

# Chapter 28

## Interpretations of Quantum Mechanics



The formalism of quantum mechanics is unambiguous. But the question remains open as to what it ‘really’ means. In this chapter, we outline some of the more popular interpretations of quantum mechanics.

The great importance of quantum mechanics for our current view of the physical world is undisputed. In the previous chapters, we have gotten an idea of how coherent it is as a theory, of how powerful it is in the treatment of various practical issues, from the hydrogen atom to the quantum computer, and what insight it provides into problems that were long considered purely philosophical.<sup>1</sup> Undoubtedly, quantum mechanics has profoundly changed our worldview.

At the same time, it raises unresolved central epistemological problems, such as the question of the existence of objective chance. It is typical of quantum mechanics that the formal apparatus is unique, but not its meaning. For example, let us consider the state vector, whose mathematical formulation and whose relation to experimental variables are precisely defined. But what does it mean? Does the state vector describe the physical reality of an *individual* quantum system? Or has it nothing to do with an individual system, but is applicable only to an *ensemble*? Or is it simply an indisputable *calculation recipe* which allows us to determine the probability of an experimental result?

Here, the *interpretations of quantum mechanics* appear on the scene. Interpretation essentially means explanation, clarification and giving meaning to the formalism. The aim of an interpretation of quantum mechanics is a better understanding of

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<sup>1</sup>For a long time, the study of the foundations of quantum mechanics was considered a humanistic rather than a scientific activity. However, the search for better explanatory models is not necessarily a glass bead game, but, on the contrary, it can have very practical consequences, such as Bell’s inequality, entanglement, decoherence, quantum computers etc.

the terminology, namely in the sense of a physical picture of the world which is as consistent as possible.<sup>2</sup>

It is characteristic of different interpretations that they make the *same* predictions for measurements, as they refer to the *same* formal apparatus. Therefore, one cannot differentiate one of them from another on the basis of experimental results, and thus could argue all day about them without reaching a convincing conclusion. In contrast, different theories lead in general to different predictions or experimental results that allow a decision as to which theory is more appropriate. However, the situation is currently such that the proposed changes to quantum mechanics lead to such subtle effects that they cannot (yet) be detected. Therefore, one also usually subsumes under 'interpretations' in addition those approaches that are, strictly speaking, new theories.

As we shall see, the interpretations of quantum mechanics provide some very different answers to the open questions. These different points of view have, as we want to emphasize again, no effect on the *practical* application of quantum mechanics; it is excellently *fapp* (one of the best validated physical theories known) and in this respect there is no fundamental disagreement. The dispute concerns only the ontological significance of quantum mechanics, i.e. what it 'really' means. As the various interpretations cannot be distinguished experimentally, it is largely a matter of faith, conviction or taste which interpretation one prefers (and this is sometimes expressed with missionary zeal).<sup>3</sup>

Especially when teaching quantum mechanics, one is often asked questions of meaning by lay people; it is not for nothing that 'bizarre' is a regularly recurring adjective when popular scientific descriptions of quantum effects which are so strange to our everyday experience are under discussion.<sup>4</sup> Hence it is of great interest not just for professionals, but also (in an appropriate form) for physically less-trained people, to know the conceptions of the world in which quantum mechanics is embedded, and to appreciate the differences between these explanations; in short, to learn the state of our physical worldview. That the general public is very open to these issues is shown for example by the widespread interest in the many-worlds theory, ideas about entanglement, considerations of the relationship between consciousness and measurement and the like. Of course, one must clearly distance oneself from

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<sup>2</sup>Since time immemorial, philosophy has concerned itself, in one form or another, with interpretations of our world. Here are two opposing voices from the nineteenth century:

"No, just the facts do not exist, only interpretations. We can not state a fact »itself«: perhaps it is nonsense to want such a thing. »It's all subjective« you say: but even this is interpretation, the »subject« is not given, but something added and invented." Friedrich Nietzsche, in *Legacy*, KSA 12.

"The philosophers have only interpreted the world differently; it is important to change it." Karl Marx, in *Theses on Feuerbach*.

<sup>3</sup>The situation is confusing even for physicists: "Quantum theory was split up into dialects. Different people describe the same experiences in remarkably different languages. This is confusing even to physicists." David Finkelstein (born 1929), American theoretical physicist.

<sup>4</sup>The special theory of relativity is also suspect to our common sense. But there are no controversies within physics concerning the explanation and visualization of the Twin paradox and Co. This is different in quantum mechanics; here, there exist a number of distinct explanations.

any esotericism; but with appropriately popularized descriptions of the problems of quantum mechanics and the way in which different interpretations address them, interest and motivation can be established to a high degree.

## 28.1 Preliminary Remarks

### 28.1.1 Problematic Issues

In Chap. 14 (Vol. 1), we have identified some ‘difficult’ concepts of quantum mechanics—for example, the special role of measurement in quantum mechanics, the occurrence of probabilities, the collapse of the wavefunction, the relationship between classical mechanics and quantum mechanics (Heisenberg cut). They are all related to the measurement process and are therefore not entirely independent. In Vol. 2, we have learned more of the conceptual peculiarities of quantum mechanics. Of central importance is *entanglement*. On the one hand, it led us to the phenomenon of decoherence (via the reduced density operator), on the other hand to the question of the validity of local realism (via Bell’s inequality). We recapitulate briefly the state of the most important problem areas in the following:

1. The Kochen–Specker theorem shows that in quantum mechanics, not *all* properties can be fixed prior to measurement. The classical idea—that measuring means finding out fixed properties as part of reality—cannot be maintained in quantum mechanics; there are situations in which quantum systems do not possess objectively-determined physical characteristics.<sup>5</sup> Bell’s inequality and the GHZ states show that quantum mechanics cannot be simultaneously local and realistic. Whether just one of these properties is not satisfied (and if so which one), or both, is still unclear. In any case, it is obvious that the worldview of quantum mechanics differs in very essential respects from that of classical mechanics, and thus also of our everyday understanding. Indeed, according to current knowledge there is no getting around this fact.<sup>6</sup>
2. The concept of the collapse of the wavefunction denotes the fact that there are seemingly two different time evolutions: On the one hand the process defined by the SEq, which is deterministic, unitary and reversible, and on the other hand the rapidly changing, non-deterministic, non-unitary and irreversible course of a measurement, where the only distinction is that between ‘before’ and ‘after’.

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<sup>5</sup>We repeat the remark that these conclusions are based on the fact that quantum mechanics takes place in a Hilbert space.

<sup>6</sup>The belief that quantum mechanics implies a drastic break with classical physics was also expressed earlier (albeit partly for reasons other than those listed here): “Against all reactionary efforts . . . I am certain that the statistical nature of the Psi-function and thus the laws of nature . . . will determine the style of the laws, at least for several centuries . . . Dreaming of a way back, back to the classic style of Newton-Maxwell . . . seems to me hopeless, absurd.” Wolfgang Pauli, Nobel Prize 1945, writing in 1952.

As we have seen, the collapse can be explained by the mechanism of decoherence—but only insofar as, due to the flow of information into the environment, superpositions (apparently) collapse very rapidly (which is why we see no macroscopic superpositions). However, decoherence does not describe how the selection of the actual measured value comes about. For this reason, decoherence provides a very plausible explanation of the state reduction, but, by strict logic, it is not the only possible description.

3. Assuming that the measurement apparatus obeys the rules of classical mechanics, one is confronted with the problem of drawing the line between classical mechanics and quantum mechanics. If one describes quantum systems as *open* systems, however, one stays within the validity of quantum mechanics, i.e. one does not require the ‘services’ of classical mechanics. Thus, decoherence provides some clarification also in this respect.

But e.g. the assumption that quantum mechanics is valid for our entire universe shows that this does not mean that all questions of demarcation have been resolved. Thus, there must be a SEq for the whole universe (even if we do not know the Hamiltonian). Then the temporal evolution of the universe would be deterministic, which raises many questions; among others, the question of free will. One might, of course, assume that our universe is an open system—but what would its environment then be?

These considerations are based on the belief that the present form of quantum mechanics is essentially valid. But of course it is not impossible that in fact it still has certain shortcomings, in one way or another.<sup>7</sup> The question arises as to whether a single consistent theory that can explain the world in fact exists, including all observable phenomena (Theory of Everything, TOE); or if certain aspects may be described only by certain theories which are mutually exclusive.<sup>8</sup>

4. The fact that quantum mechanics, even with complete knowledge of the state, generally provides only probability statements, can be interpreted from a number of very different positions. We consider three of them. One view assumes that quantum mechanics is complete and reflects a fundamental limitation of our knowledge of nature, so that we must content ourselves with probability statements—its probabilistic aspect is natural (objective chance). Another view also assumes the completeness of quantum mechanics, but rejects the existence of objective chance; according to this view, probabilities arise due to the limited perspective of the observer. Finally, there is the view that the present theory is not complete and should be complemented by introducing hidden variables, the consideration of which would allow us to predict results exactly, as we are accustomed from classical mechanics.

The formalism of quantum mechanics (i.e. the postulates introduced in Chap. 14,

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<sup>7</sup>In this connection, we recall that there is still no satisfactory unification of general relativity theory and quantum mechanics.

<sup>8</sup>A very critical attitude towards the reductionism of modern science is shown by e.g. Robert B. Laughlin (Nobel prize in physics 1998) in his book *A different universe—Reinventing physics from the bottom down* (2006).

Vol. 1) does not permit us, as noted above, to decide directly which of these (and other) points of view is the correct one. The view adopted by a majority is that there are no hidden variables; only one of about a dozen now current interpretations (namely the Bohm interpretation) makes use of them. The reason is, of course, that the considerations discussed so far have substantially sharpened the constraints on hidden variables. They may be neither non-contextual-realistic nor local-realistic—and thus are in this sense as far from classical mechanics as is quantum mechanics itself. The situation is different regarding the question of whether the probabilities are based on objective chance in quantum mechanics. Here, various models of explanation are currently under discussion.

With these questions, issues are touched that go far beyond the physical framework of quantum-mechanical physics in the strict sense—determinism, causality, verifiability, reality, locality and separability. An interpretation of quantum mechanics is expected to respond to these problem areas and to provide coherent answers to the open (physical) questions. In spite of that, one can of course take the view that quantum mechanics is only a collection of rules and calculational prescriptions (albeit very well-functioning) for solving specific problems, and that the questions raised do not affect our obtaining practical results, and are therefore uninteresting.<sup>9</sup> This *pragmatic* or *instrumental* view works perfectly in practice, but it is for many people a very unsatisfactory and unacceptable idea that such a fundamental theory as quantum mechanics should be only some sort of physical cookbook.<sup>10</sup> In this sense, *realistic* views<sup>11</sup> of quantum mechanics do not regard it exclusively as a calculation scheme, but assume that it provides, at least partially, a faithful representation

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<sup>9</sup>The old dispute between the ‘pragmatist’ Bohr and the ‘realist’ Einstein is still alive, just with different actors, for instance Stephen Hawking and Roger Penrose. Their positions are found in S. Hawking and R. Penrose, *The Nature of Space and Time*, Princeton University Press Princeton, (1996), namely:

S. Hawking: “Although I’m regarded as a dangerous radical by particle physicists for proposing that there may be loss of quantum coherence, I’m definitely a conservative compared to Roger. I take the positivist viewpoint that a physical theory is just a mathematical model and that it is meaningless to ask whether it corresponds to reality. All that one can ask is that its predictions should be in agreement with observation. I think Roger is a Platonist at heart but he must answer for himself.” (pp. 3–4)

R. Penrose: “At the beginning of this debate, Stephen said that he thinks that he is a positivist, whereas I am a Platonist. I am happy with him being a positivist, but I think that the crucial point here is, rather, that I am a realist. Also, if one compares this debate with the famous debate of Bohr and Einstein, some seventy years ago, I should think that Stephen plays the role of Bohr, whereas I play Einstein’s role! For Einstein argued that there should exist something like a real world, not necessarily represented by a wave function, whereas Bohr stressed that the wave function doesn’t describe a ‘real’ microworld but only ‘knowledge’ that is useful for making predictions.” (pp. 134–135)

<sup>10</sup>With the predominant recipe “Shut up and calculate!”.

<sup>11</sup>In the debate about quantum mechanics, the adjective *realistic* has two meanings:

(a) If we require, as discussed in Chap. 27 that properties are pre-existent in quantum mechanics also, this means that (i) quantum states refer to individual systems, not just to the results of repeated measurements, and that (ii) a measurement determines the value of a physical quantity which it had immediately before and independently of the measurement.

of reality.<sup>12</sup> There are different views, which correspondingly show up as different interpretations.

### 28.1.2 *Difficulties in the Representation of Interpretations*

There are some complicating factors in the presentation of the interpretations of quantum mechanics:

1. There is quite simply a goodly number of different interpretations, so that an overview must be limited to a relatively short description of some few selected interpretations, in order not to get out of hand.
2. The formal requirements of the various interpretations are very different and, for some interpretations, go beyond the scope of our considerations. We therefore confine ourselves in all cases to working out the basic idea in a language-oriented representation. More detailed comments on certain interpretations are given in Appendix V, Vol. 2.
3. Another difficulty lies in a certain terminological fuzziness. A comparison of relevant sources in the literature quickly shows that many terms are not very precisely defined, and accordingly the descriptions of different interpretations do not always coincide. This terminological confusion goes so far that even the exact meanings of some of the concepts involved are unclear, or the same concepts are used with different meanings. We cite in this connection Peres (Quantum Theory. Concepts and Methods, pp. 23):

The experts disagree on what is meant by “Copenhagen interpretation”. Ballentine gives this name to the claim that “a pure state provides a complete and exhaustive description of a single system” The latter approach is called by Stapp the “absolute- $\psi$  interpretation”. Stapp insists that “critics often confuse the Copenhagen interpretation, which is basically pragmatic, with the diametrically-opposed absolute- $\psi$  interpretation ... In the Copenhagen interpretation, the notion of absolute wave function representing the world itself is unequivocally rejected”. There is therefore no real conflict between Ballentine and Stapp, except that one of them calls Copenhagen interpretation what the other considers as the exact opposite of the Copenhagen interpretation.

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(b) A realistic interpretation, on the other hand, may be based only on requirement (i), so that quantum states refer (in a not specifically detailed manner) to individual systems, not just to the result of repeated measurements.

<sup>12</sup>It would not be the first time in the history of science that the mathematical formalism turns out to be more than just a clever computational recipe. Those who wanted it that way could for example initially regard Kepler’s laws as pure arithmetic, simply allowing the determination of the orbits of the planets more precisely than other rules. The realization that Kepler’s laws indeed give a picture of reality superior to the notions existing until then had first to overcome much opposition. (We recall that Galileo Galilei was rehabilitated only in 1992 by the Catholic Church.) Another example of this phenomenon is Planck’s constant, which was at first, even for Planck himself, only a pragmatic mathematical trick, introduced ad hoc in order to master convergence problems.

## 28.2 Some Interpretations in Short Form

As we said above, there are around a dozen current interpretations (some of which are also split up into different subversions), of which we present here some of the most notable in short form, by and large in the order of their dates of appearance.<sup>13</sup>

### 28.2.1 *Copenhagen Interpretation(s)*

This is a collective term for several interpretations which are not just slightly different, but sometimes even contradict each other. The first forms date from the 1920s and are due to Bohr in Copenhagen and to Heisenberg (who originated the baptismal name ‘Copenhagen’); even they differed e.g. in terms of a realistic explanation. Meanwhile, the differentiation has gone further, so that the term ‘Copenhagen interpretation’ is very blurry—in fact it should appear in the plural in the heading of this paragraph. A contributing factor to the confusion is that different authors have different opinions as to what actually constitutes the Copenhagen interpretation, as briefly described above.

The Copenhagen interpretations essentially agree that the state vector gives the best knowledge of the system. This means that measurement results are objectively random and that behind the state vector there is no deeper reality, e.g. in the form of hidden variables; there *is no reason* why in a measurement, a specific result emerges and not another one of several possible outcomes. Similarly, the Copenhagen variants agree that quantum-mechanical statements refer to *individual* systems, and that it does not make sense to assign properties to an *unobserved* system.

Concerning other issues, the individual Copenhagen variants differ considerably in some aspects; for example, the wavefunction is in one variant only a tool for calculating probabilities, in another one an ‘element of reality’.<sup>14</sup> We want to look at two versions in detail, which are usually called the minimal and the standard interpretations (one could also speak of the ‘older’ and ‘newer’ Copenhagen

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<sup>13</sup>“Whoever merely accumulates observations and experiments, seems to me like someone who keeps a register of the pieces which two chess players lift and put down or take away; someone who notices the moves they make has taken a large step forward; it will cost him much time to determine the laws of motion precisely, and much time will pass until he guesses the intention behind why all these movements are made, and that everything is done to make the king a prisoner. Without this kind of hypotheses, nothing can be accomplished. The question of whether they are useful has something absurd in itself: Because we want in the end to explain the phenomena in nature, and such a hypothesis is indeed nothing more than such a bold statement; it immediately is thrown in disarray when the phenomena contradict it. Also, the question of whether the false hypotheses can have their uses is answered at once by itself. It is not for everyone to strike immediately the best.” Georg Christoph Lichtenberg, *The Waste Books*, Vol. J (1521).

<sup>14</sup>To illustrate the bandwidth of what lies behind the term ‘Copenhagen interpretation’: The interpretation called the ‘Participatory Anthropic Principle’ also sees itself in the tradition of the Copenhagen interpretation; here it is assumed that observation by a conscious observer is responsible for the collapse of the wavefunction.

interpretations, or in the sense of the above quotation, of the ‘Copenhagen interpretation’ and the ‘absolute- $\psi$  interpretation’).

### Minimal Interpretation

The oldest interpretation of quantum mechanics is, strictly speaking, none at all, but rather an anti-interpretation, because it is purely instrumental and dispenses almost completely with the attempt to find an inner meaning. It was largely shaped by the pragmatic Bohr, who saw in the wavefunction essentially a mathematical tool for calculating probabilities and values of measurement results. Distinctive to this interpretation is the separation of each measurement into a quantum-mechanical part (the observed, measured system) and another part obeying the laws of classical physics (the measurement apparatus, the observing system). Only the classical part is real; the objects described by quantum mechanics (electrons, atoms, etc.) do not really exist. More specifically: statements about such objects which go beyond the predictions of experimental results etc. may not and should not be made. We recall Bohr’s remark, already quoted in Chap. 14, Vol. 1, in which he pointedly summarizes his position thus: ‘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 itself with what we can say about nature’.

Of course there must be a boundary between the domain described by quantum mechanics as a pure construct of thought, and the real world of the measuring apparatus (Heisenberg cut). This division has proved itself extraordinarily in practice, as we have emphasized several times, but is conceptually unsatisfying and leaves some questions unanswered—such as where exactly this boundary is located between quantum mechanics and classical mechanics. With today’s experimental techniques (manipulation of individual atoms, etc.), one can no longer simply hide behind the statement that measurement devices are just to a tremendous extent larger than the quantum systems studied.<sup>15</sup>

The minimal interpretation may also be referred to as the ‘older’ Copenhagen interpretation; at least it displays essential features of that interpretation. As a further feature of the older Copenhagen interpretation, one often mentions the aspects of complementarity, uncertainty and the correspondence principle.

In regard to the history of science, it is quite interesting that the ‘older’ Copenhagen interpretation enjoyed a kind of monopoly position for a long time; this certainly had to do with the undisputed authority of Bohr. In any case, new ideas, not fitting the minimal interpretation, experienced difficulties in getting attention for many years; an example, at least at its beginnings, is the concept of decoherence (see Chap. 24).

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<sup>15</sup>Indeed, *quantumness* is a current topic, i.e. the study of the question of to what extent a given system is quantum in nature. See e.g. E. Kot et al., ‘Breakdown of the Classical Description of a Local System’, *Phys. Rev. Lett.* 108, 233601 (2012); P. Kurzynski et al., ‘Experimental undecidability of macroscopic quantumness’, arXiv: 1111.2696v2 (2012); C. Marletto & V. Vedral, ‘Witnessing the quantumness of a system by observing only its classical features’, *npj Quantum Information* 3, Article number 41, doi:10.1038/s41534-017-0040-4 (Oct 2017).

### Standard Interpretation

The very pragmatic attitude of Bohr was not shared to a similar extent by all others. Especially Dirac and von Neumann originated that version of the Copenhagen interpretation which today is called the orthodox<sup>16</sup> or canonical interpretation, or *standard interpretation*.<sup>17</sup> In contrast to Bohr's dictum, this interpretation assumes that there *is* a quantum world, that individual quantum objects such as atoms and electrons exist, i.e. they are real. The mathematical foundation of this interpretation is found in Chap. 14, Vol. 1 in the form of postulates that describe the transformation of the properties of quantum objects into measurable quantities. A state vector of the Hilbert space (or the wavefunction) provides a complete description of a real, existing individual system. Therefore we also speak of a realistic (as opposed to an instrumentalist or pragmatic) interpretation. This does not mean that we assume that *each* element of the theory has a complete correspondence in the real world; in general one assumes e.g. that the wavefunction has no real counterpart, but rather it simply provides the maximum information about a single system.<sup>18</sup>

In contrast to the minimal interpretation, one can also attempt to include the measurement process into quantum mechanics. To that end, the concept of 'collapse of the wave function' is introduced, without its however being clear how this collapse takes place in detail. For this dilemma, the concept of decoherence seems to show at least a partial way out, as we have seen in Chap. 24. Whether one would denote the standard interpretation with or without decoherence as a Copenhagen interpretation is again mostly a matter of taste. After all, some protagonists of decoherence see themselves in their own words 'in the tradition of the Copenhagen interpretation'. In any case, the standard interpretation, complemented by decoherence, is a currently widely-accepted interpretation of quantum mechanics.

#### 28.2.2 Ensemble Interpretation

This interpretation came about in the early days of quantum mechanics along with the Copenhagen interpretation, and as a reply and alternative to it; among its supporters were Einstein and Langevin. According to this interpretation, also called the statistical interpretation, the wavefunction is an abstract mathematical entity and does not apply to a single system, but rather refers to an ensemble of identically prepared systems. Where this limitation originates is not stated. In principle, this interpretation does not immediately rule out the possibility that the measured quantity has a well-defined

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<sup>16</sup>Some authors denote as *orthodox* the view that an observable has no definite value if the state (or ray) is not in an eigenspace of the observable.

<sup>17</sup>We note that some authors denote every formulation which involves no hidden variables or extensions of the SEq as a 'standard interpretation'.

<sup>18</sup>This is similar to the vector potential in electrodynamics. The attitude that the vector potential is a purely mathematical entity however is in conflict with the (quantum-mechanical) Aharonov–Bohm effect, in which an electron is influenced by the vector potential instead of by the magnetic field itself.

value for each member of the ensemble (in the sense of hidden variables or pre-existing values). However, this notion received a major blow from Bell's theorem and the experiments of Aspect. Therefore, a newer version excludes the question of the determinism of physical quantities, which of course limits its value for making meaningful statements.

### 28.2.3 *Bohm's Interpretation*

This interpretation, developed in 1952 by David Bohm, is based on the 'pilot' or 'guiding' wave theory, which Louis de Broglie originated in 1927 (which is why it is also called de Broglie–Bohm theory). The wavefunction here plays two roles: On the one hand, its squared value provides information on the most probable position of the particle; on the other hand, it affects the coordinates of the particle in the form of a 'quantum potential'. The physical state of a particle is completely determined by the combination of the wavefunction *and* the particle position. Both the wavefunction and the particle coordinates are regarded as real; however, the latter are unobservable and are thus the hidden variables in this interpretation.

The probabilistic character of quantum results is attributed to our ignorance of the hidden variables, i.e. to the factual impossibility of determining the initial values of all particle coordinates. In this interpretation, there is no collapse, and the particles move along well-defined trajectories. Measurement means, therefore, only the reduction of our ignorance about the system, not the generation of the measured values themselves.

A major difference from classical physics is that this interpretation is nonlocal.<sup>19</sup> and that there are accordingly instantaneous interactions. If we make changes, for example, to a particle in a many-particle system, then the total wavefunction changes instantaneously, and with it also the quantum potential and thus the trajectories of all the other particles.

In Appendix V, Vol. 2, a brief description of the mathematical approach of the Bohmian interpretation is given. We point out that the Bohmian and the Copenhagen interpretations make the same predictions, so that experiments cannot decide between the two approaches. On the other hand, this also means that the Bohmian interpretation also contains the same problematic superpositions.

### 28.2.4 *Many-Worlds Interpretation*

The many-worlds interpretation dates back to Hugh Everett (1957). It is an example of how to rigorously keep the mathematical part of quantum mechanics and yet make other statements about reality.

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<sup>19</sup>This is insofar striking, as Bohm's ideas really were aimed at the elimination of the non-locality e.g. in the EPR experiment through hidden variables. But, as he says himself: "If the price of avoiding non-locality is to make an intuitive explanation impossible, one has to ask whether the cost is too great." David Bohm et al., *Phys. Rep.* 144, 321 (1987).

The basic idea is to assume that it makes sense to speak of the state vector of the *entire* universe; it is real and evolves deterministically (and reversibly) according to the SEq. In contrast to the (older) Copenhagen interpretation, there is neither a collapse of the wavefunction nor is there, in addition to quantum mechanics, a classical domain describing the measurement apparatus. Instead, it is assumed that in a measurement, or in each physical interaction, *all* physically possible events are realized. This is accomplished by the splitting of the entire universe into many parallel worlds, whereby in each parallel world exactly one of the possible outcomes is realized. Accordingly, we must therefore imagine an ongoing birth of many parallel worlds.

As a result of decoherence effects,<sup>20</sup> *macroscopically* different parallel universes develop independently. This is also true for the observers—in each parallel universe, there is a separate observer, not perceiving the other observers (his ‘parallel clones’ or ‘parallel egos’). *Microscopically* different parallel universes, however, can interact, and an observer can interpret this as interference effects. Thus, the collapse of the wavefunction is a process noticed only by the respective observer, and it bears the character of objective chance, since it is not objectively predictable by that observer. However, the entire universe is, as we said above, strictly deterministic, and on this scale there is no objective chance.<sup>21</sup>

It goes without saying that the many-worlds interpretation was enthusiastically taken up by science fiction and fantasy fans.<sup>22</sup> In physics it is very controversial. Some see in it the solution to (almost) all problems, while for others it has the status of silly esoteric paraphernalia—both of these attitudes can be associated with the names of renowned physicists. After all, this interpretation solves the measurement problem without any modification of the formalism of quantum mechanics. As such, it enjoys great popularity with quantum cosmologists. For example, C.J. Isham writes (Lectures on Quantum Theory, Mathematical and Structural Foundations, pp. 183): ‘Indeed, it is rather difficult to think of *any* interpretation of quantum cosmology that does not invoke this view<sup>23</sup> in one way or another. Thus ‘post-Everett’ schemes<sup>24</sup> have become almost obligatory for those working in the physics of the very early universe.’

Some further comments on the many-worlds interpretation can be found in Appendix V, Vol. 2.

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<sup>20</sup>Today, one can argue in this way; in 1957, the term ‘decoherence’ was not yet known.

<sup>21</sup>The idea of parallel or multiple universes is not a peculiarity of quantum mechanics; in general relativity and string theory, there are several models of multi- and pluriverses (keywords e.g. ‘infinite space’, ‘bubbles’ or ‘eternal inflation’, ‘nested multiverses in black holes’).

<sup>22</sup>A short version, with a wink of an eye: “There are indeed such things as parallel universes, although parallel is hardly the right word—universes swoop and spiral around one another like some mad weaving machine or a squadron of Yossarians with middle-ear trouble. And they branch. But, and this is important, not all the time. The universe doesn’t much care if you tread on a butterfly. There are plenty more butterflies” Terry Pratchett, in *Lords and Ladies*.

<sup>23</sup>I.e. the many-worlds interpretation.

<sup>24</sup>‘Post-Everett’ essentially refers to the assumption that there are no external state reductions and thus the time-dependent SEq always applies.

### 28.2.5 *Consistent-Histories Interpretation*

This interpretation, which summarizes and generalizes in a sense the Copenhagen and Many-worlds interpretations, was introduced in 1984 by R. Griffiths. The term ‘history’ here means simply an ordered sequence of physical events—it is about the construction of inherently consistent processes. A history  $H_i$  is a set (a sequence) of statements  $A_{i,j}$ , each at a time  $t_{i,j}$ , in the form  $H_i = (A_{i,1}, A_{i,2}, \dots, A_{i,n})$ . A physical process can be generally described by a number of different histories, which are combined into a history family. The core of the interpretation is a consistency criterion by which it can be checked whether the probability of the history family equals the sum of the probabilities of the individual histories, and thus the additive law of classical probabilities is satisfied.<sup>25</sup> Such history families are called consistent. An observer is not needed in this interpretation, but, on the other hand, here also the measurement problem is not solved in the end. Some further comments can be found in Appendix V, Vol. 2.

### 28.2.6 *Collapse Theories*

The first collapse theory (also called dynamical reduction theory) was developed 1984/5 by Ghirardi, Rimini and Weber and is named GRW theory after the authors. In the meantime, several variants have appeared. All have in common that the SEq is extended by non-linear and/or stochastic additional terms<sup>26</sup>; in this sense, they are therefore actually more likely to be seen as new theories than as interpretations. The additional terms are constructed in such a way that they ‘disentangle’ entangled states of large systems, and that a system collapses spontaneously into a spatially-localized state (spontaneous localization, dynamic collapse). Of course, the additional terms are adjusted so that these effects are very small in isolated microscopic systems, but very large and pronounced in macroscopic systems. Hence, these are realistic theories without hidden variables; a special observer is not needed. Because of the additional terms, one can in principle experimentally detect deviations from the usual quantum mechanics, even though this is not yet possible with current technology. Some further remarks on the GRW formalism can be found in Appendix V, Vol. 2.

A kind of mass-bounded mechanism was suggested by Roger Penrose. Accordingly, there is a gravitational effect on the mass of the quantum system that causes the collapse of the wavefunction. The heavier the system, the stronger and faster is the effect of gravity, so that for macroscopic systems, the collapse takes place almost immediately.

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<sup>25</sup>The focus is thus on the history of a system and not on the value of an observable at a particular time.

<sup>26</sup>GRW proposed a stochastic additional term. Nonlinear terms can, for example, be based on gravity in the context of general relativity.

### 28.2.7 *Other Interpretations*

There are a number of other interpretations of quantum mechanics<sup>27</sup> which arose mainly in the last 30 years. A compact and brief overview, partly in tabular format, is provided by the Wikipedia article ‘Interpretations of quantum mechanics’.<sup>28</sup> It contains also an extensive index, encompassing original articles, secondary literature, textbooks and web addresses. There are corresponding articles in some other languages, most of them also very instructive.

Finally, we want to refer briefly to the question of whether measurement has something to do with *consciousness*. This is a very controversial subject that is often classified as untrustworthy and highly speculative. Nevertheless, we want to summarize briefly some of the positions held.

In principle, these approaches differ in terms of the assumption of whether consciousness can be described in physical terms or not. The second group includes, for example, an early approach of von Neumann, according to which the human consciousness cannot be described by physics; but even so, as the ultimate measurement apparatus, consciousness transforms the possible into the factual on perceiving the result of a measurement. Of course, the introduction of consciousness as a non-physical category, which nevertheless significantly affects physical results, is very unsatisfactory from a physical standpoint. We have only to think of quantum cosmology, which starts from quantum states of the entire universe; to maintain the range of validity of the deterministic SEq, we should therefore demand a ‘universal consciousness’.

The many-minds interpretation, a variant of the many-worlds interpretation, also introduces consciousness as a new category. There is however no real, observer-independent splitting into parallel universes, but rather it is the brain or the consciousness of the individual observer which causes this splitting due to its self-awareness. There are different ideas about how this mechanism works; for example, J.B. Hartle explains (*Am. J. Phys.* 36 (1968) 704): “This ‘reduction of the wave packet’ does take place in the consciousness of the observer, not because of any unique physical process which takes place there, but only because the state is a construct of the observer and not an objective property of the physical system.”

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<sup>27</sup>Here one may also refer to *quantum logic*. This approach was suggested for the first time in 1936 by Birkhoff and von Neumann. By and large, it is about a modification of classical logic and its adaptation to the structure of Hilbert space. Classically we have, for example, yes-no statements with which, however, we cannot describe adequately the behavior of non-commuting variables such as position and momentum (is ‘wrong’ the same as ‘not true’?). The basic idea may perhaps be described as follows: The classical view of an event is a subset of a total set (Abelian or commutative, distributive); in the view of quantum mechanics, an event is instead regarded as a subspace of a Hilbert space (non-Abelian, non-distributive).

<sup>28</sup>[http://en.wikipedia.org/wiki/Interpretations\\_of\\_quantum\\_mechanics](http://en.wikipedia.org/wiki/Interpretations_of_quantum_mechanics) (accessed Dec 2017). Of course, there are always new papers on existing interpretations (e.g. D.H. Mahler et al., ‘Experimental nonlocal and surreal Bohmian trajectories’, *Science Advances* 2, doi10.1126/sciadv.150146619 (Feb 2016)) as well as new approaches and considerations (e.g. R. E. Kastner et al., Taking Heisenberg’s Potentia Seriously, arXiv:1709.03595v4 (Oct 2017)).

However, if one takes the position that consciousness can be described in physical terms, one has to somehow make sure that the brain is ‘disentangled’, i.e. that it is not found in superposition states. This can be achieved either by means of a kind of many-minds interpretation, or by a corresponding collapse theory (e.g. with suitable non-linear terms), as it was postulated in an early form by Wigner (1961).<sup>29</sup> A different approach is offered by decoherence considerations, with the argument that decoherence effects (e.g. in nerve signal propagation) proceed so rapidly that the brain (considered as a quantum-mechanical system) is never perceptibly in a superposition state.

### 28.3 Conclusion

Central concepts of quantum mechanics such as probability, entanglement, state reduction, and measurement link it to fundamental epistemological categories such as deterministic versus random chance, or realism, non-locality, positivism versus subjectivism. In these aspects, quantum mechanics, although it functions excellently fapp, leaves open many questions.<sup>30</sup> To answer these as consistently as possible on a level beyond the mere application of the formalism is the aim of the various interpretations of quantum mechanics.

Obviously, however, none of the currently-discussed approaches can be considered as *the* solution. For each interpretation, there are pros and cons; none of them can prevail against its rivals on the basis of generally convincing objective reasons. In other words, which interpretation one prefers is more a question of taste or gut instinct than of logic.<sup>31</sup> Experimentally, one cannot necessarily expect a clarification. In fact, in recent years, certain issues have been decided in the laboratory (keyword ‘Bell’s inequality’), so that in the context of modern quantum mechanics the slogan ‘practical metaphysics’ or ‘experimental philosophy’ was coined. But since most current interpretations are not experimentally falsifiable, partly in principle, partly just not yet,<sup>32</sup> it will be difficult to bring about a decision in this way.

A fascinating aspect of this situation is, among others, how well quantum mechanics ‘works’ in spite of this interpretative fog and mist; in terms of its practical

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<sup>29</sup>This approach has been quite popular at times and was then sometimes referred to as the ‘standard interpretation’. We see again how diffuse the terminology can be in this area.

<sup>30</sup>Quite apart from further implications such as that ‘entanglement’ is in direct contradiction to the analytical, reductionist approach of occidental science.

<sup>31</sup>A non-representative survey among participants of the conference ‘Quantum Physics and the Nature of Reality’ (July 2011) revealed, among other things, that 42% favor the ‘Copenhagen interpretation’, 24% an ‘information-based or information-theoretical interpretation’ and, after all, 18% the many-worlds theory of Everett. Unfortunately, the initiators of the survey left out the position of ‘shut up and calculate’ which ignores the issues of interpretation and aims at the utility of quantum mechanics in concrete applications. M. Schlosshauer et al., ‘A Snapshot of Foundational Attitudes Toward Quantum Mechanics’, arXiv:1301.1069 (2013).

<sup>32</sup>We remember that it is not possible to justify the validity of a theory from a finite set of experiments, i.e. to verify it. Only its falsification is unique.

applications, there is virtually no dissent. Although, from this perspective, the discussion of interpretations may seem unnecessary, it belongs for many physicists to the self-image of physics to provide more than a collection of formal rules, but instead to aim at the most faithful possible representation of reality in the sense of a closed physical worldview. Insofar, such discussions as those about the interpretation of quantum mechanics are not simply meaningless for science, but rather they help to identify more sharply the problems and open issues. In addition, for example, the discussion about the term ‘entanglement’ shows that such ‘soft’ and non-formal debates can lead to very concrete results, for example the quantum computer.

To be fair, we must state that today we cannot foresee with certainty which (if any) of the current interpretations will prevail. Of course, quantum mechanics will (and must) continue to develop; just think of the missing link between quantum mechanics and gravity (or general relativity). But to what extent this development will help to clarify the open epistemological questions remains to be seen.

In any case, the situation is currently such that, as we pointed out in Chap. 27, even the foundations of physics are no longer taboo, and it is being discussed, among other things, whether we need a major revision including tacitly made assumptions such as logic or causality. It would not be a particularly great surprise if necessary extensions of quantum mechanics should prove to be extremely counter-intuitive.

Be that as it may—important issues are still unclear and open at present; no one knows on what journey quantum mechanics will yet take us. Only one thing is certain: it remains exciting and fascinating—the suspense continues.