed by yotta, version 2 of 110630

Anfang, persönliche Daten, Ausbildung

(no speaker)
1. [intro small talk]

Reinhard
2. Am Anfang will ich eigentlich nur allgmeines wissen. Wie alt bist du?

Jonas
3. Ich bin 25. Ja, genau. Musste es aber nachrechnen.

Reinhard
4. Das müssen ziemlich viele Leute.

Jonas
5. Ich merke mir halt 85. Genau.

Reinhard
6. Kannst du mir sagen, ungefähr deine Ausbildung, jetzt studentisch?

Jonas
7. Genau, ich bin noch Student. Ich habe jetzt... An sich habe ich nur Physik eben in Deutschland studiert. Bin jetzt irgendwie bei der Diplomarbeitsphase.

Reinhard
8. Und wo?

Jonas
9. In Potsdam. Und schreib jetzt eigentlich in Potsdam meine Diplomarbeit und das ist aber so eine Kollaboration zwischen Jens Eisert [http://www.jense.qipc.org/MainPage.html] und hier Markus Aspelmeyer. Und dann soll ich zwischen den Beiden ein bisschen springen. Jetzt bin ich halt die erste Hälfte, habe ich jetzt gesagt, bin ich größtenteils hier. Weil wir hier noch das Teil bauen müssen, was wir dann irgewann früher oder später auch noch machen.

Reinhard
10. Ah ok. Und du hast dann eigentlich nur normale Standard-Physikausbildung gemacht?

Jonas
11. Ja, genau. Hab nur ein Diplom Physik gemacht.

Reinhard
12. Und deine Diplomarbeit ist über...?

Diplomarbeit

Jonas
13. Meine Diplomarbeit ist... Das blöde ist, wir haben noch keinen Namen, deswegen kann ich das nicht irgendwie kurz benennen. Aber an sich sind es irgendwie so... Ich weiß nicht ob dir eine Cavity irgendwas sagt.

Reinhard
14. Ja, ja.

Jonas
15. Zwei Micro-Cavities die mit einer mechanischen Brücke miteinander gekoppelt sind. Man kann beide Cavities mit Laser ansprechen, sodass dann wenn man praktisch die Eine dann anregt, dann wird sich über diese mechanische Kopplung, wird sich das eben auch auf den Anderen ausüben. Und wir wollen jetzt schauen was wir damit machen können. Bzw. was man da machen kann wenn man dreißig solcher Teile hintereinander hat, ob man da irgenwelche Transporteffekte sieht. Ich mache den theoretischen Part dazu, und dann soll dass wohl Garrett [Cole] so bauen und überprüfen, was dabei rauskommt.

Reinhard
16. Also dein Teil ist eher der theoretische...

Jonas
17. Genau. Ich solls mal durchrechnen.

Reinhard
18. D.h. auch simulieren das Teil? Oder ist das nur...?

Jonas
19. Also wir haben ein bisschen was... Wir haben die mechanischen Eigenschaften von so einem Dingen.. haben wir simuliert. Aber mit einer Standardsoftware. Das sind diese Finite-Element-Solver, heißen die. Genau, da haben wir das... Da haben wir die Struktur eben erzeugt und haben dann geschaut, was rechnet er uns denn für Eigenwerte aus. Das war was wir gemacht haben, aber sonst simulieren... Keine Ahnung, ich werde ab und an eine Differentialgleichung irgendwie numerisch halbwegs lösen müssen. Da ist noch nicht viel passiert.

Reinhard
20. Ok. Wo bist du da ungefähr jetzt?

Jonas
21. Ich hab gerade erst angefangen. Vor eineinhalb Monaten oder zwei Monaten. Ich bin noch in sowas wie der Einlesephase und hab schon das eine oder andere schon mal vorgemacht. Aber eigentlich sammle ich immer noch. Eigentlich hab ich bisher bloß studiert.

Reinhard
22. Aufwendig genug. D.h. ungefährer Zeitplan, wie das laufen soll?

Jonas
23. Nächsten April, nächsten Mai würde ich gerne abgeben.

Reinhard
24. D.h. so ein Jahr geplant.

Jonas
25. Genau, ein Jahr insgesamt ist geplant.

Reinhard
26. Und halt aufgeteilt, wie du gesagt hast, ein Teil hier, ein Teil in...?

Jonas
27. Ja. Aber es ist überhaupt nicht festgeschrieben was wo ist. Irgendwie war mein Professor in Potsdam dann irgendwann, als mit seiner [????], bin jetzt nach Wien umgezogen wie geplant war, meinte er: Aha, ich hab das nicht so geplant. Wir haben das eigentlich nicht so genau festgelegt, aber ja ist gut. Na ja, in meinem eigenen ermessen so wie es aussieht, wo ich gerade lieber bin oder so.

Reinhard
28. Oder was halt für die Arbeit irgendwie...?

Jonas
29. Genau. Gerade bin ich fast der Meinung, dass es fast sinnvoller wäre in Potsdam. Weil da könnte ich jetzt mehr theoretische Fragen stellen. Jetzt ist irgendwie der experimentelle Teil so halbwegs angestossen, oder sowas. Das da ein bisschen was passiert, wo ich jetzt sowieso gerade keinen Einfluß nehmen kann für die nächsten eineinhalb, zwei Monate. Und eigentlich wärs dann sinnvoller in Potsdam zu sein,

wo ich mehr Fragen stellen kann, zumindest zu irgendwas. Ich hab keinen Plan.

Reinhard

30. Also das heißt du bist hierher gekommen um dir einmal das Experimentelle anzuschauen? Was hier geht.

Jonas

31. Genau, um mir das anzuschauen. Und für das mechanische Zeugs, wie man das simuliert. Da kannten sich die hier viel besser aus, weil die das halt für ihre Experimente vorher kurz machen. Und dann schauen was passiert. Deswegen habe ich das eben hier gemacht. Und eigentlich ist das jetzt erstmal so, dass er [Garrett Cole] so die ersten Teile baut mit denen er was probieren will. Und dann krieg ich halt irgendwann die Daten.

Reinhard

32. Also der Garrett [Cole] baut die...?

Jonas

33. Garrett [Cole] macht das dann. Ich hab damit sofern was zutun, dass ich die Geometrie irgendwie gesagt habe das wäre interessant. Aber...

Reinhard

34. Das ist Auftragsarbeit an den Garrett das zu machen.

Jonas

35. In die Richtung. Es immer noch nicht ganz losgestossen. Aber es sollte jetzt irgendwann mal langsam klappen.

Reinhard

36. Verstehe. Und wie bist du irgendwie speziell auf das Thema gekommen. Oder, dass du überhaupt in den Bereich gehst?

Jonas

37. Ähm... Also ich bin halt über... An sich haben wir in Potsdam gar nicht soviel Auswahl gehabt. Und letztendlich wars dann der Professor. Es war dann halt Jens Eisert, der seine Quanteninformation gemacht hat. Und er hat bei uns eben auch ein... Drei Vorlesungen habe ich inzwischen bei ihm gehört. Und die Vorlesungen waren eigentlich echt ganz toll, und da habe ich mich eben halt so Stück für Stück... Zunächst habe ich Gundvorlesung gehabt und dann habe ich mich in seine Spezialvorlesungen eingearbeitet gehabt. Und dann bin ich so auf die Quanteninformation gekommen. Quanteninformation ist dann vielleicht ein bisschen zu wenig anwendungsbezogen, dachte ich dann irgendwann. Und dann bin so auf die Opto-Mechanik gekommen, wo dann auch viel Quanteninformation an sich drinsteckt, aber wo man das Ding halt baut. Oder irgendjemand baut.

Reinhard

38. Und wie war da ungefähr der... Wann tritt das ein? Ich kenne nur hier vom Studium, dass man da so irgendwann in der Mitte dann so Quantenmechaniktheorie macht. Vorher nur so en bisserl Ausblicks...?

Jonas

39. Wir haben im vierten Semester halt Quantenmechanik gehört, glaube ich... Ja, viertes Semester. Theoretische. Das fand ich damals ganz cool eigentlich. Prof war eigentlich nicht so gut. Aber doch war einfach interessant, weil da irgendwie ganz, ganz skurill, ganz anders war. Ja und dann dachte ich, irgendwas in die Richtung wäre schon interessant. Oder mal schauen. Dann einfach halt... So im Sechsten habe ich dann eben so noch nebenher angefangen Quanteninformation zu hören. Siebtes, Achtes dann mehr gehört und eigentlich andere Sachen fertig gemacht. Und bei dem irgendwie auch ein Projekt gemacht, beim Eisert. Genau, und so irgenwie. Auch Mitte würde ich sagen auf die Quantenmechanik gestossen und dann halt irgendwie gekuckt was es von dem Quantenteil noch gibt.

Reinhard

40. Und kannst du irgendwie festmachen, was dich interessiert hat? Also gerade das zu machen? Oder nur so reingerutscht?

Jonas

41. Es ist ein bisschen reingerutscht würde ich sagen, aber es war halt auch einfach irgendwie was ganz anderes. Also ich hab kurz Allgemeine Relativitätstheorie angehört, das ist wirklich schick konzeptionell und so. Aber irgenwie kam's mir so vor wie wenn man effektiv nichts machen kann. Weil es irgendwie zu kompliziert wird, sehr schnell. Und irgendwie kann man in der Quantenmechanik doch noch... Zumindest alles irgendwie auf harmonische Oszillatoren zurückführen und die dann machen. Ja, plus minus. Und dann war's eben interessant, weil's anders war. Und aber halt auch meistens noch irgendwie rechenbar, weil's abstrahiert genug ist.

Reinhard

42. Also es lässt sich sehr, sehr minimalistisch machen. Mit den Oszillatoren, mit dem harmonischen und so weiter. Das ist schon sehr...

Jonas

43. Genau man hat halt nur so ein paar Prinzipien und wenn man die dann irgendwie verinnerlicht, kann man eigentlich viel machen. Das war interessant.

Reinhard

44. Verstehe. Und, weil du vorher gesagt hast, weil es auch die Möglichkeit gibt der Anwendung oder zumindest damit ein bisserl was zu tun. Wie siehst da sozusagen das Verhältnis? Weil du einerseits ja einen theoretischen Teil machst, aber doch zumindestens ja auch hier bist um die experimentellen Sachen zu machen?

Jonas

45. Um damit Kontakt zu haben. Wie ich das sehe? Na ja, also man hat halt zumindest im Optischen... In der Quantenoptik hat man eben irgendwie einen relativ direkten Bezug zu dem ganzen Quantenzeug, weil man sogar als eine Person mit ein paar Bauteilen irgendwie einige Quanteneffekte sieht und beobachten kann. Und das fand ich auch interessant. Das wär eigentlich das Zweite gewesen was ich sonst gemacht hätte. Ich wäre wahrscheinlich in so eine Gruppe gegangen bei uns in Potsdam, die eben auch Quantenoptik macht. Also experimentell macht. Aber es hat dann einfach nicht so gut gepasst. Aber genau, da war einfach das Interessante: "Ja, bau das!" Mit der richtigen Ausrüstung kann das irgendwie jeder so ein bisschen machen. Das fand ich spannend. Aber jetzt weiß ich nicht, ob es die Frage beantwortet.

Verhältnis Theorie - Experiment

Reinhard

46. Die Frage ist eigentlich: Warum würdest du jetzt zumindestens diese experimentelle Anwendung benötigen? Du könntest ja theoretisch das nur... Also rein theoretisch machen, auf Papier.

Jonas

47. Na irgendwie gehört halt das, find ich schon noch, zur Physik dazu, dass man an sich einen Vergleich hat am Schluss zu einem Experiment. Dass man nur wenn man wirklich sich auf experimentelle Daten noch berufen kann, dann auch tatsächlich was aussagen kann. Ansonst ist es schon wieder fast nur Mathematik. Wo man irgendwelche Konzepte aufstellt und dann: Ja, die Konzepte sind in sich schlüssig und man weiß dann die widersprechen sich nicht, aber man weiß überhaupt nicht ob sie einen Bezug zu irgendwas haben. Und solange das Experiment eben noch irgendwie dahintersteht, ist es eigentlich klar was man macht. Man glaubt einfach was dieses Experiment für Konsequenzen hat und was dieses Experiment alles zeigen kann. Insofer wollte ich eigentlich einfach

weiterhin Physik machen und nicht Mathematik.

Reinhard

48. Ok, das ist der Kern. Verstehe. Du siehst sozusagen das Experiment noch als...?

Jonas

49. Eine Rechtfertigung für die Theorie.

Reinhard

50. Oh, eine Rechtfertigung. Gut. Und das hier noch möglich.

Jonas

51. Also um das ad absurdum zu treiben bin ich mir gar nicht so sicher ob Stringtheorie wirklich jetzt Physik ist. Oder doch nicht eher Metaphysik.

Reinhard

52. Das wäre die Frage gewesen, weil du auch schon vorher bei der Allgemeinen [Relativitätstheorie] gesagt hast: Ok, das geht schon ein bisschen in die Richtung...

Jonas

53. Die Allgemeine [Relativitätstheorie] kann man noch anhand von Messungen verifizieren. Insofern ist es da noch nicht so abgefahren wie bei der Stringtheorie. Aber die Allgemeine [Relativitätstheorie] ist einfach nur weil's einmal sehr schwierige Gleichungen sind. Da kann man eigentlich fast nichts analytisch machen, sondern muss fast alles numerisch machen. Und das hat mich irgendwie ein bisschen abgeschreckt. Das ist eigentlich mehr was ich meinte. Es ist einfach zu schwierig um schnell irgendwelche Aussagen zu machen.

Reinhard

54. Das ist hier irgendwie der Vorteil, weil er Apparat, also der theoretische Apparat sehr greifbar ist.

Jonas

55. Genau. Also an sich fand ich Quanten einfach einfacher.

Reinhard

56. Siehst du neben diesem Bestätigungswert den das Experiment, wie du gesagt hast, hat, noch irgendwie einen anderen Zugang...? Dass es irgendwie beim Verständnis hilft. Nicht nur in der Theorie zu verweilen, sondern das Ding auch am Arbeiten, im Experiment zu bauen oder zu sehen.

Jonas

57. Also jetzt wirklich diese Instrumente zu sehen und irgendwelche Ausschläge an Messapparaten hat mir bisher nichts gebracht. Weil ich da nicht genug verstehe. Aber wenn man sich eben mit den experimentalen Physikern unterhält, dann merkt man, dass die irgendwie einen anderen Bezug haben. Weil bei denen ist halt jetzt dieses Konzept, ist jetzt nicht eine Formel, sondern es ist der Ausschlag an dem Instrument, der da und da passiert. Und das ist irgendwie... Das ist komisch. Am Anfang redet man aneinander vorbei, aber es ist an sich interessant. Also ich glaub, dass man's dadurch ein bisschen besser kennenlernt. Wobei bisher ärgere ich mich eigentlich mehr darüber.

Reinhard

58. Dass das so unterschiedliche Konzepte sind vom Verstehen?

Jonas

59. Das sie nicht über irgendwelche Gleichungen reden können. Weil sonst kann ich es nicht überprüfen. Da muss ich dann sagen ja vielleicht. Kann sein, dass das damit zutun hat. Aber eigentlich ist es doch das hier [klopft auf den Tisch]. Also man versteht zumindest noch eine andere Seite. Lernt sie kennen, ich weiß nicht ob man sie versteht. Wahrscheinlich schon und somit wahrscheinlich besser.

Reinhard

60. Dann ist ja die Frage, wie sieht's beim Verständnis aus? Oder, wenn du dir diese Dinge anschaust, jetzt Quanteninformation usw., die Phänomene oder Effekte, wie immer man das nennen soll, wie ist da dein Verständnis? Es gibt ja die Aussage, dass das irgendwie kontraintuitiv ist und dass das nicht mit einer täglichen physikalischen Beobachtung vereinbar ist. Und dass das irgendwie problematisch ist und befriedigt werden sollte. Das es besser passt.

Jonas

61. Ok. Ähmmm. Also ja. Ich meine man sieht... Man ist einfach gewohnt irgendwie aus der Intuition, dass wenn irgendein ein Körper irgendeine Eigenschaft hat, dass dann die Eigenschaft tatsächlich da ist. Oder, dass das irgendwie tatsächlich realisiert ist. In der Quantenmechanik muss man sich da vollkommen von verabschieden. Sondern, dass sich viele Eigenschaften sich wirklich erst festlegen, sobald man eben da eine Messung macht. Und sie vorher auch tatsächlich nicht festliegen. Und dass es irgendwie sowas wie Standpunktsabhängigkeit gibt. Für einen kann's anderes sein, als für einen anderen. Also es sind Phänomene die konterintuitiv sind. Die man sich irgendwie, na ja, vorstellen kann? Man kann sich maximal daran gewöhnen.

Reinhard

62. Die Frage ist, ob man sagt, dass... Jetzt habe ich meine quantenmechanische Theorie, da rechne ich, und da gelten sozusagen diese Dinge...

Jonas

63. Ja. An sich ist das das Optimum; das stimmt. Aber man entwickelt schon automatisch, alleine aus den Gleichungen raus, irgendwie so ein Gefühl. Das Gefühl passt nicht zu dem, was man vielleicht, als jetzt einer der sich damit nicht beschäftigt hat, erwarten würde. Aber es ist trotzdem... Irgendiwe ein Gefühl ist dann schon da. Also wahrscheinlich ist das am ehesten was dann als Intuition bezeichnet werden kann.

Reinhard

64. Also wenn man so einen Umgang hat mit den Dingen, dass man dann eine gewisse Selbstverständlichkeit bekommt. Wahrscheinlich merkt man das beim Sprechen, wenn man einfach Vokabeln und gewisse Sätze sagt, die für andere recht kontraintuitiv wären. Oder recht merkwürdig klingen würden, wenn man die in anderen Zusammenhängen sagt.

Jonas

65. Das Problem irgendwie, wenn man... Ne, ich weiß jetzt nicht wie ich das zusammenfassen kann. Stell einfach nochmal ganz kurz die Frage. Sorry.

Reinhard

66. Ähm. Wir waren gerade eigentlich bei der Frage, ob man sich sozusagen an diese Dinge gewöhnen kann. Dieses Kontraintuitive das man sagt, dass es vielleicht möglicherweise verschwindet in dem man sich mit den Dingen beschäftigt.

Jonas

67. Ja. Das würde ich auf jeden Fall sagen, dass das passiert. Ich meine jetzt ist es für mich relativ selbstverständlich, dass wenn ich über ein Beispiel rede, dass ich dann weiß: Wenn jetzt der Beobachter das und das macht, verändert sich das System so und so, und für andere so.

Reinhard

68. Also es ist nicht mehr so eine Art hypothetische Annahme, die man immer so im Hinterkopf hat -- unter der Annahme, dass dem wirklich so ist --, sondern es ist einfach so.

Jonas

69. Die Quantenmechanik, bzw. das Konzept, was man sich da aufgebaut hat, das übernimmt man dann schon. Es ist einfach die beste Beschreibung der Welt die wir bisher haben und insofern wendet man das dann wirklich auf breiteren Ebenen an, als es vielleicht gedacht ist.

Interpretationen / Theorie / Experiment

Reinhard

70. Und die Frage, wenn man das jetzt so sagen will, weil es ja Interpretationen der Quantenmechanik gibt, die versuchen das Verständnis irgendwie aufzulösen. Oder dies zumindest irgendwie mit einer Geschichte zuverbinden, sodass es irgendwie besser verständlich ist. Und die stehen ja sozusagen nebeneinander. Inwieweit sind die für dich irgendwie relevant, helfen deinem Verständnis, oder sind die... haben keine Aussagekraft sozusagen.

Jonas

71. Na ja. Es ist halt was worüber man nachdenkt bei irgendwie einer Flasche Wein am Abend oder so was. Insofer draue ich ihnen mal nicht soviel Aussagekraft zu, weil es sind einfach... Na ja, es gibt einfach die Beschreibungen. Um es konkreter zu machen: Man könnte sagen, ja unser gesamtes Weltall befindet sich in einem festem Zustand. In einem Zeiger ohne... Letzendlich gibt es damit doch wieder Determinismus.

Reinhard

72. Einen vollständigen.

Jonas

73. Eben ein vollständiger. Sobald ich allerdings nur ein Teilsystem betrachte verliere ich eben wieder diesen Determinismus und muss mich dann mit probabilistischen Aussagen zufrieden geben. Ja, das gibt es zum Beispiel. Man kann überlegen jetzt, wäre es schlüssig mit dem was wir bisher wissen. So weit ich weiß gibt's da auch niemanden der irgendwas dagegen gesagt hat. Und... ja... aber... Letztendlich sagen kann man's nicht. Es gibt genauso dann diese, diese... Ne das müsste... Ja das müsste eigentlich dann... Ist es dann die... Ne das ist nicht die Viele-Welten. Ich meine es gibt genauso diese Viele-Welten Interpretation. Das sich bei jeder Entscheidung eben irgenwie was Neues ab-branched. Ja, genau auf dem gleichen Grad.

Reinhard

74. Aber zumindest....

Jonas

75. Sie sind eben da, man überlegt's sich. Man spielt damit rum: Würde das denn gehen? Oder was könnte das denn bedeuten? Aber letztendlich, wenn man dann ins Labor geht oder so was, dann nimmt man doch wieder irgendwie nur einfach den Formalismus, den man hat ohne jetzt da eine Interpretation dem unbedingt geben zu müssen.

Reinhard

76. Verstehe. Aber sozusagen die Diskussion besteht noch.

Jonas

77. Es ist interessant. Interessant sich zu überlegen ob da... wirklich ob's dann tote Katze und eine lebendige Katze gibt. Oder ob es jetzt von Anfang an klar ist, jetzt ist die Katze tot oder so.

Reinhard

78. Würdest du sehen, dass gerade die Arbeit die gemacht wird eigentlich fast darauf abzielt da zu sagen... die Frage zu beantworten. Also wenn zu sagst, Schrödingers Katze, dass zum Beispiel jetzt wenn ich die opto-mechanischen Dinger hernehme, die schon ein bisserl makroskopischer sind, schon in die Richtung gehen würden.

Jonas

79. Ich glaube nicht, dass man es vollständig beschreiben kann. Also, dass man dahin kommt.

Reinhard

80. Also, dass es sozusagen ein Testkriterium gibt, wo man dann sagt: Ok, das ist nur mit dieser einen Interpretation kompatibel und deswegen ist die die Richtige.

Jonas

81. Kann ich mir nicht vorstellen. Also ich glaube, dass man alle Interpretationen irgendwie dann noch zurecht flicken kann um dann das noch zu erklären. Wahrscheinlich scheiden ein paar aus, aber ich glaube nicht, dass man sich wirklich entscheiden kann am Schluß. Ah, [lacht] 1900 waren wir weiter,[Lachen] was das angeht.

Reinhard

82. Also in dem Sinne ist es kein Problem, dass es da so eine Vielfalt an Interpretationen gibt, die im Hintergrund...

Jonas

83. Ich glaube man hat sich irgendwie so ein bisschen davon verabschiedet, dass man... Also zumindest ich habe mich für mich davon verabschiedet, dass ich wirklich exakt beschreiben kann wie die Welt funktioniert. Ich kann nur einfach das Modell nehmen und in dem Modell kann ich's beschreiben, und dann muss ich mich damit... Muss ich immer im Hinterkopf eigentlich haben: Das kann auch alles falsch sein, irgendwie. Aber bisher haben... sagen alle Tests die wir gemacht haben, es passt wahrscheinlich.

Reinhard

84. Das würde auch den Bezug zum Experiment erklären. Dass man das Modell immer noch abgleichen muss gegen das [Experiment], damit man halbwegs eine richtige Aussage trifft.

Jonas

85. Genau. Ja.

Technischer Fortschritt

Reinhard

86. Verstehe. Wie würdest du eigentlich jetzt den technischen Wandel... Die Möglichkeiten die gegeben sind auf technischer Seite,...

Jonas

87. Wie sich der entwickelt hat, oder?

Reinhard

88. Ja, das es sich entwickelt hat. Also das diese Dinge sozusagen jetzt möglich sind. Die Quantenmechanik ist alt.

Jonas

89. Äh, ist sie schon?[lacht] Was würde ich dazu sagen? Also die Möglichkeiten sind da auf jeden Fall deutlich besser geworden. Wenn man sich alleine... Ich weiß nicht ob das so ganz in den Anfängen war, aber wenn man sich den Stern-Gerlach Versuch [1922, Beobachtung der Richtungsquantelung von Drehimpulsen (= Spin) von Atomen] anschaut, den Stern und Gerlach gemacht haben. Da haben die so eine großen Aufwand betreiben müssen, um eine Aufweitung von so einer Ellipse zu sehen, wo man am Schluß dann nicht mal sagen konnte: Ja, das hat sich wirklich gespalten. Sondern da ist bloß da ein bisschen mehr, da ein bisschen mehr und da ein bisschen mehr, und in der Mitte halt ein bisschen weniger. Und daraus haben sie dann was geschlußfolgert.
90. Wenn man jetzt heute das... Also gut, wir haben das im Fortgeschrittenen-Praktikum in so ein, zwei, drei Stunden nochmal nachgemacht, diesen Versuch. Und wir sehen einfach eine... einfach zwei Linien und vielleicht noch so ein bisschen Rauschen in der Mitte. Da ist es auf jeden Fall deutlich einfacher geworden dann zu sagen, ja die Theorie stimmt. Bei denen musste man sich dann

schon rechtfertigen: ja es ist sehr wahrscheinlich, dass es richtig ist, sonst könnten wir uns jetzt diese komischen Abweichungen nicht wirklich erklären. Es ist auf jeden Fall einfacher geworden, da so Aussagen zu treffen und auch irgendwie deutlich feinere Überprüfungen praktisch zu haben, von der Theorie.

91. Oder diese ganzen Für und Wider für das Michelsons-Interferometer [Untersuchung des Lichtäthers als Medium für die Ausbreitung des Lichts]. Wo manche am Anfang gesagt haben, dass: Ja, oh. Jetzt drehen wir das in eine andere Richtung und wir kriegen genau das Gleiche raus. Und dann kommt später wieder einer: Ja ihr habt das überhaupt nicht gekonnt. Ihr habt viel zu viele Abweichungen um wirklich sagen zu können, dass ihr das tatsächlich jetzt gemessen habt. Vielleicht gibt's ja doch noch den Äther. Das ist überhaupt nicht klar. Und dann macht man das halt wieder genauer mit neuen Instrumenten, und wieder genauer mit neuen Instrumenten und irgendwann kann dann auch keiner mehr was dagegen sagen.

Reinhard

92. Also es ist schon kein schlechtes Indiz, dass es da Studenten- oder Schülerexperimente gibt, die das nachweisen...

Jonas

93. Genau. Die einfach das abdecken können, was in den zwanziger Jahren oder auch sogar schon vierziger Jahren irgendwelche Leute mit sehr, sehr viel Aufwand... Die wirklich da Millionen reingesteckt haben, oder was weiß ich wieviel Geld man da jeweils zahlen musste, dann jetzt für so Studenten nachgemacht werden kann. Das zeigt auf jeden Fall auf, dass es sich anscheinend verbessert hat. Das man jetzt irgendwelche Millionen reinsteckt, dass man dann ganz schön viel bessere Ergebnisse rauskriegt, oder feinere Ergebnisse.

Reinhard

94. Ja, bzw. es scheint auch... Man scheint die Anwendungsmöglichkeiten entdeckt zu haben und deswegen scheint sozusagen mehr Druck dahinter zu sein. Das ist die Frage? Aber scheint zumindestens so.

Jonas

95. Ich denke mal die Gesellschaft hat inzwischen einfach festgestellt, dass da doch wieder immer irgendwas, was abfällt, was man verwerten kann. Wenn man sich schon soviel auf die Entwicklung beruft, das macht natürlich schon ein bisschen mehr Druck. Es sind auch jetzt einfach deutlich mehr Leute, die sich um sowas wie einen Fortschritt kümmern; als es damals war.

Reinhard

96. [leise] Das habe ich schon gefragt.

Perspektive

Reinhard

97. Wie sieht es eigentlich Plan-mäßig bei dir aus?

Jonas

98. Danach?

Reinhard

99. Ja, danach.

Jonas

100. Ja, ich würde gerne einen Doktor machen. Wo weiß ich nicht. Wahrscheinlich ganz gerne weiter Quantenoptik, oder Opto-Mechanik, oder Quanteninformation. Irgendwie so in dem breiten Feld. Ja, mal schauen. Was da genau weiß ich aber noch nicht. Also ich hab nichts wirklich in Aussicht.

Reinhard

101. Die Diplomarbeit einmal als Nahziel?

Jonas

102. Die Diplomarbeit einmal nach Hause fahren. Bisher kam's mir auch so vor wie wenn eigentlich sich die Profs, Jens Eisert oder so was zum Beispiel, sich da schon irgendwie darum kümmert und mir dann sagen: Bewerb dich mal bei dem und dem, das würde eigentlich relativ gut passen. Da kannst du das und das machen.

Reinhard

103. Also die treiben das schon in eine Richtung, dass da Leute entstehen die das machen.

Jonas

104. Die haben da irgendwie schon ein bisschen einen Überblick, scheint es mir.

Reinhard

105. Es scheint da sozusagen, zumindestens hier im Aufbau begriffen zu sein. Da zumindestens Dinge in die Richtung voranzubringen.

Jonas

106. Genau, es irgendwie immer noch so, dass irgendwie alles wo "Qu" drin steckt, ist einfach gerade in. Da hat man auch gute Möglichkeiten selbst noch was zu machen [lacht].

Reinhard

107. Verstehe.

Jonas

108. Je mehr "Qu"s desto besser.

Verschränkung

Reinhard

109. Im Prinzip wären das meine Fragen gewesen. Wenn du nichts...

Jonas

110. Jetzt haben wir nicht viel zur Verschränkung gemacht? Ich weiß nicht, jetzt da irgendwas aus dem Nähkasten was darüber zu sagen ist natürlich auch nicht unbedingt einfach. An sich was Verschränkung ist, definiert sich bei mir hauptsächlich eigentlich damit was man halt machen kann. Weil irgenwie was es ist, glaube ich weiß keiner so richtig. Man weiß inzwischen so ein bisschen wie man es quantifiziert. Wie man sagen kann ich habe viel, ich habe wenig Verschränkung. Und man... Na ja, was man dann eben für Effekte sehen würde. Irgendwie Teleportation oder Informationsübertragung. Genau. Einfach nur irgendwie als eine Ressource.

Reinhard

111. Und würdest du sehen, dass man daraus mehr Erkenntnis gewinnt. Wenn jetzt einmal die Frage...

Jonas

112. Also Anwendung auf jeden Fall. Also ich meine die Anwendungen die bisher aus den Quanten rausgekommen sind, berufen sich fast -- nein das kann ich jetzt nicht sagen --... Aber es gibt auf jeden Fall Anwendungen wie in der Kryptographie, eben zum Beispiel, oder jetzt eben in der Kontrolle von irgendwelchen kleinen Systemen. Und da spielt dann schon die Verschränkung eben eine prinzipielle Rolle. Also zumal wir jetzt auch... Zumal irgendwie inzwischen mein Verständnis ist, dass Verschränkung eigentlich das ist, was die Quanteninformation... Oder was die Quanteninformation überhaupt ermöglicht, dass die irgendwie besser würde als die Klassiche. Dass man damit Sachen machen kann, die die Klassische nicht kann. Das ist auf jeden Fall auf die Verschränkung zurückzuführen. Insofern, ja. Aber was es ist, weiß man auch nicht so richtig, würde ich jetzt behaupten. Also

manche haben wahrscheinlich ein besseres Gefühl, manche ein schlechteres Gefühl. Ich habe noch kein so richtiges.

Reinhard

113. Also du blendest... Eigentlich nicht einmal ausblenden wahrscheinlich, sondern es ist halt nicht relevant.

Jonas

114. Ich einfach wirklich noch kein Gefühl dafür. Dazu habe ich wahrscheinlich zu wenig mitgemacht. Ich weiß wie so eine Teleportation mit so Verschränkung funktioniert. Und ich weiß wie ich damit mehr Information übertragen kann. Und ich weiß auch wie ich Verschränkung eben messen kann, oder quantifizieren kann. Und an sich ist das für mich dann Verschränkung. Dieser operationelle Komplex. Damit kann ich aber auch nicht wirklich sagen, was es jetzt...

Reinhard

115. Wie würdest du den Anwendungsbereich der Verschränkung sehen? Es scheint ja nicht an die Größenskala gebunden zu sein oder an das System. Es scheint ja mehr so, wenn man das sagen will, prinzipiellen Charakter zu haben. Sobald ich ein System entsprechend präparieren kann, entsprechend von der Umwelt isolieren kann, habe ich die Möglichkeit Verschränkung herzustellen.

Jonas

116. Genau. Wobei das Isolieren eben dann, gerade wann es an die Größe geht, der zentrale Punkt des Problems ist. Und so, worin man dann genau die Anwendung sieht?

Reinhard

117. Na ja, die Frage ist wie du sozusagen den Status siehst. Weil das scheint ja auch eine gewisse Merkwürdigkeit auszumachen, das es systemunabhängig ist. Oder, das es eher einen prinzipiellen Charakter hat.

Jonas

118. Also wir haben wirklich mit dem Isolieren ist es das größte Problem. Und deswegen geht es eben mit kleinen Systemen wie irgendwelchen Atomen, oder hauptsächlich natürlich Licht, verdammt gut und alles darüber hinaus wird immer vedammt schwierig. Und wenn, nur mit großem Aufwand. Da geht noch nicht sehr viel Anwendung würde ich sagen. Es ist alles noch prinzipiell und proof of concept.

Reinhard

119. Solange keine Anwendung da ist, oder nicht so Art die Möglichkeit da ist, das irgendwie wirklich so auch in größeren Skalen zu fassen, würdest du sagen, das ist nicht ganz sicher, dass es auch dort relevant sein könnte. Verstehst du was ich meine? Weil die Theorie gibt ja nicht vor, die Größenskala, oder wo das seine Grenzen hat, oder seine Limitierung. Also die Verschränkung.

Jonas

120. Also ich bin schon der Meinung, dass die Verschränkung wirklich überall prinzipiell auftreten kann. Und auftreten wird. Dass ich aber nicht weiß ob man jemals irgendeine Anwendung mit großen Systemen machen kann, weil es einfach vom Aufwand her viel zu kompliziert ist. Das meinte ich. Aber es wird überall... Bin mir wirklich sicher, dass das Prinzip wirklich überall anzuwenden ist. Vielleicht könnte man sogar irgendwelche Planeten miteinander verschränken.[lacht]

Reinhard

121. Verstehe.

Jonas

122. Also zumindest... Soweit sehe ich das jetzt, dass es in der Theorie, sobald ich die so beschreiben kann: Als irgendwie zwei Systeme mit irgendwelchen Zuständen, dass ich dann diese Zustände auch verschränken kann.

Reinhard

123. Also solange das Experiment nichts gegenteiliges behauptet. Wenn nicht irgendwann auf einmal auftauchen würde...

Jonas

124. Wenn das dann wirklich auftauchen würde, dann würde das wirklich heißen: Dann ist unsere Quantenmechanik irgendwie falsch. Und davon gehe ich jetzt gerade nicht aus.[lacht] Insofern bin ich der Meinung: Das müsste auf allen... Das geht auf allen Skalen.

Reinhard

125. Ok.

Jonas

126. Aber ja das kann wirklich... Sowas kann zu einem Test für Quantenmechanik ausarten, irgendwie am Schluß. Oder Quanten generell.

Reinhard

127. Aber eher erst wenn Probleme auftauchen. Es würde es nicht bestätigen wenn nichts passiert, sondern eher wenn Probleme auftreten und das nicht mehr funktionieren würde...

Jonas

128. Also wenn man das irgendwann richtig gut unter Kontrolle hat so ein System zu isolieren, sodass es nicht mehr seine Verschränkung in die Umgebung abgibt, praktisch. Also dekoheriert. Wenn man da irgendwie mal was prinzipiell gefunden hat, dass man das exakt oder vollständig irgendwie isolieren kann und man dann keine Verschränkung herstellen kann, dann ist was sehr kaputt. Da muss man wahrscheinlich fast neu anfangen. Aber davon gehe ich nicht aus. Aber kann natürlich passieren.

Ende

Reinhard

129. Gut. Danke für das Interview.

Jonas

130. Ja, kein Problem.

(no speaker)

131. [small talk]

Florian_110525

Interview mit Mag. Florian Blaser vom 25.05.2011
Transcribed by yotta, version 1 of 110527

Anfang, persönliche Daten, Ausbildung

Reinhard

1. In the beginning it's just some general questions. How old are you?

Florian

2. I am 30.

Reinhard

3. That took you a while.

Florian

4. I stopped counting five years ago.

Reinhard

5. What is your educational background? I mean where did you study?

Florian

6. I studied physics in Switzerland, in Neuchatel. It was a very small university that was not really specialized in quantum information stuff. Most of the quantum stuff I learned... So I did have quantum mechanics in my courses, but quantum information was not very strong. And we never talked about entanglement there. As you studied in Vienna, I guess it is quite the opposite.

Reinhard

7. And when did you come here?

Florian

8. I came here to do my diploma thesis. I started in the group of Zeilinger [Anton Zeilinger]. And basically I started to work on the opto-mechanics experiments in the very beginning.

Reinhard

9. So this was two years ago?

Florian

10. 2005, 2006. And then after my diploma thesis I went on working in the industry. And then came back for a PhD.

Reinhard

11. What was your diploma thesis about?

Florian

12. I did simulations of the mechanical systems we have. And also worked on the experiments that produced the first cooling of the motion of the cantilever.

Reinhard

13. What did you do in the industry?

Florian

14. In the industry I did computer stuff. So no physics.

Reinhard

15. When did you get to entanglement? Was it just here in Vienna, or somewhere before?

Florian

16. I think that was the reason to come to Vienna. During my studies I started, so I learned a bit about entanglement, and started to read on my own two books. Books about quantum information. I started reading the Nielsen and Chuang book [comprehensive introduction to quantum computation and information]. I got quite interested. And I started to read the papers that were going in this direction. So it was the time of the cluster computing with the multi-photon experiments. And I read about this and so ok there is this group in Vienna. They seemed to be good at that and I tried to apply there.

Reinhard

17. And it worked.

Florian

18. And it worked. They were crazy enough.

Reinhard

19. So that was the reason to come here and join the group. Become involved in this. And what are your ambitions to get done here. I mean your PhD probably?

Florian

20. Yeah, so I am PhD. I am working on a project to do also the kind of experiments that we did with the mirrors, which are still continuing, but with trapped nano particles instead.

Reinhard

21. So you and Nikolai [Nikolai Kiesel] are working on the same experiment?

Florian

22. Exactly.

Reinhard

23. So it is just you two, or?

Florian

24. There is third guy named Uros [Uros Delic].
25. So again. As in my diploma thesis, it is mostly classical physics. With some chance we will reach the ground state. That will be my PhD then.

Reinhard

26. Ok. So that is your PhD topic to get there?

Florian

27. To get there is quite a challenging goal. It might still happen.

Reinhard

28. At what time scale? How long will it take you, you think?

Florian

29. So I a PhD usually three years. But three plus internally. And I did one and a half year up to now.

Reinhard

30. So you got another one and a half to get it done.

Aufgabe im Experiment / Rolle in der Gruppe

Reinhard

31. As already said you are working with Nikolai [Nikolai Kiesel] and Uros [Uros Delic]. I talked with Nikolai anyway how far you got in the experiment. And at which state you are.

Florian

32. So we really want to see the proof of principle right now.

Reinhard

33. Is there any stress from other groups? Do you know of other groups that are...?

Florian

34. Definitely. We know a few groups who are for sure working in the same direction. [??? a sentence I could not get ???]

Reinhard

35. So they are on the same level?

Florian

36. It depends. One group is more advanced. We don't know a lot of the other groups, because nobody has published anything. Except one group has published already some paper, where they don't really were interested in cooling. But they had a trapping and measured the Brownian motion [stochastic random movement of particles suspended in a fluid] of the particle. And with this they then showed feedback cooling. Our guess is that they continue in the same direction.

Reinhard

37. Would be logical to go on from there.
38. Could you describe what your hands on job is at the experiment? I mean, Nikolai told me that you did at the moment LabView [graphical programming environment to develop measurement, test, and control systems].

Florian

39. Yeah, currently I am doing LabView. We basically need to plan and discuss how we want to do it. That is something we do quite a lot with Nikolai. We try to get the ideas to get rid of the noise. And have the best measurement possible. Then there is the really hand on work of aligning the optics. Setting up the electronics for making the setup work. And adjusting electronics, optics and... When it's in the experiment and if we see the signal. Lately we have seen the signal in the way we wanted it to appear. Another part of the job is actually to make bets with Nikolai. Whether this will work or not. That adds some fun to it.

Reinhard

40. That depends on how often you win. Or lose.

Florian

41. We anyway go for a beer. The bet is a way to randomize who pays.

Reinhard

42. If the result is ok, it's fine.

Florian

43. So currently we get the signal. We roughly know how to do the measurement. We are still processing the data to see if we have the effect that we want. And the next step, what we do in parallel, is just to program. To have an automatization of the experiment. Now that we know that it somehow should work.

Interpretation / Theorie / Experiment

Reinhard

44. So how would you see the connection between the theory and the experimental part of this experiment?

Florian

45. Here I think the theory is pretty clear. In the sense that... So it is a different system to which we apply the theory that is already known. So there is still a lot of back and forth. The interesting theory part is the limitations of the system and how we can improve that. So here in theory we have a collaborate of this project. We have a collaboration with the persons who actually proposed the experiment. So we don't do most of the theory. But to predict something, we have to do the last bit of theory in applying the calculations.

Reinhard

46. So at least to compare the results with some theory. What you expected.

Florian

47. Exactly.

Faszination an der Quantenmechanik

Reinhard

48. What in your eyes is it that fascinates you about quantum mechanics? Or why you do this?

Florian

49. So the easy answer is entanglement, right. The most profound motivation is the fact that we have a theory that is hard to grasp in normal terms, or common day experience. It is hard to bring that knowledges to the quantum world. Or to make an analogy of the quantum world using day-to-day experience. I think that's quite a revolution in science. It didn't start recently. A century ago it started and I think it's very interesting to see how this affects our perception and our view of the world... physically.

Reinhard

50. So do you see this rather as a problem or some motivation to go ahead and do some things?

Florian

51. It is rather a motivation to understand. This battle between realists and local non-realists is quite fascinating. Because right now it is becoming hard to find a guy who believes in local hidden variable theories [the EPR paper argues for those], or even non-local hidden variable theories [Bohm's theory is one of those]. To me personally this looks like people trying to keep the old way of looking at things. Not making the step necessary to understand quantum mechanics.

Reinhard

52. The question is how far it really matters? As you said before at the experiment, right now, it is quite classical.

Florian

53. For me that was the motivation to come here. I know that I'm not researching in this direction. So I'm doing classical physics [sarcasm]. The hope of the experiment is to go really in the quantum regime. But it is a long way. And it's actually a challenge. I don't think anybody would doubt that it will not work, but it's an area of physics that has not been tested.

Reinhard

54. At least you have to do the things. Proposing is quite ok, but at sometime you'd like to, at least, show or see that there is something.
55. And do you think that experiments help? If you think of it personally that you get a better idea about the situation?

Florian

56. You mean relative to quantum mechanics?

Reinhard

57. Yeah. You get more accustomed to it?

Florian

58. So with this current experiment, no. Definitely not. From the theory I read, the theory papers I read, I get a bit. I guess I still increase my understanding of the things through interactions with other people from the quantum group.

Reinhard

59. So it is more like the exchange of the views that are circulating around here that...

Florian

60. And I think even though we are not... I think the common determinitor of everybody in the quantum group is an interest for this kind of things. Even if the systems we are dealing with are not the same, we can always find a ground for discussions.

Reinhard

61. Do you have any idea or... What would you think would make it easier to understand quantum mechanics? Do you see a kind of hope that there will be some changes so that you get some easy access?

Florian

62. The only way I think it can... Unless there is a big change to quantum mechanics and there is a big change in the theory, because we found some way to explain it. Or to get the same results without resorting to the wave function. I think the change that might happen is only at the pedagogical level. People learning it differently. Having access to more examples. I think the experiments that have happened in Innsbruck and Vienna in the last twenty years are good examples that can be used to learn more about quantum... To get a bigger grasp of quantum mechanics.

Reinhard

63. So it is more like a technological progress?

Florian

64. I was not speaking of the technological progress. I was just thinking of basically the realisation of Gedankenexperiments. That this really works. And you have many different ways of making the experiment work. You have many different systems. And they all agree with quantum mechanics. From all of those different systems, you can somehow make a better picture in your head.

Reinhard

65. As you already said. From your type of education you had, did you find something lacking? Because you said that more privately you got interested in these kind of things, outside of studying physics.

Florian

66. I have to say it is more a personal thing. But I think it was lacking, because I'm interested in it. We also didn't have any courses on plasma physics. I'm less interested in that, so... I had the basis to go on and seek quantum information. What was missing from the courses was just the definition of quantum entanglement right away. We knew [??? a word I could not get ???], we knew density matrices, we knew everything that leads up to that point. We never had a bipartite system [system of two parts; can sport entanglement or not] described and then show you that you can have states that are not separable [i.e. that the are entangled].

Reinhard

67. This is a very basic level of quantum mechanics.

Florian

68. Yeah, of quantum information.

Reinhard

69. Oh yeah, quantum information.

Florian

70. So in quantum mechanics we went more in the direction of quantum field theory [theory about quantum systems classically represented by an infinite number of dynamical degrees of freedom (fields)], or particle physics. That is why I learned a lot about path integrals and things like that. Which is also advanced stuff. I think the quantum information stuff is more easy to grasp, because it has less mathematics behind it. Once you have the basis of quantum mechanics... So you can actually understand quite easily open problems. You can easily go to open problems from a basic... That does not mean you can solve them.

Reinhard

71. But you are getting there quite quick in respect to other fields of science, where you have to go through a lot of theoretical concepts. Just to get near something where you can make something new or have ideas about how experiments could look like.

Florian

72. I think that's also quite attractive in this field. When you look at the foundations, then you will never look at a very complicated system. We always try to make it as simple as possible. And as counter-intuitive as possible, in the case of the foundations of quantum mechanics.

technischer Fortschritt

Reinhard

73. How do you see the technical progress; how far your insight goes?

Florian

74. For experiments the technical progresses are simple what allows us to make better experiments. In a sense it is really important. We don't do a lot of applied research, but we definitely need other people to do it. To get better detectors, better electronics, better optical components. We are only trying to use all the newest and best toys that we can buy.

Interpretation / Theorie / Experiment

Reinhard

75. In respect to interpretations of quantum mechanics, do they mean anything to you? They might not matter in the experiment. Of course not. When you are in the lab and doing things... But at what stage, if at all, do you mind about them?

Florian

76. So I don't mind about them. I think it is actually good to look for new ones. Actually I'm a bit reluctant to look at interpretations. All of them are falling into this category: They are not really predictive. To me they are interesting only as a way to think about theories that could have a different prediction than quantum mechanics. I think they are useful. Just as a tool to think about what could change in quantum mechanics. What modifications could be made to quantum mechanics and then how to test them. But personally I don't have strong feelings about any of them. I'm basically more pragmatist.

Reinhard

77. If they are not predicting anything, how could they play a big role?

Florian

78. I mean they could play a big role in the way we see or teach quantum mechanics. But I think they are all a bit more... It is an extra layer of information on top of the stuff that you really need to know to do quantum mechanics. I'm always tempted to learn more about them, just to find the differences. I think they really have an impact on the way we popularize science or quantum mechanics. If you take the many-worlds theory, that is a very strong way to insist on the peculiarities of quantum mechanics. But, it is also a nice way to pinpoint the measurement problem.

Reinhard

79. So it is a question of... If you exaggerate the point that there is the measurement problem or you don't?

Florian

80. That is actually a good point. It is a way to exaggerate it.

Reinhard

81. Could I think of something else? Let me see. Probably not. So if you want to add something? Something I didn't mention?

Florian

82. Sorry that I don't have a lot of hands-on experiments with entanglement right now. If you have questions later you can always send an email or...

Reinhard

83. So, thank you very much for the interview.

(no speaker)

84. small talk

Markus_110706

Interview mit Markus Aspelmeyer vom 06.07.2011
Transcribed by yotta, version 2 of 110708

Anfang, persönliche Daten, Ausbildung

(no speaker)

1. [small talk]

Reinhard

2. Ich werde versuchen es wie bei allen anderen zu machen; allen anderen Interviews. Allgemeine Fragen: Wie alt bist du?

Markus

3. [lacht] Da muss ich selber immer nachdenken. 37. Warte. Ja. Irgendwann hört man zu zählen auf.

Reinhard

4. Ja, ja. Das habe ich schon öfters gehört.

Markus

5. Dann schätzt man einfach.

Reinhard

6. Reicht ja.
7. Wie war deine Ausbildung? Oder sagen wir so, wo hast du studiert? Wie ist es dann ein bisserl weitergegangen? Spezieller dann in Richtung: Wie bist du zur Quantenmechanik gekommen, oder dem Feld, sagen wir so?

Markus

8. Also studiert habe ich in München, an der LMU, Physik. Und an der Hochschule für Philosophie, Philosophie. Also zuerst nur Physik und dann ab dem sechsten, siebten Semester in der Physik habe ich dann Philosophie angefangen. Habe dann irgendwann mein Diplom in der Physik gemacht und mein Bakkalaureat in der Philosophie. Bei Balzer [Wolfgang Balzer] meine Wissenschafttheorie im Nebenfach gemacht. Das war ganz lustig. Und bin... Habe danach dann meine Promotion in der Physik angefangen. Das war in der Festkörperphysik. Ich habe ein Diplom schon in der Festkörperphysik gemacht und zwar war ich da in Houston für eineinhalb Jahre; mit Simon Moss. Habe da meine Diplomarbeit gemacht, experimentell. Und habe da am selben Thema weitergearbeitet; also über strukturelle Phasenübergänge in Kristallen. Martensitische Phasenübergänge und ferroelektrische Phasenübergänge.
9. Habe dann also meine Doktorarbeit gemacht in München an der LMU beim Peisl [Johann Peisl] und war also oft da in Houston. Und an Synchrotrons [Teilchenbeschleuniger] auf der ganzen Welt, weil das hauptsächlich Untersuchung von diesen Kristalleigenschaften, von diesen Phasenübergängen... Denn es ging um Phasenübergänge bei denen sich die Gittekonstante [Parameter (Längenangabe, Winkel) zur Beschreibung eines Gitters, insbesondere der kleinsten Einheit des Gitters, der Elementarzelle] ändert.

Reinhard

10. Ah ok. D.h. die zu messen.

Markus

11. Genau, die zu vermessen mit verschiedenen Methoden und zu verstehen. Und habe dann 2002 abgeschlossen; die Diss. Habe nebenbei dann angefangen... Habe die Zulassung mir geholt für eine Diss in der Philosophie. War offiziell dann schon eingeschrieben als Doktorand bei den Philosophen. War gerade so auf Themensuche. Habe mit Bluthrupp [???] und so weiter verhandelt, was man dann da machen könnte. Und habe aber nebenbei dann auch geschaut, was sind so weitere Möglichkeiten in der Physik. Und da gabs viele Möglichkeiten in der Festkörperphysik weiterzumachen.
12. Und allerdings habe ich mich auch gefragt: Wäre es jetzt nicht eine gute Gelegenheit einmal was anderes zu machen? Und die ratio war ganz einfach. Ich habe mich gefragt, was ist das was mich am meisten interessiert und worüber ich am wenigsten weiß. Und die Überlegung war einfach. Wenn man sich nicht auskennt mit etwas, dann muss man einfach anfangen auf dem Gebiet zu arbeiten. Ja, also die Quantenphysik war seit jeher mein Steckenpferd, auch während des Studiums. Ich glaube das geht einem jeden so der irgendwie an Grundlagen interessiert ist, dass er an diesen Fragenstellungen hängen bleibt.
13. Und damit war die erste Frage beantwortet. Und die zweite Frage war dann natürlich, wie stellt man es an. Ich hatte dann das Glück, dass der Zeilinger [Anton Zeilinger] dann mich genommen hat als Post-Doc, obwohl ich überhaupt keine Vorbildung in der Quantenoptik, whatsoever, hatte. Das war reines Glück. Und dann, ja damit ging's los mit der Quantenphysik. Seitdem bin ich in Wien und so weiter.

Reinhard

14. Seitdem läuft das. Und seit wann hast du sozusagen die Gruppe?

Markus

15. Also wir haben... Ich habe dann sehr viel gelernt vom Anton [Anton Zeilinger] und in Anton's Gruppe sehr viel Photonenexperimente gemacht. Und bin dann mit ihm an das Akademie Institut, das Institut für Quantenoptik und Quanteninformation[ÖAW, IQOQI], gegangen. 2004 war das, 2005. Und das war dann auch die Zeit als wir angefangen haben erstmals über diese mechanischen Systeme nachzudenken. Und ob man da nicht mit der Quantenoptik sowas wie Verschränkung und so weiter erreichen kann.
16. Und da habe ich dann angefangen die Experimente hochzuziehen. Also der Anton [Anton Zeilinger] hat die ursprünglich mitfinanziert und hat natürlich auch mitdiskutiert am Anfang. Hat mir aber im Prinzip völlig freie Hand gelassen, also in der Auswahl der Leute und in der Art und Weise wie wir das Experiment hochziehen. Ja, und so ist es dann passiert. Wir haben dann 2006 die ersten Arbeiten publiziert. Für's erste Laserkühlung zur Mechanik gemacht. Das ging weiter und im Prinzip... Da kamen auch die ersten Drittmittel und ich habe dann damit im Prinzip die ganze Forschung selbst finanziert, aus eigenen Mitteln. Das war so ab 2006. Und dann 2009 gab es dann ein paar Rufe an Universitäten, unter anderem Wien. Oxford und Calgary habe ich dann abgelehnt. Wien habe ich angenommen. Seitdem bin ich auf der Uni.

Reinhard

17. Über die Brücke gegangen und... [IQOQI und das Physikinstitut sind in zwei Gebäuden gleich nebeneinander, verbunden durch eine Fußgängerbrücke].

Markus

18. Seit April 2011 offiziell haben wir sämtliche Labors umgezogen und sind vollständig auf der Universität.[lacht]

Reinhard

19. Vollständig das Gebäude gewechselt.

Markus

20. Eineinhalb Jahre gedauert, aber immerhin. Ok, soviel zur kurzen vita.

Aufgabe im Experiment / Rolle in der Gruppe

Reinhard

21. Genau. Kurze Frage, weil ich das auch die anderen gefragt habe. Was ist dein Job, sozusagen? Dein hands-on...? [lacht]

Markus

22. Ja, gute Frage. Ich versuche meine Zeit an der Uni zu nutzen um möglichst viel mit den Leuten in meiner Gruppe zu interagieren. Ich versuche ins Labor zu gehen und dort zu helfen wo geht. Ich versuche die Finanzierung aller Experimente am Leben zu erhalten. Ich versuche neue Impulse zu geben. Einfach neue Richtungen zu definieren. Ja, und damit ist der Tag dann schon ausgefüllt. Ich versuche hauptsächlich blöd daher zu reden.[lacht]

Reinhard

23. Also funktioniert das noch, dass du ins Labor kommst und...?

Markus

24. Ja, was sich zeitlich nimmer ausgeht, leider Gottes, ist, dass man so vier, fünf Stunden am Stück, einfach mal zur Justage verwendet. Das funktioniert deswegen nicht, weil es nicht damit getan ist, dass man einmal vier, fünf Stunden am Stück sich hinstellt, sondern das muss man konstant machen. Und das ist diese Konstanz die fehlt. Also, ich kann mir durchaus diese Zeit nehmen. Und das machen, einmal. Ja, aber dann ist am nächsten Tag schon wieder was anders. Bzw. die nächsten vier, fünf Stunden, wo man dann Kontinuität haben müsste. Also diese Art von Kontinuität im Labor ist ein bisserl verloren gegangen. Aber die erkämpft man sich so Schritt für Schritt wieder... oder versucht sie sich wieder zurück zu kämpfen.
25. Also de facto bin ich im Prinzip im Labor um dort halt mit den Leuten zu diskutieren und zu sehen wo ich helfen kann. Aber ich kann nicht dadurch... Also derzeit jetzt nimmer konkret dadurch helfen, dass ich dann mitjustiere. Leider. Aber das ist ein reines Zeitproblem.

Reinhard

26. Ja. Und wie schaut das so die Aussicht aus?

Markus

27. Worauf?

Reinhard

28. Wie das läuft? Morgen hat man dann das fertige Ergebnis...

Markus

29. Das ist immer so.[lacht] Das ist meine Aufgabe diese Erwartunghaltung ständig zu projizieren.
30. Nein, ich würde jetzt einfach... Ja das ist halt Experimentalphysik. Das dauert halt einfach. Da glaubst du hast nächste Woche das Ergebnis und dann dauert's zwei Jahre. Aber, mein Gott, so ist es. Deswegen ist es wichtig, dass die Ziele die man sich steckt und die Experimente die man macht, einfach spannende Fragen addressiert. Dass man auch selber nicht die Motivation daran verliert.

Reinhard

31. Und erreichbar in einem gewissen Ausmaß...?

Markus

32. Zumindest muss man glauben, dass sie erreichbar sind. Manchmal schadet eine gewisse Naivität überhaupt nicht. Wenn ich daran denke wie wir die Experimente angefangen haben 2005 zur Mechanik. Wie naiv wir waren. Was wir gedacht haben wie schnell das alles geht und was wir alles machen können. Hätten wir damals das Ganze realistischer eingeschätzt, hätten wir es vielleicht niemals angefangen. Weil wir dann soviel Angst davor gehabt hätten, was da alles auf uns zukommt, dass wir es gelassen hätten. Und so ist es jetzt ständig motiviert, was jetzt als nächstes kommt, die nächste Hürde zu überspringen. Man kommt zwar langsamer voran, aber man hat tolle Erfolge.

Theorie - Experiment

Reinhard

33. Also, dass ist dann soundso auch die Frage: Wie würdest du dann die Beziehung zum Experiment sehen? Theorie - Experiment. Weil im Endeffekt ja irgendwann der Schritt ist, wo man sagt: Ok, jetzt muss man es, wenn's auch naiv ist, machen, anstatt es nur papiermäßig zu entwickeln. So sollte es eigentlich theoretisch ausschauen, aber...

Markus

34. Ich glaube man kann keine generelle Regel aufstellen. Es ist oftmals so, dass die Theorie ein guter Ideengeber ist. Ja, dort wo Experimente tatsächlich Vorhersagen falsifizieren können, möglicherweise, sind Theorien natürlich immer sehr gefragt. Gleichzeitig ist es aber auch so, dass einfach neue experimentelle Möglichkeiten -- die jetzt völlig unabhängig sind von der Theorie --, einfach dir ermöglichen neue Dinge zu messen, neue Größen zu messen oder mit ungeahnter Auflösung zu messen. Wo auf einmal eine experimentelle Entwicklung dich in einen völlig neuen Parameterbereich bringt. Da kann es durchaus sein, dass also theoriefreies Experimentieren... dich auf einmal das Experiment soweit nach vorne bringt, dass dann wieder auf einmal erstmals theoretische Vorhersagen die existieren, dann überprüfbar werden.

Reinhard

35. Wäre das in dem Feld sozusagen der Fall? Oder, würdest du sehen, dass das hier, jetzt konkret bei der Opto-Mechanik, zutreffen würde?

Markus

36. Ja, auf jeden Fall.

Reinhard

37. Also, dass du so was wie 'frei' experimentieren kannst? Bzw. halt...

Markus

38. Na ja, es ist im Augenblick wirklich ein ständiges Nehmen und Geben. Also wir haben, als Beispiel... Die ganze Methodik der Seitenbandkühlung die für Ionen, zum Beispiel, verwendet wurde, die kann man jetzt einfach anwenden. Also da hilft's natürlich die Theorie zu verstehen, weil man damit die Experimente optimieren kann. Gleichzeitig kann man allerdings dieses Kühlen an und für sich zunächst mal völlig unabhängig davon entdecken. Wir haben das einfach, dieses Kühlen, gemacht und sind im Prinzip erst ein Jahr später draufgekommen, dass das eigentlich völlig äquivalent ist zu dem was man in der Ionenphysik schon seit zwanzig Jahren kennt. Es zeigt so ein bisserl die Naivität mit der man an manche Sachen rangeht und die dann auch notwendig ist.
39. Andererseits haben wir jetzt durch Entwicklungen, was jetzt zum Beispiel der Michael [Michael Vanner] gemacht hat mit diesen Ideen, dass man durch gepulstes... das gepulste Betreiben der optomechanischen Cavity, diese Zustandstomographie [(zerstörungsfreies) Auslesen des Quantenzustandes eines Systems] machen kann, gibt's jetzt ganz tolle neue Möglichkeiten Effekte zu beobachten, die man mit Vorhersagen aus der Quantengravitation vergleichen kann. Das war vor zwei Wochen noch nicht absehbar. Das sind auch völlig neue Entwicklungen. Im Prinzip geht das erst... ist und das erst aufgefallen, als dann eben dieses neue experimentelle Konzept da war. Das theoretische Konzept zum Auslesen, dass man jetzt experimentell umsetzen wollen. Also jeden Tag einen neue Überraschung.

Reinhard

40. Ist ja nicht schlecht. Ja?

Markus

41. Also ich glaube es gibt keine einheitliche, keine universelle Antwort auf das Wechselspiel zwischen Theorie und Experiment. Oftmals ist es so, wenn du die Theorie besser verstehst, dass du Experimente einfach in eine neue Richtung lenken kannst, weil du manches mit deinem System machen kannst auf das du vorher gar nicht gekommen wärst.

Reinhard

42. Man hängt dann vielleicht nicht zu sehr am Technischen. An den technischen Hürden und hängt dort fest, sondern kann sich auch wieder lösen und theoretisch Richtung machen.

Markus

43. Genau. Die Theorie hilft durchaus einfach… Ja das Experiment von einer Meta-Ebene zu betrachten.

Interpretationen

Reinhard

44. Und wie würde in dieses Verhältnis dann sowas reinkommen wie, noch etwas meta-ebeneriges wie Interpretationen? [lange Pause] Weil es ist ja schon irgendwas was man zugrunde legt, den Theorien, in dem Verständnis und das wirkt sich in gewisser Weise auch aufs experimental Verständnis aus. Oder nicht?

Markus

45. Na ja, mein Zugang zu Interpretationen ist, dass das ideale Experiment ein solches ist… sagen wir ein schönes Experiment, ein solches ist, dass es dir gerade erlaubt deine zugrundeliegenden Annahmen, die also hinter jeder Interpretation stehen, auf den Prüfstand zu stellen. Deswegen glaube ich sind die schönsten Experimente überhaupt, sind beispielsweise Bell-Experimente. Ja, weil du in diesen Experimenten tatsächlich Aussagen über ganz basale Annahmen über physikalische Theorien erhältst. Du testet nicht einfach die Vorhersage,… bzw. das stimmt nicht ganz. Du testet natürlich die Vorhersage der Quantentheorie, die sagt, dass die Korrelationsfunktion, wenn du da diesen Winkel in einem verschränkten Zustand misst, einfach zwei Wurzel zwei ist. Also im Prinzip kann man sagen, na ja du testest einfach die Quantentheorie.
46. Aber der Puntk ist, dass gerade dieser Test, diese Bestätigung in dem Fall der Vorhesage der Quantentheorie, eine ganz klare Falsifizierung von basalen Aussagen über die zugrundeliegende Natur der Vorgänge dir liefert. Ja und das ist absolut, das ist absolut faszinierend. Ich persönlich finde jeder sollte solche Experimente machen. Experimente müssen so gestrickt sein, dass sie dir erlauben grundsätzliche… grundsätzlich dein Verständnis über die basalen Annahmen über die Natur zu liefern. So sollte jedes… jedes Grundlagenexperiment sollte so aufgebaut sein.

Reinhard

47. Also, dass du dann wieder unabhängig wirst von dem [meinte hier Interpretation] und vielleicht dann später, wenn du Ergebnisse vom Experiment hast, noch einmal dir anschauen kannst: Die Annahmen die du getroffen hast, bzw. die dann mit anderen Überlegungen in Einklang versuchst zu bringen.

Markus

48. Genau.

Reinhard

49. Von mir aus dann die Interpretation auszutauschen und schauen ob das noch immer irgendwie lebt.

Ziel: konsistente Weltanschauung

Markus

50. Weil was ist das ultimative Ziel? -- ist natürlich eine konsistente Weltanschauung zu entwickeln. Womit konsistent? Na mit dem Satz der Beobachtungen die du machst. Und damit musst du deine Beobachtungen gegenüber irgendetwas abgleichen. Das heißt im Prinzip was du da machst… Ich glaube das Bell'sche Theorem ist da ein gutes Beispiel. Du schaust eben was wären die Konsequenzen, wenn dein Weltbild das eines lokalen Realisten wäre. Und auf einmal merkst du, dass dann deine Erwartungen inkonsistent sind mit deinen Beobachtungen. Ich glaube das ist… Also wenn man es schafft, glaube ich, diese Offenheit gegenüber Interpretationen zu haben, dann hat man es geschafft. Damit ist man offen genug, dass man seine eigene Position immer wieder abklopfen kann.

Reinhard

51. Gibt es dann sowas, dass man trotzdem schauen will, dass es sozusagen nur eine konsistente, erklärbare Ansicht gibt? Und nicht eine multiple, die ich dann ziemlich gleichwertig austauschen kann?

Markus

52. Unbedingt. Ich glaube das ist wahrscheinlich eine ganz fundamentale Motivation für Grundlagenforschung, dass man glaubt, dass… Na, na wobei. Nehme ich wieder zurück.[Pause] Also ich denke schon das die Hoffnung ist, dass es eine richtige Weltanschauung gibt. Ja, wobei das jetzt nicht im Sinne eines naiven Realismus gemeint ist, sondern die Weltanschauung selbst kann auch wieder eine sein die Offenheit zulässt. Die zum Beispiel zulässt, dass es verschiedene Weltanschauungen gibt. Wobei jeder Jesuit dich jetzt wieder knüppeln würde, weil das schon wieder ein Widerspruch in sich ist.
53. Ja, das ist eine gute Frage. Also ich denke, dass zumindest eine implizite Annahme hinter, zumindest in der empirischen Wissenschaft, die ist, dass es ein Weltbild gibt, dass man letztlich herausschälen kann. Wobei ich betonen möchte, es muss vielleicht gar nicht der Fall sein. Also vielleicht ist Komplementarität durchaus etwas, was sich bis in die Epistemologie zieht. Komplementarität auch im Prinzip das sich auf Weltanschauungen anwenden lässt. Dass es verschiedene gleichwertige Beschreibungen gibt der Welt, die sich gegenseitig ausschließen, weil sie komplementäre Begriffe verwenden, aber sich auf ein und die selbe Natur beziehen, ein und das selbe Sein beziehen. Das mag sein.
54. Ganz naives Beispiel allein aus der Physik. Es gibt drei, vier verschiedene Arten letztlich Quantenelektrodynamik zu verstehen. Pfadintegrale ist einfach ein völlig anderer Zugang als avancierte und retartierte Momente, und so weiter.

Reinhard

55. Aber das wäre dann etwas das man nicht durch die Betrachtung von Theorien und Interpretationen irgendwie direkt herauslesen könnte? Die Frage ist welche Rolle das Experiment spielt? Was ich mich frage ist, warum es in letzter Zeit oder in den letzten zehn, zwanzig Jahren einen gewissen Zug gibt hin in Richtung, erstens des Experiments und dann auch in Richtung einer Anwendung, oder eines Umgehens sozusagen mit den Dingen? Weil, ich sage mal, erläutert und besprochen sind sie auf Interpretationsebene schon sehr lange.

Markus

56. Was?

Reinhard

57. Quantenmechanik.

Markus

58. Na ja. Besprochen, aber nicht verstanden.

Kann Experiment helfen?

Reinhard

59. Ja, das ist eben die Fragen ob jetzt das Experiment hier helfen kann?

Markus

60. Ich denke das Bell Theorem ist ja... Die Bell Experimente sind ja ein eindeutiger Beleg dafür, dass es kann. Wenn du ganz konkret eine große Klasse von möglichen Weltanschauungen ausschließt, nämlich die Klasse der lokal-realistischen Anschauungen.

Reinhard

61. Ja. Also da wären wir sozusagen wieder bei der Hoffnung hier im Ausschluß sich anzunähern.

Markus

62. Genau. Wobei natürlich man klar sagen muss, jedes Experiment, jeder experimentelle Aufbau definiert die Sprache in dem ich jetzt meine Beschreibung der Natur fasse. Also es kann durchaus sein, dass ich einfach... Also dass diese Rede von Komplementarität, das ist ja durchaus etwas das komplementäre Beobachtungszugänge mir... mir unterschiedliche Beschreibungen ein und der selben Realität liefern. Das kann durchaus sein. Aber wenn ich mein eigenes wähle, wie jetzt zum Beispiel die Quantentheorie, bzw. jetzt diese Art von Apparaten die ich verwende in der Quantenoptik zum Beispiel, dann, glaube ich, gibt es nur eine konsistente Beschreibung am Ende des Tages.

Reinhard

63. Ja. Und die sozusagen durch das Experiment...

Markus

64. Auf jeden Fall. Ja, ja. Wobei man dann natürlich... dann wieder den Zirkel gemacht haben und zurück sind beim logischen Positivismus. Dann ist das empiristische Sinnkriterium vielleicht durchaus etwas was selbst für die Metaphysik beginnt Bedeutung zu haben. Also dieser Begriff 'experimentelle Metaphysik', der ja von Abner Shimony geprägt worden ist, ist aus der Sicht des Wiener Kreises ja so ein gewisser [Pause] Widerspruch. Eine Quadratur des Kreises, sozusagen. Aber gleichzeitig könnte das auch die Auflösung sein zu dem Ganzen. Es wäre interessant mal so den Begriff experimentelle Metaphysik der Quine'schen Analyse gegenüber zu stellen.

Reinhard

65. Mmh. Ja. [nachdenkliches Schweigen]

Markus

66. Ich glaube das ist die große Leistung. Es gibt ja Leute die durchaus von der Kopernikanischen Wende, von der zweiten Kopernikanischen Wende sprechen, wenn sie über das Bell Theorem reden. Zum Beispiel der Bernard d'Espagnat. Weil hier tatsächlich in einem sehr einfachen Experiment eine ganze Klasse von Weltanschauungen eliminiert wird. Und der Witz ist eben, dass selbst wenn die Quantentheorie zusammenbrechen wird und das wird sie irgendwann... Selbst in einer Nachfolgetheorie der Quantentheorie kann diese Weltanschauung nicht wieder auftauchen, weil sie einfach inkonsistent ist mit dieser Klasse von Beobachtungen. Unabhängig welche Theorie dem Ganzen zugrundeliegt. Das ist das eigentlich faszinierende.

Reinhard

67. Das heißt man würde eigentlich auf was Neues hoffen um eine größere Konsistenz zu haben? Oder...

Markus

68. Na ja, sagen wir, um die jetztigen Interpretationsschwierigkeiten mit der Quantentheorie aus dem Weg zu räumen. Genau.

Reinhard

69. Das scheint nicht mit bestehenden Denkweisen und Mitteln möglich?

Markus

70. Solange wir noch so viele, wie soll ich sagen, phänomenologisch äquivalente Interpretationen haben, und damit meine ich solche die keinen offensichtlichen Widerspruch mit Beobachtungen generieren. Solange wir noch so viele phänomenologisch äquivalente Weltanschauungen haben, glaube ich, denken wir einfach noch fundamental falsch. Ich denke schon das es hier nur eine geben kann. Das heißt jetzt ist die Frage können wir über Experimente hier neues lernen. Wer weiß.

Reinhard

71. Ok, ja. Dass man das zumindestens auch als Mittel ausschöpfen kann um in diese Richtung zu gehen.

Inkompatibilitätstheoreme

Markus

72. Auf jeden Fall. Na, na, auf jeden Fall. Ich denke das... Ich fasse das immer so unter dem Stichwort 'Inkompatibilitätstheoreme' zusammen. Für mich ist das Bell'sche Theorem ein Inkompatibilitätstheorem. Es ist ein Theorem das letztlich mehr als zwei Aussagen, also in dem Fall sind es also drei Aussagen. Aussage 1: Die Vorhersagen der Quantentheorie sind korrekt. Aussage 2: Lokalitätsannahme. Aussage 3: Realismusannahme. Und gegeben das die erste Aussage korrekt ist, ist mindestens eine der beiden anderen falsch. Diese Inkompatibilität eines Satzes von Aussagen, wobei mindestens eine der Aussagen experimentell überprüfbar ist, das sind für mich Inkompatibilitätstheoreme. Da gehört das Bell Theorem dazu, das GHZ-Theorem, was Legett gemacht hat zu dieser Klasse von Nicht-lokal-realistischen Theorien. Und stehen wir noch am Anfang.
73. Also ich bin mir sicher wir werden Inkompatibilitätstheoreme auch in anderen Bereichen aufstellen können. Also ich denke eine ganz große Herausforderung für die nächsten Jahre wird jetzt sein, wie sieht es mit dem Verhältnis... unser Veständnis von Quantenphysik und Gravitation aus. Ich bin mir ganz sicher, dass hier die Grundannahmen, die da jeweils einfließen auch inkompatibel zueinander sind. Und die wird man in Inkompatibilitätstheoremen letztlich aufspüren.

Reinhard

74. Die dann wieder Experimente brauchen.

Markus

75. Ganz genau. Ganz genau. Ja, und da wird man Fundamentales über entweder Quantenphysik oder Gravitation, oder beides lernen. Da bin ich ganz fest davon überzeugt.

persönliche Motivation / Faszination

Reinhard

76. Und kann man das auch auf das Persönliche runter brechen?

Markus

77. Mein persönliches Inkompatibilitätstheorem? [lacht]

Reinhard

78. Nein. Das man auch persönlich am Experiment lernt oder an den Dingen?

Markus

79. Auf jeden Fall. Ich meine das ist die Aufgabe des... Ich meine das ist jetzt... Ich denke Grundlagenforschung rührt an einem zutiefst menschlichen und einem ganz basalen menschlichen Bedürfnis. Nämlich eine widerspruchfreie Auffassung der

alltäglichen Wahrnehmungen zu generieren. Also man möchte ein... Also menschliche Neugier dient dazu, dass man Dinge, die man erfährt wenn man beobachtet, einbettet in ein Weltbild. Und man lernt Neues um sein Weltbild dann anzupassen. Bzw. Neues ist normalerweise genau etwas was dann wieder leichte Anpassungen an sein eigenes Weltbild impliziert. Irgendwie was Neues ist überraschend für mich, also war es vorher nicht in meinem Weltbild drin. Das heißt ich werde das entsprechend anpassen.

80. Und ich glaube es ist ein fundamentales menschliches Bedürfnis, bzw. eigentlich sollte es eine fundamentale... es ist eine konstante Herausforderung eigentlich an den Menschen, dass er es schafft alle seine Erfahrungen in ein widerspruchsfreies Bild zu bringen. Ich finde das ist eine intellektuelle Herausforderung, eine emotionale Herausforderung. Ich habe das Glück, dass Teil davon mein Beruf ist. Aber ich denke das ist eine zutiefst persönliche Angelegenheit daran zu arbeiten. Weil es gibt nichts persönlicheres als ein widerspruchsfreies, zumindest ein widerspruchsarmes, Bild über die Welt zu generieren.

Reinhard

81. Und wäre das dann sozusagen auch deine persönliche Motivation speziell Quantenmechanik zu machen? Weil ja hier sozusagen die 'Herausforderung' relativ groß ist; sozusagen was sich dem entgegenstellt konsistent zu sein.

Markus

82. Gut, da spielt jetzt natürlich persönliche Faszination mit eine Rolle. Jeder hat seine eigenen Vorlieben und ich war schon immer von diesen Fragestellungen fasziniert. Jemand anders der auf einem anderen Gebiet forscht, ist von anderen Fragestellungen fasziniert. Also für mich muss ich sagen, ist es einfach ein, wie sagt man so schön, a perfect match. Und deswegen passt es. Aber ich glaube man sollte nur wirklich sich mit diesen Sachen, mit solchen Dingen beschäftigen, die einen wirklich berühren. Weil nur dann hat man den Pathos um wirklich was neues zu lernen.

Ende

Reinhard

83. Mmh.
84. Muss ich fast noch nachschauen.[schaue auf Zettel, ob ich noch eine Frage habe] Nein.

Markus

85. War's das schon?

Reinhard

86. Ja. Von meiner Seite aus wäre ich mit meinen Fragen fertig.

Markus

87. Super.

Reinhard

88. Danke für die Zeit.

Markus

89. Gerne, gerne.

(no speaker)

90. [small talk]

D Resume

DI(FH) Reinhard Stanzl

Date of Birth September 18, 1977

Nationality Austria

✉ reinhard.stanzl@gmx.at

Education

09/1987 – 05/1995 **Secondary School (Bundesrealgymnasium)**, *Bruck an der Leitha*.

Degree: Matriculation

Studies

09/1995 – 06/1999 **University of Applied Sciences Technikum Wien - Electronic Engineering [Fachhochschul-Studiengang Elektronik]**, *Vienna*.

Thesis: "Implementierung eines Koppelfeldalgorithmus mit einer VLIW-DSP-Architektur"

Degree: Graduate Engineer for Electronics [Diplom-Ingenieur für Elektronik (FH)]

03/2005 – **University of Vienna**, *Vienna*.

- Philosophy (Diploma Programme)

  Thesis: "On the Counter-Intuitiveness of Quantum Entanglement"
- Physics (Diploma Programme)

Professional Experience

05/2000 – 03/2005 **Frequentis Nachrichtentechnik GmbH**, *Vienna*.

Systems Engineer in the Business Segment 'TETRA' (TErrestrial Trunked RAdio)

Languages

German **Native Language**

English **Proficient**

French **Basic Knowledge**

E Abstract

E.1 Abstract (English)

There is a rather common dictum that quantum entanglement, a key feature of quantum mechanics, is counterintuitive. This assertion can be assigned not only to laypeople, but also to scientists engaged in quantum mechanics. How can we make sense of this?

I elaborate the issue based on four intertwined aspects: First, on a theoretical level by introducing the fundamental differences between classical physics and quantum mechanics. This is mainly carried out along the lines of the EPR thought experiment and the corresponding perspectives of Einstein et al. and Schrödinger. Second, on an experimental level by illustrating the counter-intuitiveness of quantum entanglement in the context of a specific field of research. Namely quantum opto-mechanics, and more particularly the experimental set-up of the research group *Quantum Foundations and Quantum Information on the Nano- and Microscale* at the University of Vienna. Third, on a personal level by utilizing my interviews conducted with members of this very research group. Fourth, on a philosophical level by exploiting key concepts of Gaston Bachelard's epistemology, such as epistemological profile or scientific reason being instructed by fabricated experience.

All of these four aspects are brought into contact to accomplish two tasks: On the one hand to flesh out the specifics and characteristics of counter-intuitiveness in the context of quantum entanglement. On the other hand to consider the question whether and how experimenting with quantum entanglement could assist in coping with its counter-intuitiveness, for example by familiarization. Overall, this thesis does not provide an in-depth analysis of these two main issues, but a plausible approach to and depiction of the subject matter.

E.2 Abstract (German)

Es gibt die verbreitete Aussage, dass Quantenverschränkung, ein Schlüsselkonzept in der Quantenmechanik, kontraintuitiv sei. Diese Behauptung kann aber nicht nur Laien zugeschrieben werden, sondern findet sich auch bei Wissenschaftlern der Quantenmechanik wieder. Wie können wir uns das verständlich machen?

Ich bearbeite dieses Thema auf Basis von vier miteinander verwobenen Gesichtspunkten: Erstens, auf einer theoretischen Ebene lege ich die hier relevanten Unterschiede zwischen der klassischen Physik und der Quantenmechanik vor. Dies geschieht hauptsächlich anhand des EPR Gedankenexperiments und den entsprechenden Standpunkten von Einstein et al. und Schrödinger. Zweitens, auf einer experimentellen Ebene veranschauliche ich die Kontraintuitivität der Quantenverschränkung im Zusammenhang mit einem spezifischen Forschungsfeld. Im Konkreten erfolgt dies anhand der Quanten-Optomechanik, genauer der Experimente der Forschungsgruppe *Quantum Foundations and Quantum Information on the Nano- and Microscale* der Universität Wien. Drittens, auf einer persönlichen Ebene werte ich meine Interviews mit den Mitgliedern ebendieser Forschungsgruppe aus. Viertens, auf einer philosophischen Ebene mache ich mir Schlüsselkonzepte von Gaston Bachelards Epistemologie zunutze, wie zum Beispiel das epistemologische Profil oder einer durch Erfahrung belehrten Vernunft.

Alle diese vier Aspekte werden zusammengenommen um zwei Aufgaben zu erfüllen: Einerseits die Konkretisierung der Besonderheiten und Merkmale der Kontraintuitivität im Kontext der Quantenverschränkung. Andererseits die Betrachtung der Frage ob und wie das Experimentieren mit Quantenverschränkung den Umgang mit dessen Kontraintuitivität erleichtert, zum Beispiel durch Gewöhnung. Im Großen und Ganzen stellt die Diplomarbeit keine tiefgreifende Analyse dieser beiden Themen zur Verfügung, sondern liefert eine plausible Annäherung an das Problem.