Quantum Mechanics – the dream stuff is made of (Part 2)

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In the first part of this essay I have tried to give an insight into the strange, if not even mystifying, properties of the quantum mechanical world. In this second part I want to present the attempts to capture these phenomena mathematically and to find a generally accepted interpretation for them, that is a physical explanation. It will become clear that the first part of this task can be seen as completed and the second as completely open. There are many different interpretations of quantum mechanics by today which have only one point in common: they are at least as fantastic as the quantum mechanical effects they attempt to explain.

We begin therefore with the things that we already know quite well.

1. The Theory of Quantum Mechanics

Quantum mechanics, discovered almost 100 years ago by Erwin Schrödinger and Werner Heisenberg, is a most elegant theory. For capturing this elegance in its entirety, an understanding of some mathematical elements such as vector space, eigenvalue or operator is however indispensable. These concepts are not overly difficult (the underlying linear algebra is often already part of school mathematics), but their explanation is beyond the scope of this essay. Interested readers are referred to one of the many good books on this subject. The essential features of the theory of quantum mechanics can nevertheless be outlined without mathematical formalism, as I will try in the following. Curtain up for the perhaps most successful physical theory ever invented!

Quantum mechanics has three components:

Q1: The state of a quantum system is completely described by its location- and time-dependent wave function[1] Ψ.

Example: hydrogen atom
As a very rough picture of the wave function of an electron orbiting a proton, Ψ can be thought of as a (in this case time-constant) cloud around the nucleus, in which the position of the electron is smeared.

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[1] This function has values from the field of complex numbers, which are an extension of the real numbers for solving the equation $x^2 + 1 = 0$. For this purpose, a new number i is introduced with the property $i^2 = -1$. These numbers are neither more nor or less "real" than real or natural numbers, they are just very well suited for the compact formulation of mathematical structures.

Q2: The time evolution of the wave function follows a time-symmetric, linear and deterministic law, the *Schrödinger equation*[2].

Remarks:

- Time-symmetric means that no direction of time is preferred.
- Linear: when Ψ_1 and Ψ_2 are solutions of the same Schrödinger equation, then their sum $\Psi_1 + \Psi_2$ is also a solution of the Schrödinger equation.
- Deterministic: the total time evolution is uniquely determined if the state and the external conditions are known at any point of time.

Q3: Classical states with concrete measurable (observable) values are only a subset of all possible quantum mechanical states. When measured, the system "jumps" into one of these classical states with a probability given by the absolute value of the wave function[3].

Example hydrogen atom:
The probability of finding the electron at position **r** after a measurement is $|\Psi(\mathbf{r})|^2$.

An important aspect of quantum mechanics is therefore that it makes only *statistical* statements about the outcome of a measurement. It predicts a certain probability of the occurrence of an event, but not the actual result of a single measurement, which is entirely left to chance[4]. This theory even claims that this is a "objective randomness" that can not be traced back to subjective ignorance. This follows from Q1, which claims that the state is *fully* described by the wave function. The probability *distribution* of the results over a large number of measurements, i.e. averaged over many particles or temporally successive measurements on individual particles, can however very well be derived from the formalism and corresponds with a fantastic accuracy to the experimentally obtained results.

Empirically, the theory of quantum mechanics leaves nothing to desire. Up to the present day, *none* of their predictions has proved to be wrong. It is remarkable how important this theory has become for us, mainly due the growing importance of semiconductor and computer technology: it is estimated that more than a third of the world economy depends on products that are directly based on the application of quantum mechanics!

The search for a mathematical theory of quantum mechanics has thus found a successful end. This does however not change the strangeness and lack of understanding of the phenomena presented in the first part of this essay – a generally accepted *interpretation* of this theory is still missing. In other words, we do not know how to explain the phenomena physically.

[2] The equation is a partial differential equation in the form $\frac{i\,h}{2\pi}\,\partial_t\Psi = \mathrm{H(t)}\,\Psi$ with the imaginary unit i, the Planck constant h and the Hamiltonian H representing the energy of the respective system.

[3] The absolute value of a complex number is always real, which allows the interpretation of the magnitude of the wave function (with a suitable normalization) as a probability between 0 (impossible) and 1 (certain).

[4] Exceptions are the cases where the calculated probability is 0% or 100%, for which quantum mechanics predict the measurement outcome with certainty.

The main problems can be identified as follows:

P1: How can the wave function Ψ, in particular in form of the superposition states, and the probabilities given by $|\Psi|^2$ be interpreted physically?
P2: How can we explain the phenomenon of entanglement, i.e. the instantaneous formation of correlations over arbitrarily long distances?
P3: What defines a "measurement", i.e. what are the circumstances under which it takes place and what happens during a measurement? How does the transition from quantum to classical states work?

Especially the measurement problem is completely unsatisfactory from a physical point of view. The quantum mechanical formalism does not specify what happens during a measurement and what defines a measurement. It is only certain that the measurement process can *not* be described by the Schrödinger equation: this equation is deterministic, linear and time-symmetric, whereas the measuring process includes an intrinsic randomness and a non-linear transition from superposition into classical states with a distinguishing time direction. This transition is therefore called "state collapse" or "collapse of the wave function".

Schrödinger's cat paradox takes exactly the same line. To escape the result of the neither dead nor living cat, the linear time evolution of the Schrödinger equation must be broken at any point. But where is this boundary located and how could this transition be described?

These problems were already evident in the formulation of quantum mechanics. What were the answers from the founding fathers of this theory? The most common interpretation that still dominates the textbooks of physics was given of Niels Bohr. It is often called the "orthodox" viewpoint of quantum mechanics and is outlined in the following chapter. It won't be the last chapter in this essay...

2. The Copenhagen Interpretation

The Copenhagen interpretation claims that explanations beyond the measurable results are neither possible nor needed. According to Niels Bohr, after which place of activity this view was named[5], the study of quantum mechanical systems is only possible by using macroscopic systems such as measurement devices and must also rely on our "classical" language for describing the experimental setup and the obtained results. Furthermore, the measurement process includes always a non-controllable coupling between the observed system and the measurement device. For these reasons, Bohr saw no sense in trying to interpret and understand a purely quantum mechanical world. Statements can only be made on the actually obtained measurement results and these are very successfully described by the theory of quantum mechanics. The collapse of the wave function is in this view a purely mathematical operation that doesn't require a specific physical mechanism.

[5] The interpretation attempts of Bohr's student Werner Heisenberg are also often attributed to the Copenhagen interpretation. There are however significant differences to Bohr's point of view. Heisenberg saw the elements of the quantum world as "potentials" that are no less real than ordinary particles. The philosophical explanations of Bohr were in general so ambiguous that there is no unanimous opinion to this day about the "right" version of the Copenhagen interpretation.

Superpositions and the uncertainty principle were explained by Bohr by the concept of "complementarity": wave and particle are complementary properties of the electron and the experimental setup decides which property emerges. One can either get an accurate reading of the position *or* of the momentum of a particle. The question which properties have been present *before* the measurement is meaningless and not answerable for Bohr, because physics can only make statements about concrete measurement results. In his words:

> There is no quantum world. There is only an abstract quantum physical description.
> It is wrong to think that the task of physics is to find out how nature *is*.
> Physics concerns what we can *say* about nature.

Amazingly, a relatively large part of the physics community is still satisfied with this very positivistic standpoint which postulates an *ad hoc* limit for the search for physical. It puts the desire into question to discover the essence of nature via scientific methods which has started with the ancient Greeks. This interpretation gives also no answer to the (physically well-defined) question about the point of time on which a measurement-induced state change occurs and about the circumstances that must be present for such an event. A fundamental problem is also the postulated difference between the non-real microscopic world of quantum mechanics and the real macroscopic world. The Copenhagen interpretation provides no objective criteria for this distinction and does not explain how the laws of quantum mechanics can be limited to microscopic systems even though macroscopic systems are composed of them. This is even more incomprehensible when quantum mechanics is seen as a universally valid theory which Bohr certainly did. Even the principle of complementarity stands on shaky ground: there are nowadays experiments[6] in which individual photons show their particle and wave character at the same time.

Can this capitulation that the absolute limit of understanding has been reached somehow turned away? In recent decades, a number of vastly different ideas have been developed for solving this problem. The progress in the quantum mechanical interpretation debate is undeniably and its intensity (measured for example by the number of scientific publications on the subject) is not about to decline but has steadily increased in recent years. This discussion, and thus the content of the following chapters, takes naturally place at the intersection between physics and philosophy and can't be decided by "hard facts" that are unambiguous like experimental results. The history of physics has however shown that such interdisciplinary questions have repeatedly led to fruitful insights that often brought forth new physical theories within the "hard" sciences.

A good example of such a finding is presented the next chapter. It was only in the 80s that an important peculiarity of quantum-mechanical systems was discovered that can be seen as a link between the microscopic and the macroscopic world.

[6] See for example [Gribbin 1998].

3. Decoherence – Melting Quantum States

Why is the behavior of objects of our everyday world so different from microscopic systems described by quantum mechanics, although they are constructed from them? The principle of decoherence is at least partly able to answer this question.

The time development of a quantum-mechanical state in a closed system consisting of a coherent superposition of individual sub-states is given by the Schrödinger equation. How is such a system changed if it is allowed to interact with the environment? It was interestingly only found in the 80s[7] that the system undergoes irreversible changes in this case, because the interference terms of the wave function are weakened and get eventually entirely lost – the state loses its coherence within fractions of a second. The sub-states corresponding to measurable properties, i.e. the “classical” states of theory postulate Q3, are on the other hand stabilized and intensified. This is sketched in Figure 1.

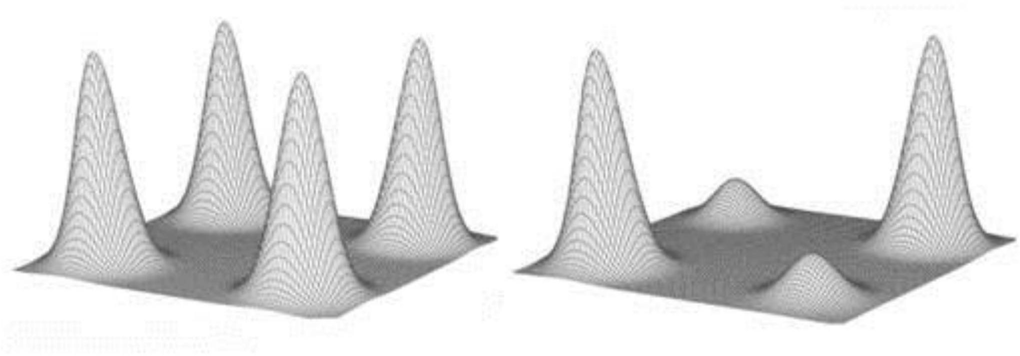

Figure 1: Change of the wave function of a quantum system by decoherence. Through the interaction with the environment, the interference terms are strongly damped, leaving only the two classical terms that represent the possible outcome of a subsequent measurement.

The effect does also arise for measurements, because they are always associated with the introduction of interactions between the surveyed system and the measurement device. This result does not depend on a particular interpretation, it can be derived from the pure quantum mechanical formalism and is therefore considered as an undisputed new physical insight.

At first glance, the phenomenon of decoherence seems to perfectly explain why the mysterious peculiarities of the quantum world do not show up in our everyday world. Since interactions with the environment are virtually inevitable (for example by heat radiation), the transition from coherent to decoherent states happens so fast that quantum mechanical interference and correlation effects can occur in closed microscopic, but not in macroscopic systems. Also the paradox of Schrödinger's cat seems to vanish, since such a large system would lose its coherence in a split second, the cat would thus be either dead or alive before the box is opened.

[7] The effect was first described by H. D. Zeh, subsequent work was provided by W. Zurek and E. Joos.

Unfortunately, decoherence provides only a part of the answer. The components of the wave function that are responsible for the interference effects are indeed disappearing on interactions with the environment, but *all* of the classic parts related to alternative measurement outcomes are preserved. According to the laws of quantum mechanics, the overall state is still a superposition of these states. At the end of the measurement, this superposition is however destroyed, because there is always exactly *one* classical state left, namely the concrete result of the measurement. The mysterious collapse of the wave function is therefore still needed as an essential additional element for the time evolution of the Schrödinger equation and is not explained by the decoherence principle. The concept provides therefore, despite its physical relevance, no solution for the interpretation problem of quantum mechanics. It is indeed compatible with *all* of the interpretations presented in this essay.

The conceptual limits of the principle of decoherence emphasize the same question that has been raised in the formulation of quantum theory: how can the collapse of the wave function as integral part of the measurement process be explained? A rather obvious approach is presented now – the extension of quantum mechanics by a second law of development.

4. The State Collapse as Physical Process

As described before, the measuring process leading to the collapse of the wave function can not be described by the Schrödinger equation. Thus another, as yet completely unknown, law of development seems to be effective for the duration of this process that must be integrated in the standard theory of quantum mechanics. Rating the measurement process as a real physical process (what else could it be otherwise?), this conclusion is actually unavoidable. It is therefore not surprising that they were very early attempts to uncover this second law. The most important question is the application area for this law, which is equivalent to the question under what circumstances the Schrödinger equation loses its validity. Quite different proposals have been made for this. Denoting the Schrödinger equation with S and the state-collapsing law as S*, some examples were as follows:

- S applies only to microscopic systems, whereas S* applies to macroscopic systems

- S applies only to systems in which no measurements described by S* take place

- S applies only to material systems, whereas S* applies to systems with conscious observers

None of these definitions provide a real solution. Nobody was able yet to provide physical criteria for any of these variants to distinguish between the two applications. We will come back to the last version in the next section. The terms "macroscopic", "measurement" or "conscious observer" are thus only linguistic constructs with no explanatory value that are basically not different to the tautology "S* applies in the application area of S*".

The proposal of G.C. Ghirardi, A. Rimini and T. Weber from the year 1985, shortly called "GRW theory", goes one step further. It contains a new law of evolution *instead* of the Schrödinger equation. As the only difference, the wave function can collapse spontaneously, i.e. without any external influence. This happens however extremely rarely (for a single particle once every billion years), so the effect would be visible only in larger systems. Up to now, there is however not the slightest experimental evidence for this theory. Even thinner is the evidence for the assumption of Roger Penrose that the collapse is triggered by gravitational effects in the human brain. These effects are described by the (not yet discovered) unified theory of quantum mechanics and relativity and are enhanced to macroscopic sizes (in as yet unknown manner) by certain protein structures.

The fact that this law S* holds itself hidden so well is probably the most important indication that we lack a crucial element in understanding the state collapse. Despite steadily improved experimental methods, which resolve the measurement process into very fine-grained periods of time, not the slightest deviation to the Schrödinger equation has been discovered up to now. This applies even to experiments including interferences of whole molecules as described in the first part of this essay, which is an area that would without hesitation be called "macroscopic" in former times. This approach of an additional or changed dynamical law is also not able to give an explanation for the phenomenon of entanglement of two widely separated particles (the interpretation problem P2).

For all these reasons, the interpretation of the measurement process as a physical process, by which the Schrödinger equation should be supplemented or modified, does not look attractive. The search will continue, but the current experimental results give no hint for the existence of a second law of evolution.

If the collapse is not a physical process, could it be a mental one? We would then have discovered a link to our own consciousness in physics and there are indeed some physicists who see this connection as inevitable.

5. The Power of Consciousness

As the previous chapter has shown, there seems to be no limit for the physical applicability of the theory of quantum mechanics and hence for the superposition-preserving time evolution of the Schrödinger equation. It was already shown in the 30s by the mathematician John von Neumann, the most important pioneer for the modern mathematical version of quantum mechanics (and together with Konrad Zuse the inventor of today's computer architecture), that these superpositions would also spread over the measuring instruments when the theory is taken seriously and would also not stop at the eye retina or at the nerve pathways of the observer. As only concrete test results but no superimposed states occur in our own perception, he concluded therefore that it must be the human consciousness lying outside the laws of physics that causes the collapse of the wave function[8].

This assumption has dramatic consequences. Classic conditions arise only through the collapse of the wave function, i.e. they are only then getting "real" in terms of concrete measurability.

[8] This idea was later taken up by Eugene Wigner, who wrote: "It was not possible to formulate the laws of quantum mechanics in a fully consistent way without reference to the consciousness".

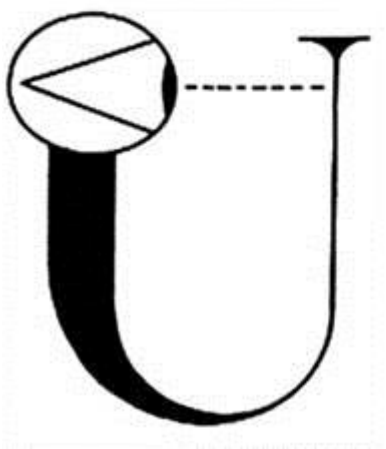

Figure 2: The universe creates itself

When human consciousness is the only authority that can cause this collapse, our universe does not exist since the big bang, but was created at the point of time when the first human turned his attention to it! The physicist John Wheeler, who significantly influenced many interpretations of quantum mechanics, illustrated this rather absurd notion in the adjacent picture.

What can be said about this approach? A very specific question is of course whether only the human mind has this special property or if for example Schrödinger's cat is already "conscious enough" to cause the collapse before the box is opened. Will an artificial intelligence, should it one day be possible, have this property?

The main weakness of this approach is that the problem of the state collapse is just put under the "magic carpet" of a non-physical entity that is identified with the human consciousness[9]. It requires to assume the dualism of material and non-material entities and inherits with this the basic problem of this philosophically and religiously charged worldview: how can matter and consciousness (spirit, soul) interfere with each other when they are, according to the premises, completely different entities? Additionally, this approach shares a major limitation with the collapse theories of the previous section: it can't provide a real contribution to the interpretation questions beyond the measurement process, especially for the explanation of the correlations of two distant subsystems.

It is therefore clear that an even more radical approach is necessary in order to understand quantum mechanics. Such an attempt will be presented now.

6. Hidden Parameters – Bohm's Quantum Potential

A very classical conception is the idea that quantum mechanics with their statistical predictions shows only an incomplete picture of our world. In reality, "normal" deterministic laws would apply that have just not been discovered yet and are therefore called "hidden parameters". The oddities of quantum mechanics could then result from the degree of incompleteness and would no longer require an explanation. With Albert Einstein, we have already met a passionate advocate of this theory in the first part of this essay – but also the final refutation of this hope in the form of Bell's inequality! The unambiguous experimental evidence for the violation of this inequality has shown that *none* of these classical theories are able to reproduce the observed phenomena. Is this then the last word on hidden parameters?

[9] Even Eugene Wigner as representative of this approach had to admit: "It may well be said that we explain a riddle by a mystery".

Not quite. An important requirement for the derivation of Bell's inequality was the *locality* of the described mechanisms. For two-particle systems as in the Einstein-Podolsky-Rosen experiment, this corresponds to the (absolute obvious!) assumption that correlations arise only at the source of the two particles. Generally, locality means that no signal can travel faster than the speed of light, i.e. that the special theory of relativity is not violated. This fact allows an interesting implication: in spite of the violation of Bell's inequality, quantum mechanical effects could be explained by theories with hidden parameters – when they are *nonlocal*[10].

How would such a theory look like? First of all – and this is the central difficulty – it would need a mechanism for superluminal signals while explaining why such effects have never been directly observed so far. Even the entangled properties of two widely separated particles can, as explained in Part 1, not be utilized for the exchange of such signals. But also in the countless other experiments from the quantum scale to the order of stars and galaxies, Einstein's theory of relativity has passed all tests with flying colors[11]. From what we know, the speed of light remains therefore an insurmountable barrier for the exchange of signals.

There is yet another argument that makes the theory of hidden parameters appear very unattractive. A few years before Bell's discovery, a formal proof was found that these theories (even if they are nonlocal) can only reproduce the predictions of quantum mechanics when they contain so-called "contextual" variables[12]. When such variables are measured, their value depends not only on the properties of the quantum system but also on the precise circumstances of the measurement itself. A modified arrangement, such as a different spatial orientation of the measuring equipment, could therefore lead to a completely different outcome. It seems therefore that the unwanted special position of the observer of the Copenhagen interpretation creeps into the theory via the back door.

Despite these difficulties, the idea of the hidden parameters can't be regarded as refuted. There is a fully formulated theory of David Bohm of this type that is in complete agreement with the experiments. The essential element of this theory is a ubiquitous "quantum potential" that deterministically determines the position of each elementary particle. In the double-slit experiment, the electrons would therefore follow specific spatio-temporal trajectories from the source through the upper *or* the lower slit to the detector screen. Their path would however be determined by the exact form of the quantum potential[13] which in turn depends on the condition if both or only one of the two slits is open. In addition, this potential is influenced by the type of measurement. The probability predictions of quantum mechanics could then simply be interpreted by our ignorance about the actual tracks. There would also be no collapse of the wave function, the measurement would only notify us which path the electron had taken.

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[10] It was assumed for a long time that even non-local theories with hidden parameters could not be possible. This was probably one reason why the Copenhagen interpretation has experienced such a high level of acceptance. The corresponding proof by John von Neumann turned however later out as incomplete.

[11] This also applies to experiments carried out in the 90s in which photons were transferred from one place to another by using the quantum mechanical tunneling effect. The signal speed was also in these setups found to be limited by the speed of light despite the media-effective choice of a frequency-modulated Mozart sinfonia.

[12] This insight is known as "Kochen-Specker-Theorem".

[13] Bohm saw this influence not as a force, but as a guide field that provides the particles with the information that is necessary for its path.

The above-mentioned general restrictions do of course also apply to this theory. In Bohm's approach, the position is actually the *only* locally assignable variable, all other properties are contextual variables in the sense described above. The quantum potential has also a completely non-local structure – its effect on the "guided" particle depends in an instantaneous manner on the properties of all other particles that ever interact with it. Since the properties of all these particles depend in turn from their interaction partners, the motion of a particle would thus depend on the state of the entire universe. Even this theory does therefore not allow an objective description of quantum mechanical systems without consideration of the observer and the chosen experimental setup – it describes a world that is completely holistic.

An additional inherent problem of Bohm's theory is its limitation to a fixed set of particles[14]. The generalization to quantum fields and dynamically created and destroyed particles, as described by quantum field theories as special relativistic extension of quantum mechanics, turned out as an extremely difficult – perhaps even impossible – task. Even David Bohm himself sees his theory therefore not as the final solution, his main goal was to prove that it is *in principle* possible to reproduce the quantum mechanical phenomena with (non-local) hidden parameters.

Should someday another hidden parameter theory be discovered that shares the elegance as well as the empirical success of quantum mechanics, it would of course be a serious candidate for the explanation of quantum mechanical phenomena. I leave it to the judgment of the reader whether the experiences with Bohm's theory speaks rather for or against this possibility. It is however certain that those theories could neither get rid of the property of non-locality nor of the contextuality.

[14] Another limitation is the missing explanation of the spin properties of elementary particles.

7. The World is Not Enough

As the previous sections have shown, the collapse of the wave function, transforming superpositions into concrete classical states, is a central problem for the interpretation of quantum mechanics. What would result, asked a certain Hugh Everett[15] in 1957, if there is no collapse and instead any state is actually realized? With the help of a mathematical reformulation of quantum mechanics on the basis of relative state descriptions, he proved that this is possible in principle. A quantum-mechanical system would then *always* follow the Schrödinger equation and the resulting superpositions would be realized without exception, which means that every possible measurement would also actually occur. A measurement would then (in contrast for example to the Copenhagen interpretation) not be mysterious at all, since it merely uncovers the pre-existing condition. It would also not bring any random element into the theory – this approach describes a completely deterministic world.

Perhaps the reader already noticed the main drawback of this interpretation? How can every possible measurement result actually be realized, whereas the alternatives contradict each other and every measurement indicates always only one result? Schrödinger's cat consists for example of a superposition of dead and alive, how can both states simultaneously be real? Everett's answer to this question was that the various states are “delocalized” from each other, together with the observers who measure it. So there is a “branch” of reality, in which option A (e.g. dead cat) is realized and detected by an observer in this branch, and another branch separated from this which realizes option B (living cat). This branching is instantaneous and happens continuously whenever the decoherence effects described above cause irreversible changes in the wave function[16]. Afterwards, the resulting branches can no longer interact with each other. Due to further decoherence effects, any of these branches would create more branches, leading to vast number of separated “realities” in a very short time.

But what does “delocalized” mean? Everett provided no further explanation or proposal about this question, which was some time later picked up by other physicists.

The most prominent interpretation of the Everett approach was given by Bryce DeWitt and later by David Deutsch. They see the separate branches as real worlds, i.e. minimally different copies of the entire universe which are newly created at each branch and then exist in parallel with each other[17]. The “Many Worlds Theory” was born that inspires physicists as well as science fiction authors by today. In this view, an observer would be either in the world with the dead cat or in the world with the living cat. Since he does not know initially in which world he is located, he would have to perform a measurement, which consists in opening the box in this case. He will find either a dead or a living cat. The measurement would however only

[15] The work of Hugh Everett III (his full name) was a doctoral dissertation under John Wheeler, who later dissociated himself from this interpretation. Disappointed by the lack of positive resonance to his idea, Everett turned instead to the application of game-theoretic methods – which later made him a millionaire as company founder and military adviser of the Pentagon.

[16] This role of decoherence was introduced later, after Everett’s work. There is however no consistent opinion amongst the representatives of the many worlds theory about the precise definition of the triggering event. Typical examples are “measurement interaction” or “observation process” which are similar to the undefined “measurement” term in the Copenhagen interpretation.

[17] David Deutsch prefers a slightly different interpretation: There has always existed an infinite number of parallel worlds which are only “filled” by Everett splittings. The key characteristics and also the weak points of the many worlds theory apply however also for this variant.

reveal in which world he is located and would therefore not require a mysterious collapse of the state vector. The Schrödinger equation thus remains the only law for the time evolution of quantum systems, which is the real charm of this interpretation.

It would not be possible to switch from one (the "own") into another world, even though it is just as real[18]. At the microscopic level, the worlds are however not completely separated from each other as illustrated by the example of the double-slit experiment. The interaction of the electron with the intermediate wall would split the universe in one world in which the electron flies through the upper slit and a second world in which it is flying through the lower slit. These two electrons are able to interfere with each other which produces the observed interference pattern, even if only a single electron passes the setup. In other words, the electron interferes with its own "shadow doppelganger" from a parallel world.

The many worlds theory has found many followers in the community of physicists, who see it as *the* solution for the interpretation problem of quantum mechanics. If one considers the fact that this interpretation has to postulate the existence of a myriad of constantly multiplying "parallel worlds" that are not directly experimentally accessible but are yet as real as our "own" world, it becomes really clear how deep the dilemma is that quantum mechanics brought to us. But is this theory actually able to fulfill the high expectations?

On closer inspection, it becomes clear that the theory is not able to perform this task. The three biggest problems shall now be discussed.

A central (and obvious) question is not answered by the many worlds theory: how does the process of world division happen, in which a whole universe with billions of galaxies is duplicated without delay, and which mechanism is driving it? Even the trigger for the split is not really clarified (see footnote 16). It seems therefore that the postulated world splitting is at least as mysterious as the collapse of the wave function which elimination was the main motivation for this approach.

An even more specific problem is the reconstruction of the quantum mechanical probabilities. How can there be a "probability" for a particular measured value if always *all* measured outputs are realized in the form of real worlds? Even with a splitting for two alternatives that occur with a chance of 1% and 99% according to quantum mechanics, exactly two worlds would be generated and the probability for each observer to find the realized alternative in his world would of course be 100%. There are several approaches to solve this problem by introducing additional concepts, but so far this program was not successful.

There is a third problem. In the formalism of quantum mechanics, only the choice of the coordinate system determines how the state vector is composed, that is whether it consists for example of the individual states "black"/"white" or of the states "hard"/"soft". When a world is splitted, only one of these variants can be realized, i.e. there is either a "black" and "white" or a "hard" and "soft" world. Which physical factors influence this selection that can just as well be seen as a reduction of the state vector that was undetermined before the split? For this

[18] Although the many worlds theory is quite clear on this point, it has been speculated that a transfer into a parallel world could allow logically consistent time travels, as it would affect the "history" of that world without changing the originating world.

problem of the system's preferred reference system, there is no generally accepted solution yet[19].

The supporters of the many worlds theory should also be aware of the following aspect: because every possibility is realized without exception, there can be no free will in this interpretation. For each deliberately made decision, there is a parallel world in which an otherwise completely identical observer had come to a different decision[20]. One could also ask the question whether "all is real" is not synonymous to "nothing is real".

It thus turns out that the many worlds theory is subject to exactly the same problems regarding the measurement process and the non-localities for which solution it was invented. In addition to the lavish plenitude of additional worlds, it has also a number of serious theory-specific weaknesses[21]. It is of course always possible that future findings will come to a different assessment.

Given the problems with the introduction of actually existing worlds, two alternative interpretations of the Everett approach have been established that shall now be briefly outlined.

Starting from the idea that the wave function never collapses, the split into alternative measurement results can also be moved into the realm of the human consciousness. This is the assumption of the "Many Minds" theory formulated by H. Dieter Zeh in 1970 according to which it is not the world around us, but "only" our consciousness (mind) that is splitted into a variety of almost identical copies. They would only differ in the registered measuring result, without being able to perceive the other copies. In addition to the doubtful introduction of non-physical spiritual beings, the problems described above do however apply to this approach just as well as for the many worlds theory.

The "Consistent History" theory of Robert Griffiths from the year 1984[22] is also based on the Everett ideas, but it makes a big step towards the Copenhagen interpretation. It declares itself as agnostic regarding the reality of constantly emerging branches, i.e. it doesn't need the assumption of actually existing parallel worlds. This makes it more plausible than the many worlds theory, but reduces at the same time its explanatory value. The focus is on "histories" (stories), i.e. temporally ordered sequences of physical events. A plurality of histories can be combined to "history families", for example the electron flying through the upper slit and the electron flying through the lower slit. These families are called "consistent" if their probability equals the sum of the probabilities of the individual histories, which corresponds to the condition that the individual histories do not interfere. Inconsistent histories aren't

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[19] Some authors hope that decoherence may solve this problem, but so far all attempts in this direction were unsuccessful (see for example [Jaeger 2009], pp. 156-159).

[20] There is a curiosity of this worldview that is definitely not recommended for imitation: Every suicide attempt would be doomed to failure, since it can always happen by a random appearance of contingencies that the attempt fails. After that, there would therefore exist at least one world in which you would find yourself alive and wonder at the incredible coincidence of rescue. With repeated use of this method, one could even convince oneself about the plausibility of the many worlds theory – but unfortunately no one else.

[21] The analysis in [Albert 1992], [Price 1996], [Barrett 1999], [Zeilinger 2003] and [Jaeger 2009] also conclude that the many worlds theory is currently no serious alternative for the interpretation of quantum mechanics.

[22] Later work was done by Roland Omnes, Murray Gell-Mann and James Hartle.

physically meaningful and would thus never appear. For the double slit experiment, there are for example three consistent history families:

1. the electron flies as a particles through the upper or lower slit
2. the electron shows interference effects
3. there is a macroscopic superposition state of the total system

This interpretation makes however no statement which of these three families are actually correct, this is only decided in the experiment. This reflects the already known measurement problem, i.e. the collapse of the wave function. Additionally, this approach shares the problem of the preferred reference system.

8. Information is Everything

There is a fundamental connection between quantum mechanics and information theory: a quantum system with N possible discrete states corresponds exactly to the amount of information of N bits, since it can unambiguously be defined by N yes-no decisions. A two-valued state thus represents the smallest possible unit in the quantum world as well as in information theory and can be seen as the basic building block of our world. Anton Zeilinger, who is well known for his experiments on "beaming" photons, explained the connection as follows: how can we learn about our world? The only way is to collect and evaluate information. A "reality" over which we can't obtain any information is completely inaccessible to us and therefore an empty concept. Reality and information can only be experienced in conjunction with each other, which provides no scientific reason for preferring reality over information. The basic laws of nature must therefore not make any distinction between reality and information which means that these terms are two different names for the same concept.

This leads to a remarkable new perspective. The quantum mechanical state and thus the wave function corresponds to the information that we have about the world. Every system has however only a limited amount of information that we can obtain experimentally. The kind of this information depends on the proposed questions about the system, i.e. on the choice of the measured variables. When for example an electron is asked about its position, it will not have enough information for an exact value of its momentum afterwards. The particle "forgets" this value as reflected in the Heisenberg uncertainty principle. This would also explain the experiments described earlier, in which the interference pattern behind the double slit disappears when any information about the path of the atom or molecule is obtained, even when there is no direct influence on the particle position.

The correlations of widely separated particles appears also less surprisingly from this view. It is only the overall system that contains certain information in this case, such as the opposite direction of the particle spins with respect to a fixed axis chosen by the experimenter. The results of the individual measurements were, taken by itself, completely random and independent of the location and time of the measurement, which avoids a contradiction to the theory of relativity which constrains only the maximal speed of information-bearing signals.

Some authors go so far as to give information an ontological status and to see it as *the* basic building block of this world. The material world would then only be a derived concept that could no longer claimed to be real. John Wheeler invented the formula "It from Bit" for this program. Many physicists, like the information theorist Gregg Jaeger, see however the attempt to reduce physics to information as just as implausible as the reduction of the information concept to physics[23]. An undoubtful promising program is instead the investigation how physical laws *restrict* the information processing in a characteristic manner. Especially in the case of quantum mechanics, it turned out that the non-classical properties become particularly clear and quantitatively analyzable from this perspective[24].

Back to the information-theoretical reconstruction of quantum mechanics in the sense of Zeilinger. One can view this approach as a variant of the Copenhagen interpretation, because it was the main idea of Niels Bohr that the theory does not describe the elementary particles "as they really are" (which he held to be impossible), but is only able to provide answers to the questions asked in the experiment. The impossibility of any further description or explanation of the phenomena like the path of the electron in the double-slit experiment would however no longer be postulated ad hoc, but would reflect the objective absence of any further information. In my opinion, the information-theoretic reconstruction is therefore a more consistent and therefore more plausible version of the Copenhagen interpretation. A very interesting variation of this approach is called "Relational Interpretation", which is briefly described in the following chapter.

But even this interpretation has its limitations. It provides in particular no concrete answers to the question how and exactly when the continuous development of the quantum mechanical state is replaced by the discrete "information extraction process" and which conditions must be fulfilled for this transition. The entanglement effects may appear less mysterious, but the approach does not provide any concrete mechanism that could explain this phenomenon. Other than the (quite dubious) assumption of the Copenhagen interpretation that only macroscopic, but no microscopic objects are real, the information-theoretic reconstruction encompasses also to the entire range of nature. It does therefore not claim less than the statement that the objective observer-independent reality of our world is an illusion and that the question whether there is the moon, when nobody watches it, can not easily be answered with Yes.

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[23] See [Jaeger 2009], Section 4.7, for a detailed discussion of this topic.

[24] See [Jaeger 2009] for such an analysis.

9. Other Interpretations

The following interpretations, which are only briefly outlined here, are based on a particular philosophical perspective or are modifications of previously presented ideas. Although they provide very interesting aspects for the interpretation debate, they can in my opinion not be regarded as fully elaborated interpretations of quantum mechanics as an alternative to the already described main approaches.

According to the **Ensemble Interpretation** (M. Born and A. Einstein in 1926, later represented by L. Ballentine) only ensembles, that is a large numbers of particles, can be physically described in a reproducible manner. This is not possible for individual events, it would therefore be pointless to try to find an explanation for them. Apart from the question how many particles are needed for an ensemble (with a strict interpretation, this theory would only be applicable for an infinite number of particles) and the lack of explanation for the entanglement phenomenon, this approach has the problem that quantum mechanics *does* make testable statements about single events under certain conditions, namely whenever the predicted probability is 0% or 100%.

The aim of **Quantum Logic** (G. Birkhoff and J. von Neumann, 1936) is the reconstruction of quantum mechanics based on a more general logic, which is seen as more adequate for this theory. It involves a weakening of classical logic with the particular aspect that *P and (Q or R)* does no longer automatically entail *(P and Q) or (P and R)*. This approach has however failed so far to provide any physical insights.

The **Modal Interpretation** (B. van Fraassen 1972) sees itself as a variant of the Copenhagen interpretation that does not require the questionable postulate of the collapse of the wave function. It introduces next to the "dynamical state", which time evolution follows the Schrödinger equation, a "value state" that describes the *possible* observable quantities for the respective system. The dynamical state determines the probabilities for the elements of the value state and is not subject to a collapse.

The plausibility of this approach, which dissected into several sub-variants, depends on how naturally the introduction of a second state variable appears and whether this concept can be generalized to quantum field theories. The latter turned out as an extremely difficult or even impossible task. This interpretation provides also no explanation for the entanglement effects.

The **Relational Interpretation** (C. Rovelli 1994) is a variation of the information-theoretic reconstruction of quantum mechanics. It assumes that only relations between systems and observers can be considered as real and that the wave function corresponds exactly to these relationships. There is therefore no objective overall state encompassing more than one observer[25]. The collapse of the wave function is caused by *any* kind of interaction, which avoids the introduction of the dubious terms "measurement" or "macroscopic world". The restriction of the realm of reality makes also the entanglement effects less mysterious, since there is no absolute total state any more that could show instantly occurring correlations for two differ-

[25] Rovelli sees this approach inspired by the success of the theory of relativity, which brought new insights by discarding absolute elements such as the absolute space.

ent observers. In this sense, this interpretation is even local, albeit only with respect to each observer.

What this interpretation does – apart from an objective overall state of the world – not provide is an explanation for the observed correlations between entangled systems. This *can* actually be worked out by a single observer who can just gather and then compare the results of the two measurements even when they were previously far apart from each other.

An even more radical conception is suggested by **Quantum Bayesianism** (C.M. Fox, C.A. Caves and R. Schack, 2002)[26]. Physical objects such as electrons are taken for real, but they do only possess dispositional properties, i.e. the *ability* to cause certain physical events on interactions with other quantum systems. The wave function represents then only the evaluation of a rational agent about the result of a measurement, i.e. the "bet" for a particular outcome. The collapse of the wave function becomes then a metaphysically unproblematic knowledge insight. This completely subjectivist interpretation has the problem that it does not provide further explanations for the observed phenomena and that it fails to recognize the goal of physics to describe physical systems instead of decision criteria for rational agents.

There are a number **of other interpretations,** but they are typically only variations of the previously presented approaches, especially of the Copenhagen interpretation[27].

[26] The term goes back to the mathematician Thomas Bayes who interpreted probability as the degree of personal conviction.

[27] A good resource for further research is the page "Minority interpretations of quantum mechanics" at Wikipedia.

10. An Interim Conclusion

It is worthwhile to make a short resume. Without aiming for a final judgment, which wouldn't be possible anyhow, the following can be said: the "real" interpretations, that assume an objective reality independent of us observers, encountered serious difficulties in providing a satisfactory explanation of quantum mechanical phenomena and in solving their interpretation-specific problems. This applies in particular to the entanglement effects that almost magically connect systems that are arbitrarily far away from each other without direct violation of the theory of relativity – their explanation turned out as the biggest challenge. In comparison, the empirical approaches such as the information-theoretic reconstruction as a modern version of the Copenhagen interpretation look much more plausible. They are however not able to fulfill the desire for an objective and observer-independent description of our world and to reveal the mechanisms behind the quantum mechanical phenomena. My personal interim conclusion is therefore negative: despite many decades of discussions and many new ideas and improvements, *none* of the interpretations described here can provide a really convincing explanation of the quantum mechanical mysteries.

It is again Albert Einstein, who found the right words. Many readers might know his saying "Subtle is the Lord, but malicious He is not!" reflecting his deep faith in the rationality and comprehensibility of our world. Less well known is a quote from him from only a few years later in the face of the new world of quantum mechanics:

> I have second thoughts. Maybe God *is* malicious.

This tour de force through the interpreting landscape of quantum mechanics is however not over yet. In the third part of this essay I want to present an approach that provides a realistic description of our world with the potential to explain all the peculiarities of quantum mechanics. It has only one problem: it is hard to believe. The distinguishing feature of this approach are *waves that run back in time.*

In this third part I will try to convince you that this approach is not nearly as crazy as it sounds. The key point is a clarifying discussion of the concept of time itself, which will reveal a surprising result. Stay tuned!

Appendix

Overview of the Interpretations

The following table lists the most important properties of the interpretations of quantum mechanics discussed here. The assignments turned out as surprisingly difficult and are often controversial even among the followers of the respective approach. This table, which already includes the transactional approach from the third part of this essay, should therefore only be taken as a rough guide.

Interpretation	Representative	Wave Function is real	Wave Function Interpretation	Collaps / Splitting		Explanation of Entanglement	Deterministic	Observer-dependent
Copenhagen	Bohr, Heisenberg	No[1]	Measurement Relations	Collaps	Interaction with Meas. Device	NI (not real)	No	Yes
Information	Zeilinger	No[2]	Information	Collaps	Information Transmission	NI (not real)	No	Yes
GRW	Ghirardi, Rimini, Weber	Yes	NI	Collaps	Spontaneous Collaps	NI	No	No
Consciousness	v. Neumann, Wigner	Yes (dualist.)	NI	Collaps	Interaction with Consciousness	NI	No	Yes (causal)
Transactional	Cramer, Price	Yes	Retarded & Advanced Waves	Collaps	Transactional Handshake	Advanced Waves	No	No
Quantum Potential	Bohm	Yes3	Statistical[3]	-	No	Holistic Potential	Yes	No[4]
Many Worlds	Everett, DeWitt	Yes	Many Worlds	Splitting	Measurement Interaction	NI	Yes	No
Many Minds	Zeh	Yes (dualist.)	Many Minds	Splitting	Interaction with Consciousness	NI	Yes	Yes (causal)
Consistent Histories	Griffiths	agn.[5]	agn.[5]	Splitting	Measurement Interaction	NI (not real)	agn.[5]	Yes

Abbreviations: NI = No Informations, agn. = agnostic

1: Only makroscopic (classical) world is real

2: Information is indistinguishable from reality

3: Wave function is only statistical, but hidden parameters (particle position and quantum potential) are real

4: But contextual, i.e. Dependent from respective measurement setup

5: Same as Many Worlds when real

(www.frwagner.de/qm.html)

Recommended Books

As an introduction, I would particularly recommend the books by A. Zeilinger, J. Gribbin and Rosenblum & Kuttner. The mathematical theory of quantum mechanics is well explained by D. Albert and the best advanced presentation of the different interpretations is in my opinion given by J. Baggott. Really remarkable in many aspects is furthermore the book by R. Kastner. For the phenomenon of time, I recommend the books by H. Price and A. Bardon.

Albert, David Z. (1992): Quantum Mechanics and Experience
Despite the somewhat odd writing style an excellent introduction to the interpretation problem and the mathematical theory of quantum mechanics as well as a sophisticated discussion of the various interpretations.

Allday, Jonathan (2009): Quantum Reality
A detailed presentation of the theory and the interpretations of quantum mechanics and quantum field theory for readers with physical knowledge.

Baggott, Jim (2003): Beyond Measure
Comprehensive and in-depth overview of the different interpretations in their philosophical context and many interesting details (but unfortunately without the transactional approach). Medium level difficulty with mathematical details in the appendix.

Bardon, Adrian (2013): A Brief History of the Philosophy of Time
Together with the book by Huw Price a real eye-opener about the nature of time, short and excellently written.

Barrett, Jeffrey A. (1999): The Quantum Mechanics of Minds and Worlds
A detailed and sophisticated monograph on the Many Worlds theory and other Everett interpretations.

Davies, Paul & Brown, Julian (ed.) (2001/1993): The Ghost in the Atom
In addition to a good short introduction, eight physicists give a vivid insight into their interpretation of quantum mechanics.

Gribbin, John (1984): In Search of Schrödinger's Cat
Very well-written introduction, his second book is however more current.

Gribbin, John (1996): Schrödinger's Kittens and the Search for Reality
Very good introduction to quantum mechanics and its interpretations as well as an excellent explanation of the transactional approach.

Jaeger, Gregg (2009): Entanglement, Information, and the Interpretation of Quantum Mechanics
Demanding representation of the properties and interpretations of quantum mechanics in the light of mathematical information theory.

Kastner, Ruth (2015): Understanding Our Unseen Reality: Solving Quantum Riddles
This excellent book provides not only a non-mathematical introduction into the peculiarities of the quantum mechanical world and the details of the transactional interpretation, but show also a wide range of philosophical implications of this theory.

Price, Huw (1996): Time's Arrow and Archimedes' Point
A very well-written and inspiring book about the physics of time and its relation to quantum mechanics. A real insider tip that will be discussed in more detail in the third part of this essay.

Rosenblum, Bruce & Kuttner, Fred (2008): Quantum Enigma
Perhaps the best introduction to the history and interpretation problem of quantum mechanics for readers without physical knowledge. The presentation of the interpretations in the second half is somewhat unbalanced (mainly due to the questionable thesis that all approaches lead to a particular role of the consciousness), but offers interesting speculations.

Scarani, Valerio (2006): Quantum Physics: A First Encounter
An interesting introduction to quantum mechanics and its interpretation.

Zeilinger, Anton (2010): Dance of the Photons
Very good introduction to quantum mechanics, especially for the entanglement effects.