Quantum Mechanics – the dream stuff is made of (Part 1)

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Quantum mechanics builds today together with the general theory of relativity the cornerstone of theoretical physics. The predictions of this theory have been confirmed in countless experiments with an almost fantastic accuracy, enabling technologies such as lasers, solar cells and transistors as building blocks of modern computers. This remarkable empirical success contrasts however with the equally remarkable fact that this theory has not found a generally accepted interpretation – almost 100 years after its final formulation we still don't know how to interpret it physically. But one thing seems certain: our usual "classical" understanding of nature will have to be completely revised in light of the phenomena of the quantum world.

Since I have been interested in this topic for quite some time and am still fascinated about new contributions, I decided to make an attempt to highlight the special properties of the quantum world as clearly as possible and to gather the strengths and weaknesses of the current interpretations. I am confident that the amazing – if not downright shocking! – behavior of this world can be illustrated also for readers without physical knowledge and I want to enable them (that is you) to come to an own point of view in the current interpretation debate. This essay in three parts is the result of these efforts, for which I took advantage of many books and articles on this subject. The main sources are referenced at the end of the second part.

- Part One: The Puzzles of Quantum Mechanics
- Part Two: The Interpretations of Quantum Mechanics
- Part Three: The Transactional Interpretation

This much may already be revealed: every single interpretation attempt will turn out as so weird and unsatisfying, each in its own way, that the statement of Niels Bohr, one of the founding fathers of quantum mechanics, has not lost any of its relevance: "Anyone who is not shocked by quantum theory has not understood it."

Let the shocking discovery journey begin...

The story of quantum mechanics is a good example how certain properties of nature *force* their way into the physical description and how they resist any attempt to be integrated into a familiar world view. A small excursion into the history of this theory is therefore very rewarding, even if it is not absolutely necessary for the understanding of the other sections.

The story begins with an act of desperation. The fact that hot materials such as wrought iron radiate a temperature-dependent light from glowing red to glaring white is a well-known phenomenon, but it resisted all attempts of a detailed explanation at the end of the 19th century. The solution to this problem was provided in 1900 by Max Planck, who was told during his education that physics is substantially completed and has already made all basic discoveries. For his own annoyance, he succeeded only with a highly unusual assumption that contradicts with the two major theories of his time, Electrodynamics and Newton's laws: the electrons don't deliver their energy continuously, but rather "intermittently". The electrons would thus vibrate a long time without any loss of energy and would then, without apparent external influence, instantaneously emit a certain amount of energy. The amount is not arbitrary, it corresponds to the product of the frequency and a newfound constant h, which is now known as Planck's constant. Under this assumption, the observed frequency response was exactly reproducible.

Despite this discovery, his contemporaries and also Planck himself continued to believe that nature develops constantly. They searched desperately for an alternative solution without the "damned quantum jumping", as Planck put it. The next setback for classical physics came however five years later from a third-class Swiss patent officer...

In 1905, Albert Einstein published not only a proof for the existence of atoms and the complete version of the special theory of relativity, but also a basic building block of quantum mechanics, for which he later received the physics Nobel Prize. He analyzed how light is able to release electrons from metallic materials, which is called "photoelectric effect". This was a very puzzling phenomenon because the effect occurs even for small light intensities – electrons can normally only be separated by very high temperatures or strong electric fields. It turned also out that the energies of these electrons depend on the frequency of the light and not as expected on its amplitude (intensity).

But what would be, Einstein thought, if light does not propagate continuously and spherically, but is instead concentrated in fixed "packages" whose energy is as large as the energy jumps postulated by Planck? These packages could transfer their entire energy to a single electron. The energy of this electron would then be proportional to the light frequency with the proportionality factor *h,* Planck's quantum of action. It took 10 years for a detailed experimental verification – which showed a complete success for this theory! Nowadays the light packets are called *photons* and every solar cell and digital camera relies on this effect.

Even many years after this insight, Einstein was interestingly the only one who took the particle nature of light seriously[1]. After all, everyone *knew* since the 17th century that light propagates like a wave, how could it simultaneously behave like a particle? Einstein had no concrete answer to this question, but he realized that this mystery is a part of nature that we can't ignore. He would be stunned if he knew how this question is answered today, more

[1] Max Planck wrote for example in his Nobel Prize nomination for Einstein: "That he might sometimes have overshot the target in his speculations, for example in his light quantum hypothesis, should not be counted against him too much."

than a hundred years later: *we still don't know.* The quantum mechanical riddle, which will be discussed in greater detail later on, showed up for the first time.

Figure 2: The heroes of quantum mechanics - Max Planck, Albert Einstein, Niels Bohr, Louis de Broglie, Erwin Schrödinger, Werner Heisenberg.

The next chapter in the history of quantum mechanics was opened in 1913 by Niels Bohr. It was already assumed that atoms consist of a compact core orbited by electrons. Since electrons are electrically charged, they should however constantly loose energy via radiation and therefore fall into the core in a very short time. Bohr "solved" this problem by an ad hoc assumption: the torque is quantized, i.e. it exists only in multiples of a finite amount. As a result, only certain electron orbits are allowed, in particular a minimum one, which explains the stability of atoms. The truly remarkable fact about this trick was a direct derivation of this theory: it allowed the exact calculation of the energy spectrum of the hydrogen atom and could therefore accurately reproduce the characteristic frequencies of light emitted by such an atom in excited states, which was by then completely inexplicable.

Ten years later, Bohr's assumption turned out as a result of an even more fundamental concept. If light can behave like a wave and like a particle, couldn't then electrons or atoms also show wave properties? This revolutionary and at the same time strikingly simple idea led Louis de Broglie to a physical explanation of the Bohr electron orbits: Similar to the vibrations of a violin string, such orbits can only contain whole multiples of a fixed wavelength, which is the wavelength of the electron. With this model, De Broglie could accurately deduce the relations discovered by Bohr. The wave character is normally hidden, because the wavelength for large particles is very small[2], but a few years later, de Broglie's assumption was also confirmed experimentally: an electron beam guided through a thin metal film showed the same interference pattern as light or water waves! Nowadays, this trick can be performed for large atoms and even molecules.

In 1926, the search for a mathematical quantum theory came to an end. Erwin Schrödinger and at the same time the Bohr-student Werner Heisenberg discovered the wave equation, now called *Schrödinger equation*[3], that forms the basis of the theory of quantum mechanics. It explains all of the phenomena described above and also in the countless experiments and practical applications that have been conducted since that time, *not one* of their predictions proved to be wrong.

[2] More specifically, it is inversely proportional to the momentum of the particle, i.e. the product of mass and velocity. This relationship and the small wavelength of electrons is the basis of the later-developed electron microscopes.

[3] Heisenberg used a different mathematical formalism which turned out to be equivalent to the Schrödinger formalism.

This theory is not only exact, but also universal: as a limiting case for large objects, it contains the complete classical mechanics, and its application to quantized fields[4] results in the theories of electrodynamics and special relativity! If you are familiar with mathematical concepts such as vectors, eigenvalues and operators, the complete formalism can also be summarized on a single DIN-A4 page. Nobody could explain until now *why* physical theories such as quantum mechanics, relativity theory or even the classical Newtonian mechanics can be so successful in their respective scope, i.e. why the world is so "simple" that their basic causal mechanisms can be described by a few mathematical relations. This insight seems to me even more amazing and remarkable then the phenomena of the quantum world.

A fundamental flaw of today's physical description of nature should however not be concealed: the *general* theory of relativity, which has also passed all tests in its scope without the slightest deviation, can not be reconciled with quantum mechanics. Their unification into a single fundamental theory, which is currently pushed forward through highly complex mathematical constructs[5], is the holy grail of theoretical physics. We don't know yet if this search will ever be successful.

At this point, the obvious question is why you have to worry about the interpretation of quantum mechanics when this theory is maybe later replaced by another, even more fundamental theory with possibly completely different properties. This objection occurs very often in discussions of quantum mechanics. The answer to this question may be surprising and is a central part of this essay: even when such a "Theory of Everything" would be found, it could not resolve the interpretation issue. As we will see soon, the fundamental mystery shows already up in the quantum mechanical *phenomena* independent of any theory.

[4] These so-called quantum field theories take the creation and annihilation of elementary particles into account and are based on the fact that not only particles, but also force fields are quantized. I won't discuss these theories further in this article, because they are not conceptually different from quantum mechanics.

[5] There are currently mainly two rival approaches discussed, superstrings and loop quantum gravity.

Incompatible Properties and the Role of Chance

We now leave the historical perspective and jump straight into the description and interpretation of some pioneering experiments. It will require a bit of patience, but in the end the reader will hopefully get an idea about the mystery and strangeness of the quantum mechanical world. Perhaps – and I would see this as a great success of this essay – he or she will feel the same as the great Albert Einstein: "It was as if the ground had been pulled out from under one, with no firm foundation to be seen anywhere, upon which one could have built.”

We start with an electron with the two properties hardness (hard / soft) and color (black / white). Of course, these are not actual physical properties of elementary particles, but the terms are helpful for explaining the following experiments, which have been carried out in recent decades with respect to properties such as position or pulse. No "medium-hard" or "gray" electron has ever been found in these experiments, which corresponds to the discovery of Max Planck that for certain properties only quantized, i.e. discrete values, are allowed.

First of all, we need appropriate instruments to measure the two properties. We will use "test boxes" for this task as shown in Figure 3. The electron leaves the box via exit h for hard or s for soft or b for black or w for white when it has the respective property.

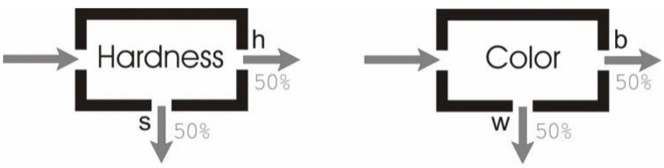


Figure 3: Measurement of the properties of hardness and color.

Let us now consider a group of electrons with equally distributed characteristics, such that we get a 50-to-50-distribution of the respective property when we measure the hardness or the color (see Figure 3).

To make sure that the measuring boxes fulfill their function and that the properties are not changed on the way between them, an additional measurement can be performed directly after the first measurement. All electrons found as hard should then leave the second measurement box by the output h, the same applies for the other properties. The corresponding experiment (see Figure 4 left) actually shows the expected result.

An interesting question is also whether there are correlations between the two properties. As an example, all hard electrons could also be black. This can be verified with the experimental setup of Figure 4 right. As you can see, there are no such correlations in our example: the 50-to-50 ratio with respect to color results regardless of the hardness and vice versa.

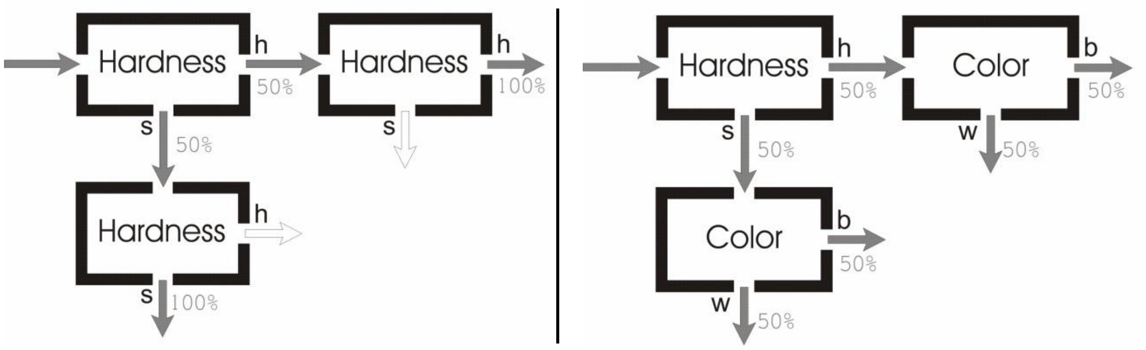


Figure 4: Check if the measured properties change between the measurement boxes (left) or if correlations are present (right).

So far, so good. What would be expected when the electrons leaving the last experimental arrangement are re-examined with respect to their hardness? Correct, 100% of the electrons found as hard by the first box should take the output h as shown in Figure 4 top left. This is however *not* what happens in the real experiments. Figure 5 shows a completely different result: only half of the electrons previously measured as hard are now measured as hard, the other half is measured as soft! After the preliminary consistency checks for this experiment, this result should be impossible.

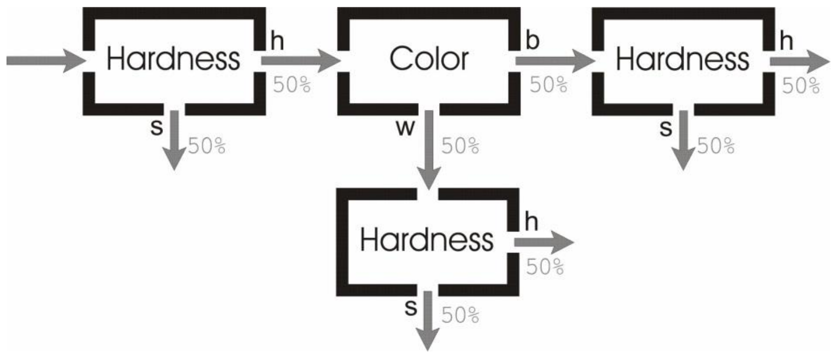


Figure 5: After a color measurement of hard electrons, only half of the electrons are measured as hard.

Maybe the measurement was performed wrongly? But whichever device was chosen in the real experiments, that were performed for single as well as for many electrons, the distribution was always very close to 50-to-50 and never even close to 100-to-0. It seems therefore that these experiments show a strange behavior of the electrons themselves. Two basic characteristics of the microscopic world described by quantum mechanics are indeed already visible in this simple experiment: the uncertainty principle and the inevitable role of chance. It is worthwhile to take a closer look.

In the experiment of Figure 5, the measurement of the color property obviously leads to a "smearing" of the hardness property. This fact is reflected in the famous Heisenberg uncertainty principle: some properties, in the example above the hardness and color of the electron, are incompatible witch each other – they can't be determined exactly at the same time.

The product of the uncertainties for the position and momentum of an electron is for example even under ideal conditions always greater than Planck's constant. Two other incompatible properties are energy and time. This discovery is of fundamental importance, because the physicists are confronted for the first time with *fundamental* limits for an exact description of nature which are not determined by improvable measuring instruments but by nature itself. A hard blow!

A special role is played by chance. Half of the electrons are recognized as hard in the experiment of Figure 5 according to the second hardness measurement and the other half as soft. But which factors decide if a single electron leaves the measuring box at h or s at the end? This decision can't be derived by the two properties of the electron, since all electrons have been detected as hard and black before this measurement. There were however no other properties found in these kinds of experiments that would influence the measurement outcome. The result for a single electron is therefore obviously undetermined and absolutely random! This is another severe blow for trying to accurately describe and predict the natural phenomena.

These two discoveries are not only very remarkable, they are also in direct contradiction to the previously known physical theories such as Newtonian mechanics, electrodynamics and the theory of relativity. But it gets even stranger.

Superimposed States

Another experiment. Suppose an electron source, a device detecting the emitted electrons (for example a screen with a fluorescent layer that emits light for each incident electron), and in between a wall that is impermeable to the electrons except two narrow slits. The question is: which distribution of electrons will be visible on the detector screen?

For getting an indication of the expected result, the experiment can firstly be carried out with only one slit, for example by covering one of the slits. The result is shown in Figure 6.

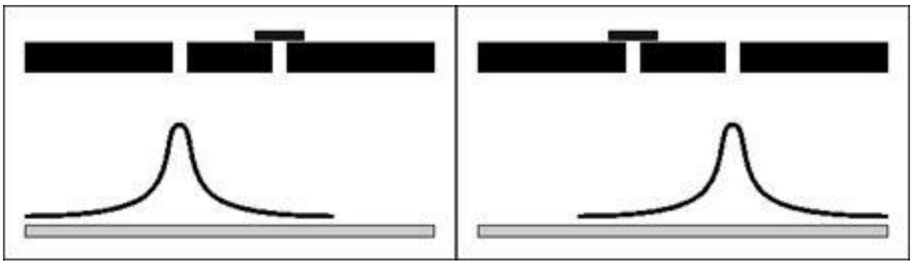


Figure 6: Distribution of electrons after single slits. The electrons pass from the top through the intermediate wall, i.e. through one of the slits, and end up on the detector screen. The detected frequency distribution is shown as a curve.

As you can see, in both cases a characteristic frequency distribution of electrons arise at a point that is - not surprisingly - located directly behind the respective open slit. We now have a good idea of the expected output of this experiment: since each electron can reach the screen either via slit A or via slit B, the distribution should be as shown in Figure 7 left.

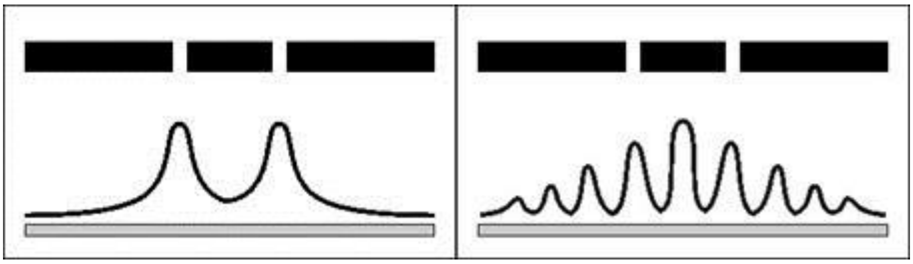


Figure 7: Expected (left) and actual distribution (right)
of the electrons in the double slit experiment.

In fact, the actually carried out experiments showed a *completely different* picture. Most of the electrons are registered at a point exactly in the middle of the original maxima, see Figure 7 right. There are also regions behind the slits that are never hit by an electron.

This result is not easy to understand. It seems that the electrons influence each other after passing the slits in a way that creates this pattern. The weird part is the fact that the same pattern occurs when the electron current is adjusted to emit only *a single electron* at a time and the results are summed up over time, and also when the results of 1000 experimental setups of this kind with only one electron per setup are brought together into one graph! How could a single electron passing through a slit "know" that there is another open (and from its view far-off) slit, i.e. how could its trajectory be influenced by that fact in any way?

One could almost doubt the outcome, but Figure 8 shows real images of such an experiment, which has been performed countless times in different forms since and each time led to the same result.

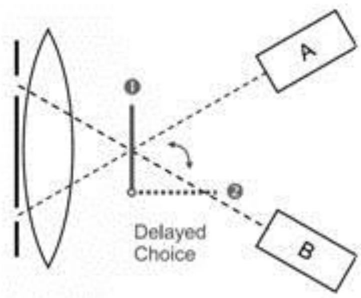
Figure 8: Images from a real experiment in which only single electrons pass the wall,
left after passage of 28 electrons, then after 1000 and finally after 10,000.

The finding of this experimental arrangement allows for only one conclusion: the natural assumption that the electron reaches the screen through slit A *or* slit B must surprisingly be wrong. On the other side, it is also not possible for the electron to pass through both slits - the screen is always hit by a complete electron and a "half-electron" has never been observed, even in any other setup. In summary, the path of the electron leads neither through slit A, nor through slit B, nor through both slits and also not through none of the two slits. And that's really weird, because these are *all* logical possibilities for the passage of the wall.

A scientific term for this phenomenon was quickly found. It is said that the electron is in a state of "superposition" which is composed of the two individual states (only slit A or only slit B open). What this phenomenon of superposition *means* is however still an open question, this is a central part of the quantum mechanical riddle.

Let's see this experiment from a different perspective. If electrons could be interpreted as waves, the pattern would be explainable as interference effects as known for light or water waves. As point on the screen and in many other experiments the electron shows itself however clearly as a particle, which is a fundamentally different type of physical description. This combination of two mutually incompatible properties has come to be known as "wave-particle duality"[6]. It depends on the choice of the experiment, i.e. on the *question* posed for the experimental arrangement, whether the electron shows itself as a wave or as a particle.

This last point is of central importance. It becomes especially clear in the following actually carried out experimental arrangement. The objective is to "catch" the electron when it passes through a slit. This shall be achieved by detectors that are placed directly in front of the two slits, for example by an irradiation of low-energy photons that are deflected by the electron without significantly disturbing it. By this means it can always be shown if the electron passes slit A or slit B. The remarkable thing is that the interference pattern shown in Figure 7 on the right *vanishes* in all of these experiments! All attempts lead to the pattern of Figure 7 on the left, even with the most clever setups to further reduce the influence on the electron by the measurement[7]. Only if we principally can't know which slit was passed by the electron, the interference pattern appears.



The highlight for these kinds of experiments is outlined left. When the detector screen is in position 1, we have the same experiment and thus the same interference pattern as in Figure 7 right. When the screen is removed by setting it into position 2, the direction detectors A and B demonstrate whether the electron has passed through the upper *or* the lower slit, respectively. In this case the interference pattern disappears, even when the screen is switched into position 2 by a quick electronic circuit *after the electron has passed the wall*! This experiment shows that even after the passage of wall, the electron does not *have* the wave or particle characteristic, it *gets* the respective property only by the choice of the measurement[8]. A discovery that is admittedly hard to believe and also hard to understand.

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[6] The wave-particle duality is often described as *the* basic problem of quantum mechanics, which is not quite correct. There are systems consisting of more than one particle that show superposition effects which can't be derived from the assumed wave nature of particles.

[7] Particularly impressive is a recent double-slit experiment in which the interference effect was demonstrated for whole atoms, more specifically rubidium atoms. The atoms going through one of the two slits were then "marked" by exciting one of their outer electrons. The interference pattern disappeared instantly at that moment, even though the path of the rubidium atoms is completely determined by its core which is over 100,000 times heavier than an electron.

[8] An example may help: Suppose that the screen was in position 2 and detector A detected a passage through the lower slit. Could the electron have been in the state "particle through the lower slit" before this measurement? No, it can't, because we

These findings also throw a different light on the interpretation of the first experiment. After measuring the color, it turned out to be impossible to predict the hardness of the electron, even if it was previously identified as hard or soft. The implicit assumption for this already strange behavior was of course that the electron *has* either the properties hard or soft after the color measurement, which is just made visible by the subsequent hardness measurement. As the double slit experiment however demonstrates, this assumption is wrong. The electron is rather in a superposition of the states hard and soft (both slits open), which is as seen above *in physically verifiable manner* different to the state hard or soft (only slit A or slit B open). In the last hardness measurement, this state is therefore *changed* to the "normal" (classical) states hard or soft, analogously to the deletion of the interference pattern by the location measurement of the electrons. This "side effect" of measurements to transform superposition states into classical states, called "state reduction", is a key characteristic of the quantum mechanical world.

Another important conclusion concerns the previously mentioned uncertainty principle and the role of chance. From the first experiment alone, you could still accept (and indeed one quite often encounters this misconception) that the properties (in this case "hardness" and "color") can't be measured simultaneously because each measurement causes unreducible *disturbances* of the system. The findings from the double slit experiments show however that superpositions are present before the measurement, i.e. the uncertainty is not carried into the system by disturbances, but is an objective part of it – the properties *are* blurred. The role of chance gets also an objective meaning. A measurement on a single particle informs us not only about an already existing result (the usual type of subjective ignorance of the actual state), the system rather *is* undetermined regarding the measurement outcome, it still holds all possibilities for the different measurement results.

Let us pause briefly. Did these remarks sound as if the properties of a quantum system were not even *real* before their measurement, but would only come into existence by this process, that is through the conscious choice of the experimenter what question he poses on the system? There is indeed no easy way to escape this conclusion. Many of the currently discussed interpretations raise the old question "Does the moon exist if we don't watch it?".

The strangeness of quantum mechanical superposition states becomes particularly clear in a prominent thought experiment, which will be presented next. It also shows that the curiosities of the quantum world are not limited to microscopic systems.

could have just as well decided to measure the wave character (screen in position 1), which result can't be explained by this particle state. Even after the passage through the slits, the electron thus still holds both (mutually exclusive!) possibilities.

Wanted - Dead and Alive

The thought experiment devised by Erwin Schrödinger works as follows[9]: a hermetically sealed container contains a living cat, an unstable radioactive atom that will decompose with a probability of 50 percent within the next hour, and a device that kills the cat by releasing a deadly poison in this case (as I said, just a thought experiment!).

Figure 9: Schrödinger's cat.

How does this system develop? According to the insights in the previous sections and also according to the prediction of the mathematical theory of quantum mechanics, the state of the atom will be a superposition of the states “decomposed” and “not decomposed” after one hour. By the conditions of the experiment, the cat would however also be in a superposition state, it would be neither dead nor alive!

An obviously absurd result. It is nevertheless very difficult to find a way out of this dilemma if one does not introduce the ad hoc assumption that quantum mechanical effects are limited to microscopic particles. It is for example tempting to see the cat itself as a measuring instrument, by which the superposition applies to the atom, but not to the cat. There is however no physical reason for this assumption and it is not clear where exactly the boundary between "pure" quantum mechanical systems and measuring devices lies.

Similar experiments in which quantum mechanical effects are amplified to a macroscopic level can nowadays actually be carried out, for example with superconducting magnets playing the role of the cat [10]. The superposition phenomena can also be seen at this level. Even nowadays, it is not clear what lessons can be learned from these experiments and how the apparently absurd result of the neither dead nor living cat can be avoided. The thought ex-

[9] Schrödinger wanted actually to unmask the paradoxical nature of quantum mechanics by this argument. His own attempt to explain the outcome of the double slit experiment in a classical manner with the help of so-called "guide waves" was however not successful.

[10] An especially remarkable double-slit experiment by the group of the Viennese physicist Anton Zeilinger is the detection of interference effects for fullerenes – spherical molecules of not less than 60 carbon atoms consisting of over 1000 elementary particles (protons, neutrons and electrons). Even in this experiment, each molecule only interfered with itself. The entanglement effect of two-particle systems could even be extended over several kilometers!

periment can be extended even further: if quantum mechanics is universally valid, an observer who opens the box for checking the condition of the cat must also be in a superposition state consisting of the states "I see a live cat" and "I see a dead cat" – an indescribably strange state of mind that directly contradicts our personal introspection. Or is it maybe exactly this human consciousness that holds the secret key for the materialization of the states!? A highly speculative but fascinating thought.

Once again: this thought experiment does claim to convince us that cats can be simultaneously dead and alive. But it illustrates the strangeness of the quantum world and enforces at the same time an answer to the question why the objects of our everyday world behave quite differently despite the fact that they are composed of microscopic systems.

Faraway, so close

It may seem impossible, but the quantum world has yet another impressive property to show. The following third and final experiment reveals that the state reduction can be enforced by a measurement without delay *at any remote location.*

A Two-Particle Experiment

For this experiment, we need a system of two electrons whose properties are again referred as "black" and "white" for the sake of simplicity. This system is prepared in a way that the colors of the two electrons are always different. Thus it has exactly two possible states, labeled A (electron 1 is white, 2 electron is black) and B (electron 1 is black, electron 2 is white). Similar to the double-slit experiment we now prepare a system state consisting of a superposition of the states A and B. As long as no interaction takes place with the environment, this state remains unchanged when the two electrons fly away from each other at a constant speed, which shall be assumed for this experiment. What result can be expected when the two electrons are then separately measured regarding their color? Figure 10 shows an analogous experimental setup for two photons whose polarization directions are measured.

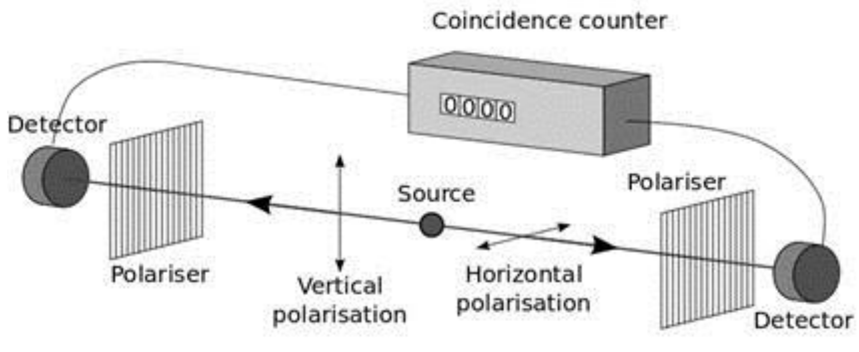

Figure 10: Measurement of a two-particle system.

With the knowledge that we have gained from the first two experiments, the outcome can already be predicted. A measurement of electron 1 will in half of the cases show the result "white" and in the other half the result "black". Consider for example the first case, i.e. electron 1 is white. Due to the expected characteristics of the overall system, electron 2 can then only be black. A subsequent measurement of this electron, even if it is already carried out immediately after the measurement of the first electron, would therefore always show the state "black". This result, which can be actually observed, does at first sight not sound unusual, as we only found out via the measurement of electron 1 that the case A is present (white electron 1, black electron 2). The crucial point is however, that the entire system is not in state A before the measurement, but instead in the superposition state of A and B, which is – as the double-slit experiment shows – physically different from state A. The measurement of electron 1 must therefore have led to a physical change of the state of the other electron.

There is yet another argument for this important point which is independent of the double-slit experiment. The initial state can also be prepared to a superposition that consists of the states black and white as well as the states hard and soft. When the experimenter then chooses a hardness measurement and detects a hard electron, the other electron turned always out as soft, whereas its color has still a 50-to-50-distribution. Since only the experimenter decides which of the two properties he wants to measure, the second electron could not have been in the soft state before the first measurement.

The amazing part of this conclusion is the fact that the location of the electrons at the time of measurement plays no role at all. If you wait long enough (the distance of the electrons grows steadily in this experiment), the second electron can therefore be arbitrarily far away despite the instantaneous reduction of the states! This connection of two systems that goes beyond any spatiotemporal description is probably the most puzzling property of the quantum mechanical world. It is called "entanglement".

This phenomenon is by no means limited to microscopic scales. In a famous experiment, the effect has been demonstrated in 2007 (and in an improved form in 2010) for entangled photon pairs with one half on the Canary Island of La Palma and the other half 144km away on the island of Tenerife! The two photons were measured simultaneously in a way that was randomly chosen at the last moment in order to avoid any communication or predestination. The subsequent analysis of the measurements nevertheless clearly showed correlations. When for example the polarization direction of a photon was measured with respect to a (randomly selected) plane, the other photon showed *always* the complementary direction with respect to this plane. This property of the photon could not have been present before the measurement: we remember the measurable difference between classical and superposition states, and additionally the polarization plane was selected immediately before the measurement. Since the experimental design doesn’t allow any communication between the two photons, the outcome of this experiment should be completely impossible according to classical and relativistic physics.

It is therefore no coincidence that it was the founder of the theory of relativity who vehemently opposed against this change of the common world view in the 30s.

The Einstein - Bohr Debate

For Albert Einstein, the idea of such "spooky action at a distance" (as he called it) traveling faster than the speed of light was simply unacceptable[11]. He published the following train of thought together with two colleagues, which became known as the Einstein-Podolsky-Rosen argument: assuming that two systems, say two electrons, are completely separated from each other, so that the manipulation of one will not affect the other one, the above described experiment still allows a 100% prediction for the measurement outcome of the second electron after the measurement of the first one without mutual influence. Einstein saw this as a sufficient criterion for the presence, i.e. existence, of the corresponding electron property before the measurement. Since the theory of quantum mechanics denies this existence before the measurement (it originates through the measurement-induced state reduction), Einstein concluded that this theory is incomplete.

Niels Bohr replied to this argument immediately. It was for him never the task of a physical theory to make statements about any properties prior to their measurement. The results of the measurements are completely described by quantum mechanics, which makes it a complete theory.

Einstein was not convinced by this answer. For a long time it looked just as a philosophical matter of taste, which point of view of the two great minds should be favored. It came therefore as a big surprise 10 years after Einstein's death that a theorem was found that allows an experimental inspection of his classical world view – with a clear result!

Bell's Inequality

Einstein had the hope that the quantum mechanical phenomena can someday be explained by a local mechanism without superluminal actions at a distance. For the experiment described above, locality means that the correlations between the two electrons are created exclusively at the source, which is of course a very natural assumption. The Northern Irish physicist John Bell rose however the question what could be said about *any* local mechanism that is able to reproduce the experimentally determined correlations between remote systems. He defined a statistical measure S for the degree of correlations and could mathematically derive that such classical mechanisms always result in a value of $S \leq 2$. This relationship is in itself not remarkable. To his surprise, he found however out that the theory of quantum mechanics allows values up to $S = 2 \cdot \sqrt{2} \approx 2.8284$ for certain experimental setups and thus a violation of this inequality. This theory makes therefore a prediction that can't be reproduced with *any* of the local mechanisms – Bell had uncovered a fundamental, experimentally verifiable contradiction between quantum mechanical and the classical world view.

It took another 15 years to actually determine this size S experimentally. The best-known experiments were performed by Alain Aspect and his team in 1982, who measured the polarization state of two photons that were far enough apart to exclude mutual influences by fast

[11] Einstein completely recognized the empirical success of quantum mechanics, to which he had himself contributed. But he never gave up the hope that this theory might one day be replaced by another, more fundamental theory, without instantaneous long-range effects and intrinsic random elements.

local effects. The result[12] was a clear violation of Bell's inequality and a complete success for quantum mechanics!

As nowadays unanimously recognized, there is thus no hope of ever being able to explain the observed quantum correlations by a classical theory with local actions.

Quantum Holism and Superluminal Velocity

Bell's theorem shows that even widely separated particles can be connected in a manner that is inexplicable to classical physics. The measurement of one particle has an instantaneous effect on the overall system, just as if this system is not resolvable into individual components but could only be seen as a whole. This "quantum holism" became a frequently cited characteristic of quantum mechanics. It provides evidence that the popular saying "everything is connected with everything" is actually true. As an important limitation, this phenomenon occurs however only for specially prepared systems[13] that must also be protected from any external influence. The interaction with one single photon may be enough to destroy the effect. For these special systems, the holism-term seems however not inappropriate.

But back again to the instantaneous effect of the measurement. Does this not contradict the theory of relativity which states that nothing propagates faster than light? The answer is a clear no, at least regarding the observable phenomena: the measurement-induced state reduction can't serve as a *signal,* i.e. it can't transmit information to the other electron, and only signals are limited by the speed of light. The measurement of electron 2 – no matter which property actually appears – does not indicate by itself whether electron 1 has already been measured. Only a subsequent evaluation can show if the measurement results were correlated. For the interpretation of quantum mechanics, the finite signal speed is however a major obstacle, because the measurements show that the correlations arise over long distances without the slightest delay.

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[12] For the chosen experimental setup, the theory of quantum mechanics predicted a measure of 2.70, while the classical limit is 2.0. The measured value was $S = 2.697 \pm 0.015$.

[13] One often encounters the argument that all particles of the universe must have been in contact and are thus synchronized with each other due to the Big Bang model. The current cosmological models do however not support this assumption, since the universe is not seen as a point after the Planck time, but rather as a space-like (probably even indefinitely large) hypersurface of our four-dimensional spacetime.

An Interim Conclusion

What can we finally say about the strange behavior of the world of elementary particles? As hopefully became clear, the described phenomena were not simply taken from a given theory, for which we could assume that it will eventually be replaced by a more "reasonable" theory at some day. They are rather experimentally detectable properties of nature itself. This quantum mechanical world, that is not even limited to sub-atomic systems, turned out as so strange that it has resisted any attempt to be explained by at least reasonably familiar thought patterns. Quantum mechanics is not only counter-intuitive – which it has in common with the theory of relativity and many other physical theories – but represents a real revolution that calls fundamental assumptions into doubt such as exact measurability, determinism, continuous spatio-temporal interactions and even the reality of the world itself.

Nevertheless, the situation is not hopeless. In the second part of this essay I will outline the highly successful theory of quantum mechanics and the most prominent approaches for its interpretation. Their suggested world views will however turn out to be just as fantastic as the phenomena itself. There is thus no other option in sight: our current view of the world – no matter how accustomed we become to it – will have to change radically. It will be interesting to see how these changes could look like. To say it with T.S. Eliot:

Not fare well, but fare forward, voyagers!