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Philosophy of Quantum Mechanics

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Quantum physics is one of the cornerstones of modern physics and a scientifically informed philosophy of nature needs to integrate it. In particular, quantum mechanics is thought to have implications for example for the question whether nature is deterministic, the (im)possibility to observe without intervening, and the possibility of non-local interactions. However, if we look more carefully at what exactly quantum mechanics implies, we encounter a problem: there are different interpretations of quantum mechanics, which are all compatible with observations but which paint very different pictures of physical reality. This entry tries to orient the reader within this complex debate. We introduce briefly what quantum physics is about, what its main interpretations look like and whether some general conclusions with regard to metaphysics and natural philosophy can be drawn from it.

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1. Introduction

Quantum mechanics or quantum physics – we use these terms interchangeably – originated in 1900 from investigations into the theory of heat radiation (Max Planck), had early applications, e.g. in solid state physics in 1907 (Albert Einstein) and eventually, starting with Niels Bohr's famous model of the atom from 1913, became the "new atomic physics". The current formulation of quantum mechanics was developed by Werner Heisenberg (1925) and Erwin Schrödinger (1926). The name "quantum" refers to "discrete quantity", and one feature of quantum physics is indeed the fact that (for bound states) certain measured quantities do not take on a continuous range of values but can only take on a restricted number of values (like a dice that can show six values, but no values in between). If, for example, a quantum system (e.g. some atom bound in a crystal) oscillates with the fixed frequency f, its energy is given by the discrete amount $\varepsilon = h \cdot f$ (or integral multiples of it) with h, the so-called Planck constant, having the (compared to everyday standards) very small value $h \approx 6.6 \cdot 10^{-34}$Js.

According to present knowledge, quantum mechanics is needed to describe the behaviour of all matter at the atomic and subatomic scale, and its predictions are supported by countless experiments. Today also the established standard model of elementary particles is formulated as a quantum (field) theory. But famously, until now the general theory of relativity defies all attempts to be reconciled with quantum theory. However, quantum effects, e.g. the discreteness of energy levels, are often negligible in macroscopic circumstances, as the Planck constant is generally too small to let its discontinuous character lead to observable effects. But there are also macroscopic quantum phenomena, such as superconductivity (i.e. the sudden disappearance of electrical resistance at low temperatures due to quantum effects which couple electrons to so-called Cooper pairs) and the so-called giant magnetoresistance (i.e. the influence of magnetization and electrical resistance in specific materials which is exploited in many computer hard drives). Furthermore, genuine effects of atomic physics have real-world impact, for example the fusion of hydrogen atoms which fuels our sun or the working of lasers and semiconductor technology (products of the so-called "first quantum revolution").

Right now we find ourselves in the midst of the "second quantum revolution" which is driven by quantum computers, quantum cryptography and other technologies which exploit the novelties of quantum physics more directly. Thus, the importance of quantum physics can hardly be overstated. This extends also to issues in the philosophy of nature (and beyond).

Quantum mechanics is routinely presented as puzzling or mysterious, and many different (sometimes very startling) conclusions about physical reality have been drawn from it. Quantum mechanics is thought to have implications for example for the question whether nature is deterministic, the (im)possibility to observe without intervening, and the possibility of non-local interactions. However, if we look more carefully at what exactly quantum mechanics implies, we encounter a problem: there are different interpretations of quantum mechanics, which are all compatible with observation, but which paint very different pictures of physical reality.

After the modern theory of quantum mechanics was introduced in 1925 and 1926, physicists debated about the foundations and proper interpretation of the theory (on the distinction between 'theory' and 'interpretation', see 4.). In the 1950s, the view became established that the main foundational issues had been solved and that a general consensus had been reached, although there were always a few dissidents (Howard 2004; Camilleri 2009). Since then, however, several alternative interpretations have been developed and new insights in the foundations of quantum mechanics have been obtained (Freire 2014). The present situation is that among physicists there is still a widespread view that there is only a single satisfactory interpretation (the 'Copenhagen interpretation', discussed in 2.2 – although in fact, there are significant differences in how it is understood by different physicists), but it is less universally accepted than before, while among philosophers of physics there is a wide variety of views and a great lack of consensus (Schlosshauer et al. 2013).

Therefore, if we want to say anything about the philosophical implications of quantum mechanics, we have to be aware of this plurality of interpretations.

We will first give an extremely short introduction to quantum mechanics and briefly introduce its mathematical formalism (we restrict ourselves to a non-relativistic formulation). We then present some of the main interpretations of quantum mechanics, which each try to give a specific meaning to the formalism. Finally, we will outline what the main messages for the philosophy of nature might be.

2. The formalism of quantum mechanics

For those readers with some background knowledge in linear algebra and calculus, the quantum novelties can be most easily explained with the help of the mathematical formalism of the theory (2.1). For an in-depth understanding of quantum mechanics, this is even a prerequisite. However, we conclude this section with a non- (or rather less-) technical summary for readers who lack this background knowledge (2.2).

2.1 The technical version …

While in other areas of physics the state of a system can generally be characterized by a full list of all its properties (say, positions, momenta etc.), quantum mechanics represents the state of a system by a wave function $\psi(x,t)$, or, equivalently, by a state-vector $|\psi(t)\rangle$ in some abstract state space. This vector is the solution of the corresponding Schrödinger equation $\frac{ih}{2\pi}\frac{\partial\psi}{\partial t} = H\psi$, which describes how the wave function of a system evolves in time. The resulting evolution is "unitary", i.e. among other things deterministic, reversible and linear.

Dynamical quantities like position or momentum ("observables") are represented by so-called Hermitian operators O, i.e. something that takes a vector $|\psi(t)\rangle$ as input and spits out another vector: $O|\psi(t)\rangle = |\tilde{\psi}(t)\rangle$. If the result is $\lambda|\psi(t)\rangle$ we say that $|\psi(t)\rangle$ is an eigenvector of O with eigenvalue λ. These eigenvalues are real numbers and correspond to the possible measurement values. For instance, the symbol H used in the Schrödinger equation is such an operator: it denotes the Hamilton operator which represents the energy of the system.

Generally, the concepts used in quantum physics to describe the properties of systems are the same as those used in pre-quantum physics: position, momentum, energy, etc. The only exception is a property called "spin" which is introduced in quantum physics. For example, electrons (but also, e.g. silver atoms) are spin-$\frac{1}{2}$ objects. A spin measurement along a specific direction can yield only $+\frac{1}{2}$ or $-\frac{1}{2}$ (in units of $\hbar = \frac{h}{2\pi}$). These states are often called "spin up" and "spin down". This discreteness is again a typical feature of quantum physics. Given the simplicity of spin-$\frac{1}{2}$ systems (being only two-valued), they serve as a popular example for quantum effects.[1]

With $\{|n\rangle\}$ an orthonormal basis of eigenvectors of a Hermitian operator A, any state can be expanded as $|\psi\rangle = \sum c_n|n\rangle = c_1|1\rangle + c_2|2\rangle + \cdots$ (with $A|n\rangle = n|n\rangle$). The so-called Born-rule states that for such a state the probability to obtain the value n upon measuring the quantity represented by A is given by $|c_n|^2$. Given this probability interpretation, expectation values and standard deviations can be defined accordingly.

Under a given basis any (Hermitian) operator can be represented by a matrix. Unlike numbers, matrices generally do not commute under multiplication, i.e. $AB \neq BA$. It is a basic result from linear algebra that operators which do not commute have no common basis of eigenvectors. Within the quantum mechanical formalism this implies that the corresponding observables cannot have sharp values simultaneously. The Heisenberg uncertainty relation for position and momentum, $\Delta x \Delta p \geq \frac{h}{4\pi}$, is a direct implication of this relationship (another example would be spin measurements along different directions). And this brings us back to our first remark: Unlike classical physics, quantum mechanics cannot describe a state by a full list of all of its properties, since the uncertainty relations restrict the quantities which can have sharp values at a certain moment in time. Additionally, all quantum mechanical predictions are merely probability statements for possible measurement outcomes.

2.2 … and the less technical version

The less technical summary of the above is the following: In quantum physics a system is described by a wave function $\psi(x,t)$. This wave function is complex valued, and it is an abstract entity which is not easily interpreted as a physical object. The wave function and its time evolution are calculated from the fundamental Schrödinger equation, i.e. the quantum analogon to Newton's law of motion $F = m \cdot a$ (i.e. “force equals mass times acceleration”) in classical mechanics.

A distinctive feature of quantum mechanics is that a system can be in a superposition of different states, which means that a system can be in a combination of two states: if ψ_1 and ψ_2 are possible states of the system, then also $\psi = c_1\psi_1 + c_2\psi_2$ (with c_i complex numbers) is a possible state of the system. For example: if an electron may be located in region A or region B, then it can also be in a superposition of being in region A and being in region B.

Importantly, the properties of the system (say position, momentum or energy) may not always be well-defined. In particular, the Heisenberg uncertainty relation states that the position and momentum of a particle cannot simultaneously have a sharp value. A state which possesses a well-defined property is called an eigenstate with respect to this property.

Generally, quantum theory only yields probabilities for different measurement outcomes, and no exact predictions. These probabilities can be calculated from the wave function.

A curious fact about quantum physics is that it introduces no new elementary properties, and the pre-quantum concepts of position, momentum, energy, etc. retain their significance. The only exception is the so-called “spin”— a novel quantum property which is a kind of angular momentum. Spin takes discrete values, for example, the measurement of the spin of an electron in a certain direction can only yield one of two possible values (which are called spin up and spin down).

Already at this point a number of “quantum novelties” are notable, namely states with apparently no well-defined properties (or being in a superposition of different properties) and fundamentally probabilistic predictions. Furthermore, because the theory does not give exact predictions for measurement outcomes but only yields probabilities, there is the question of how the measurement of a single value actually comes about. The latter turns out to be a major problem for interpreting the theory.

In closing we should emphasize that also in classical (pre-quantum) physics quantities may superimpose (e.g. forces or directions of movement). However, the corresponding (classical) system is nevertheless in a well-defined state with well-defined properties. Furthermore, classical physics also includes probability statements

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[1] In addition, the corresponding system is a possible realization of a “qbit”, i.e. the quantum bit of quantum information theory. While the classical bit can have only two values (say, “0” and “1”) the qbit can possess any superposition of these two states, which gives rise to the famous “quantum parallelism” in quantum computing.

(e.g. in statistical mechanics). However, these probabilities express only our ignorance about the specific state, i.e., are just epistemic.

An entertaining way to learn more about quantum superpositions and quantum probabilities is by playing "Quantum Tic-Tac-Toe". In this quantum version of the familiar game one can place the game icons on several fields simultaneously (i.e. in a "superposition" of several fields). Only after all fields being filled a "measurement" is performed and the "actual" positions appear randomly. Check it out!

3. Measurement problem

The "measurement problem" in quantum mechanics is the problem of how the measurement of a physical quantity can yield a definite outcome, even though according to the theory of quantum mechanics, the quantity had no well-defined value before the measurement was made. For example, a silver atom can have a spin up or a spin down, but can also be in a superposition of a spin-up and a spin-down state. When you measure the spin, however, it is always found to be either spin-up or spin-down, and never in a superposition. This has brought about the idea that it is only through the process of measurement that a quantum system obtains well-defined properties. This issue has generated much debate in the philosophy of quantum physics, and many different views have been proposed on how to understand the measurement process in quantum mechanics. (See Schlaudt 2020 for a general discussion of measurement.)

This measurement problem becomes clearer if you consider that measurement instruments are built out of atoms and should therefore themselves obey quantum mechanics. In the above example, the spin of silver atoms can be measured by directing a beam of silver atoms through a so-called Stern-Gerlach magnet: thereby a splitting into the spin-up *or* spin-down state is observed on the screen. However, in principle the measuring device could also be treated quantum mechanically; but then it seems that it should evolve into a superposition of "screen showing spin-up" *and* "screen showing spin-down". Thus, John Bell famously asked the question how a measurement turns an "and" (i.e. the sum of different terms in the superposition) into an "or" (i.e. the mutually exclusive and definite result of each measurement). This is one way to put the infamous "measurement problem".

An extreme version of the problem is the one proposed in Schrödinger's famous cat-article from 1935. Schrödinger proposed a thought experiment in which a cat is trapped in a box together with a poison which is released upon a radioactive decay. After some time, the radioactive atom is in the superposition of already decayed and not yet decayed. Hence, the cat is apparently in the superposition of "dead" and "alive", and only by opening the box ('measuring') does the cat obtain a well-defined state of being either dead or alive. This is clearly an absurd result: the thought experiment was designed by Schrödinger to show the absurdity of the implications which quantum mechanics appeared to have.

An especially helpful formulation of the measurement problem in the form of a trilemma was given by Tim Maudlin (1995). Slightly simplified, the three horns of the trilemma read:

- *(comp)* The wave function provides a *complete* description of the *individual* state.
- *(schrö)* The time evolution is *always* given by the *Schrödinger* equation.
- *(def)* Measurements have a *definite* outcome.

While all of these propositions seem reasonable at first, any two of them imply the negation of the third: therefore, at least one of these three propositions must be false. For example, suppose that (comp) and (schrö) are valid: this means that the state of a system is completely described by the wave function, which evolves according to the Schrödinger equation. In this case, if the system is in superposition, then an interaction with a measurement instrument results in the measurement instrument being in a superposition as well, and the measurement cannot not yield a definite outcome: thus, (def) cannot hold. Next, suppose that (comp) and (def) are valid: then the state of the system is completely described by a wave function, and a measurement of this state yields a definite outcome. This means that when a measurement takes place, the wave function changes in a way which is not described by the Schrödinger equation: the measurement brings about a "collapse" of the wave function, a sudden and unexplained reduction to the observed eigenstate. This means that (schrö) is false. Finally, suppose that (schrö) and (def) hold. Then some piece of information seems to be missing in the state description, in order to single out the definite outcome of each individual measurement. This would imply that the wave function provides only an incomplete state description, i.e. (comp) has to be false. Essentially all interpretations of quantum mechanics can be classified by their strategy to avoid this trilemma, i.e. by rejecting one of its horns.

4. Interpretations

The interpretation of quantum mechanics is among the most debated issues in the philosophy of physics. The very need to "interpret" the mathematical formalism is intriguing and is arguably without precedent in science. It is true that in a sense, a mathematical theory in physics always needs to be interpreted, given that the mathematical symbols need to be assigned to natural phenomena; and it is true as well that also, e.g. Newtonian mechanics, statistical physics or electrodynamics are subjects to philosophical debates on how the theory should best be understood. But in the case of quantum mechanics, the way the mathematical formalism relates to the natural world is not at all evident: the complex valued wave function does not refer to any physical object in an obvious manner, and the theory of quantum mechanics does not give a description of the process of measurement. This has given rise to a plurality of interpretations of quantum mechanics, which give different accounts of how the formalism relates to the natural world.

However, the huge success of quantum physics indicated in the introduction illustrates that the corresponding theory is operationally well understood and that, e.g., the measurement problem apparently provides no immediate threat to scientific progress. This reflects the fact that the different interpretations typically agree in all predictions.

Presumably most practicing physicists (who try to avoid philosophical debates) endorse a minimal interpretation of the theory (4.1) or some variant of the "Copenhagen interpretation" (4.2). Rivals are the "many-worlds interpretation" (4.3) and the "de Broglie-Bohm theory" (4.4) which introduce a trade-off between philosophically desirable and awkward features. Finally, there is a class of interpretations which tackles the measurement problem head-on by introducing an explicit collapse mechanism (4.5).

It has to be noted that some of these 'interpretations' should perhaps rather be viewed as alternative theories of quantum mechanics, rather than as interpretations of the same theory, given that they modify the Schrödinger equation or posit extra theoretical structure (although the precise definition of the term "theory" is a debated issue as well). This holds in particular for the "de Broglie-Bohm theory" and for collapse interpretations. However, these theories have exactly the same predictions as standard quantum mechanics and are traditionally subsumed under the label "interpretation".

Within philosophy of science, there is a debate about the possibility that scientific theories are *underdetermined* by the empirical data: This means that there can be more than one theory compatible with the available empirical evidence, so that the evidence does not suffice to choose the right theory (Stanford 2017). There are often thought to be few examples of underdetermination in actual scientific research. However, insofar as some of the 'interpretations' of quantum mechanics can be regarded as alternative *theories*, which can account for exactly the same observations as the standard theory, quantum physics provides a strong example of the underdetermination of scientific theories by data (Cushing 1994; Acuña 2021; on underdetermination in philosophy of science, see Stanford 2017).

Our list of interpretations is not even complete. As noted by David Mermin (2012): "New interpretations appear every day. None ever disappear."

4.1 The minimal interpretation

A simple way to circumvent the measurement problem is to deny that quantum physics is supposed to describe individual systems at all (be it cats – recall Schrödinger's cat discussed in section 3 – or measurement devices). On this reading, the Born rule provides only the statistics of repeated measurements, and the wave function is the description of an "ensemble" of identically prepared systems – and not of individual systems (thus, this specific version of (comp) is rejected). This view has been championed by Ballentine (1970) but, e.g., some of Einstein's writing is pointing into a similar direction.

This interpretation fits the needs of practicing physicists who often deal with huge samples of quantum systems in their labs. But this "ensemble" interpretation seems philosophically unsatisfying since it remains unclear, e.g. whether these probabilities refer to "objective" facts or express merely "subjective" knowledge. Friebe et al. (2018: 44) conclude: "For the metaphysics of science, this is not sufficient, and most physicists would also prefer to have some idea of what is behind those measurements and observational data, i.e. just how the microscopic world which produces such effects is really structured." For some of these reasons this "ensemble interpretation" plays only a minor role in the current debate.

4.2 The Copenhagen interpretation

Many textbooks call the Copenhagen interpretation (CI) the "standard interpretation" of quantum mechanics. The common claim is that this view was developed by Niels Bohr and his colleagues in the late 1920s. However, as discussed more closely in the entry on the "history of quantum mechanics", the CI was never codified and the members of the corresponding school (say, Heisenberg, Pauli, Born, Jordan and von Neumann) held partly dissenting views on important issues.

At the basis of Bohr's thought on quantum mechanics is the idea that experiments necessarily have to be described with classical concepts, while at the same time, these concepts are subject to restrictions and cannot all be applied simultaneously (Bohr 1928). Bohr coined the term "complementarity" for the mutually exclusive but jointly necessary descriptions which can be given with different concepts. For example, one can either attribute a position or a momentum to a particle, but not both at the same time; and in Bohr's view this has to do with the fact that to measure the position or the momentum of a particle requires different experimental setups, which exclude each other.

This seems (in the view of some commentators) to imply that measuring devices belong to a separate "classical domain" beyond the scope of quantum physics, which compromises the completeness of the (state-)description (i.e. ¬(comp) in the terminology of Maudlin). Most important is the fact that according to Bohr, there is always an interaction between measurement and the observed system which compromises the "independent reality" of both, the "phenomena" and the "agencies of observation" (Bohr 1928: 580).

In Bohr's version of the CI there is no "collapse" of the wave function; however, it is often taken to be part of the CI that a collapse of the wave function takes place with measurement. This is the case, e.g. in the versions of von Neumann and Heisenberg. If the collapse (or projection) postulate is included into the CI this is at odds with the universal validity of the Schrödinger equation, i.e. ¬(schrö) – but without detailing this process further. Whether the CI allows for a satisfactory solution of the measurement problem is therefore debated. Famously, Schrödinger and Einstein, two founding fathers of quantum theory, remained hostile to this interpretation.

4.3 The many-worlds interpretation

According to Maudlin's trilemma, the measurement problem can only be solved if one of its premises is dropped. The many-worlds interpretation challenges the claim that measurements have definite outcomes. This view was developed in 1957 by Hugh Everett III under the name "relative state formulation" and is also sometimes known as "Everett interpretation"; it was popularized by de Witt and Graham (1973) who also coined the catchy name "many-worlds interpretation". According to this view, only the *appearance* of definite outcomes needs to be explained. If, according to quantum mechanics, a wave function splits into different branches (say, upon measuring the spin state of a silver atom in a Stern-Gerlach experiment) the many-worlds interpretation assumes that both components of the superposition represent an actual state of the system. Metaphorically speaking, the corresponding spin-up and spin-down states are realized in different "worlds" which are separated not in space-time but dynamically. Wallace (2012: 37) puts it pointedly: "Macroscopic superpositions do not describe indefiniteness, they describe multiplicity." In order to explain the appearance of definite outcomes, one extra step is needed, namely that the observer is subject to this multiplicity as well. Thus, this interpretation assumes that "the universe is constantly splitting into a stupendous number of branches, all resulting from measurement-like interactions between its myriads of components" (De Witt/Graham 1973: 161).

Obviously, this interpretation has the air of extravagance. But there are also serious technical problems with it. At the time it was popularized by De Witt in the early 1970s Leslie Ballentine was among the first to point out that this interpretation suffers from the so-called "non-uniqueness of the state decomposition". After all, a quantum mechanical state can be mathematically decomposed in many different ways and the question which of these decompositions underlies the actual splitting needs to be answered (Ballentine 1973). The solution of this problem was eventually achieved by decoherence theory, first introduced by Heinz-Dieter Zeh already in 1970 (and unnoticed by the community at that time). The key insight was to include the unavoidable interaction with the environment (i.e. degrees of freedom which are not under control). In decoherence theory, detailed models of the interaction process between the environment and the quantum system give rise to a privileged status of a specific decomposition (i.e. the so-called pointer basis).

Zeh's work did not receive the deserved recognition and the decoherence theory only gained more momentum with the work of Wojciech H. Zurek since the 1980s. Importantly, its results hold independent of any specific interpretation, or, to put it differently, are exploited in many different interpretations (see, e.g., 4.4 below). Hence, decoherence theory holds the promise to contribute to any solution of the measurement problem that may be achieved in the future.

In recent years the decoherence-based approaches to the many-worlds interpretation have gained popularity among philosophers of physics. Its modern version is championed, e.g. by David Wallace. However, this interpretation struggles hard in order to explain the role of probability. According to widespread understanding, a probability assignment needs several possible outcomes and uncertainty about the actual occurrence. In the many-worlds interpretation both premises are missing because (so to say) “everything” is “always” happening (see Wallace 2012 for a possible way out by applying techniques from decision theory). Despite these difficulties, the consistency of the many-worlds interpretation is generally accepted.

4.4 The de Broglie-Bohm theory

The de Broglie-Bohm (dBB) theory (aka Bohmian mechanics, pilot wave theory, causal or ontological interpretation) challenges the claim that the wave function provides a *complete* description of individual systems, i.e. ¬(comp). The many names reflect that this theory was anticipated by Louis de Broglie already at the 5th Solvay conference in 1927, independently rediscovered by David Bohm (1952) and further developed by various people including John Bell, Peter Holland, Detlef Dürr, Sheldon Goldstein, Nino Zanghì and others. The strategy of the dBB theory is to add a specification of the positions of all particles (i.e. the configuration) to the description of a quantum system. In contrast to most other interpretations, here particles always have a well-defined position. The precise formulation of the theory needs to answer two questions, namely (i) what law governs the particle motion and (ii) how are the initial positions distributed. The answer to the first question is given by the so-called guidance equation (a first-order differential equation for the particle positions). Metaphorically speaking the particles are guided (or piloted) by the wave function (which is still governed by the Schrödinger equation). Here, measurements have definite results because the particle position selects a (decoherent) branch of the wave function which corresponds to the observed outcome. A collapse of the universal wave function does not occur. It is curious to note that here solely the *position* determines the outcome of measurements of, e.g. spin, momentum or energy. That is, no additional variables are needed to fix these quantities (see Passon 2018).

However, a unique solution of the guidance equation requires initial conditions, which brings us to the second question raised above. If the initial positions are chosen according to Born's rule (this is called the “quantum equilibrium hypothesis”) the Schrödinger equation ensures that all predictions of quantum mechanics will be reproduced. This includes the violation of Bell's inequality (see 5.5) and the impossibility to violate Heisenberg's uncertainty principle (see Dürr et al. 1992; Norsen 2018 for the justification of the quantum equilibrium hypothesis). Thus, no experiment can distinguish between the dBB theory and any other interpretation. While the consistency of this (non-relativistic) formulation is generally accepted, the extra structure it introduces has arguably the air of being only fictitious.

4.5 Collapse interpretations

Another school of interpretation has challenged the validity of the Schrödinger equation and has replaced it by a modified equation which includes additional (in general non-linear and stochastic) terms. These terms are designed in order to account for an (objective) collapse of the wave function upon, e.g. measurements. Already on a formal level, these models are extremely diverse. The original model by Giancarlo Ghirardi, Alberto Rimini and Tullio Weber (1986) had the quantum state occasionally collapse without any apparent reason, at a rate that was treated as a free parameter in the model. This is different in the model first defined by Pearle (1989), where the stochastic interaction with a new, otherwise undetermined field makes the quantum state collapse.

There are several issues that could be discussed in connection to objective collapse models, but we would like to focus on their "ontological" implications. Since the wave function is a highly abstract entity which is defined on a high-dimensional so-called configuration space, it is not immediately clear how the wave function relates to our ordinary experience. There are two possible ontologies that have been discussed in the context of collapse models, the *matter density ontology* (Ghirardi et al. 1995), in which the dynamics of the wave function determines the behavior of a (derivative) matter field on space-time, and the *flash ontology* (Bell [1987a] 2004), according to which tiny bits of matter flash in and out of existence in accord with the collapse dynamics on the configuration space. However, neither of these specify exactly how the wave function 'steps down' from configuration space to effect these changes, and ψ's exact role in the ontology hence remains rather unclear.

4.6 Quantum Bayesianism

In closing our section on interpretations, we would like to mention a more recent suggestion, namely quantum Bayesianism or QBism. Some ideas of quantum Bayesianism were anticipated by Edwin Thompson Jaynes already in 1990. Its main proponents are Christopher Fuchs, Rüdiger Schack and David Mermin. The name QBism was coined by Fuchs (2010) and denotes a further development of this view.

Some of Bohr's writing on the interpretation of quantum theory stresses its subjective character (compare, e.g. the above quote in 4.2 on the need to give up the "independent reality" of the phenomena). A similar attitude shines through in the so-called QBism. Here, the starting point is the observation that the notion of probability has no generally accepted meaning. Presumably a majority of physicists (and mathematicians or statisticians) sides with the frequentist interpretation of probability which links the probability of an event to the relative frequency of its occurrence. This interpretation of probability is debated for a number of reasons which are beyond the present scope.

Another influential camp emphasizes the logical simplicity of probability and adheres to the so-called "subjective interpretation". The slogan here reads "probability is the degree of belief" and in order to work with this interpretation one needs to apply a well-known theorem of statistics, called the Bayes theorem. Hence, this school of statistics is called Bayesianism. In brief, QBism results from applying this interpretation to the probabilities of quantum theory. On this view, any user of quantum physics (an "agent") is applying the formalism in order to assign personal judgments on an event – based on his or her experience. This results in a rather fundamental reinterpretation of scientific theories. The adherents of this view claim that QBsim provides a more balanced view on the relation of subjective and objective features of the quantum world (Fuchs et al 2014). According to Qbism, the act of measurement is simply a process in which the corresponding agent gains knowledge about a system and the apparent (or: "subjective") collapse simply reflects the fact that this gain happens suddenly.

5. Conclusions for specific metaphysical issues

After we have gained an overview of some of the major interpretations of quantum physics, we are in the position to explore its metaphysical implications more closely. Before entering the discussion on continuity versus discreteness (5.2), determinism versus indeterminism (5.3), observation, objectivity and the mind (5.4) as well as holism and non-locality (5.5), we should say a word on the infamous "wave-particle dualism" (5.1), an issue which is less dependent on the specific interpretational stance.

5.1 Wave-particle dualism

Sometimes the novelty of quantum physics is framed as the claim that quantum objects are neither particles nor waves but exhibit a certain "wave-particle dualism" (or "duality"). While this notion played an important heuristic role in the early history of the theory (and may still serve a doubtful educational purpose) it should be rather viewed as outmoded. It is true that, say, an electron is described by a wave function which suggests "wave properties" for this object (most notably interference effects). At the same time an electron exhibits particle properties (like a discrete mass). These observations lie at the basis of the duality-heuristics.

However, for a system of N electrons the wave function is defined on a 3N dimensional space. Thus, the wave function does not describe a "wave" in the ordinary sense (let alone that it is complex valued and specifies only probabilities). Furthermore, quantum objects are "indistinguishable", i.e. the permutation of "particles" in an N-particle state has no observable effect. In other words, quantum objects have no individuality, which is in stark contrast to ordinary particles. In this sense the wave-particle duality of electrons has to be understood metaphorically at best. Some authors relate this alleged "duality" to Bohr's notion of complementarity. However, while the early Bohr used the wave-particle duality as an example for complementarity, he avoided this application after 1934 (see Held 1994).

The so-called "photons", or light quanta, are even less particle-like than electrons. We have dealt so far with the non-relativistic theory of quantum mechanics, which is relevant for systems which move much slower than the speed of light in vacuum. Photons are obviously moving at the speed of light, thus they cannot be described by ordinary, non-relativistic quantum mechanics but rather by the generalization called quantum electrodynamics. This entails that there is no wave function for the photon with a probability interpretation in 3D position-space (Peierls 1979: 10 f.). In fact, the observable "position" is not even defined for photons (Newton/Wigner 1948). It is true that a photon state exhibits discrete energy and momentum; however, these quantities cannot be localized and belong to the whole space which is filled by the electromagnetic field. Thus, also here the wave-particle duality is highly misleading.

Summing up, it may be said that quantum objects share some properties which bear a loose resemblance with "particles" and "waves", but that these classical notions do not provide adequate tools for the description. The reference to a vague "dualism" or "duality" between these two types ignores the autonomy of quantum physics, which postulates a completely different kind of "matter". This holds even for the de Broglie-Bohm theory, which apparently introduces "particles" (in the literal sense) into the description. First, also here any vague "dualism" is rejected. Secondly – and more importantly – the "Bohmian particles" are very different from ordinary matter as well. These objects have no properties other than position and velocity; other properties, such as charge and spin, are assigned to the wave function (compare 4.4).

5.2 Continuity versus discreteness

A related issue is the question of continuity versus discreteness. Since antiquity, there have been discussions about whether nature has a continuous or discrete character (Bell 2019). Here, one should distinguish between spatial discreteness, property discreteness and the discreteness of processes. Prima facie quantum theory is by its very definition claiming that the world has discrete properties (i.e. comes in "quanta"). But note that the wave function evolves continuously and apparently only the act of measurement introduces the discrete results. Hence, the question of continuity versus discreteness (of the time-evolution) depends on the interpretation one adopts. To Bohr (1928) the discreteness was the essential feature of the theory (called the "quantum postulate"). But on the minimal (or ensemble-) interpretation one needs to be silent about this issue on the level of individual entities. If, however, one follows the many-worlds interpretation, the (continuous) wave function is all there is, and on the de Broglie-Bohm interpretation the dynamics is supplemented by the continuous movement of quantum particles. These "Bohmian particles", however, are discrete entities. Thus, quantum mechanics gives us no definite answer to the question whether nature is continuous or discrete.

5.3 Determinism versus indeterminism

It is generally thought that before the introduction of quantum mechanics, physics was strictly deterministic: given the current state of a system, the laws of physics would uniquely determine its future evolution (on the degree to which this image is correct, see van Strien 2021). This was often seen as a problem for free will: if the laws of physics determine exactly what will happen in the future, it can be hard to see how we can be free in our choices and acts. Quantum mechanics seems to have introduced fundamental chance in our physical world view, thereby making an end to determinism in physics. It is therefore no surprise that quantum mechanics is often invoked in discussions about free will (see Esfeld 2000; Hodgson 2002). However, there are several challenges to accounting for free will on the basis of quantum mechanics. First, it would have to be shown that quantum effects can make a difference on the level of our thoughts and acts, even though they are generally negligible on a macroscopic scale. Secondly, it seems that to account for free will, the introduction of an element of chance or randomness does not suffice: the fact that our choices are partly random would not make us any more responsible for our choices.

Finally, we have to ask whether quantum mechanics is indeed indeterministic. The laws of quantum mechanics only yield probabilities for measurement outcomes but no exact predictions: it therefore seems that there is an element of randomness in the evolution of systems in quantum mechanics. However, since the different interpretations of quantum mechanics give very different accounts of the process of measurement, they also give different answers to the question whether nature is deterministic.

On the ensemble view one needs to be silent (again), and Ballentine states: “Strictly speaking, quantum mechanics is silent on the question of determinism versus indeterminism: *the absence of a prediction of determinism* is not a prediction of *indeterminism*” (Ballentine 1998: 592, emphasis in original). However, in von Neumann’s version of the Copenhagen interpretation, the measurement introduces an indeterministic “collapse” of the wave function. In contrast, the de Broglie-Bohm interpretation is drawing the picture of quantum particles which move deterministically, and the probabilities for measurement outcomes which quantum mechanics yields reflect only the ignorance about the precise initial conditions: This account of quantum mechanics is therefore deterministic. On the many-worlds interpretation, determinism is also restored since the time evolution is governed entirely by the Schrödinger equation and no collapse is needed. Some (objective) collapse theories, on the other hand, involve an explicit stochastic term to account for measurement outcomes; but according to quantum Bayesianism this collapse only reflects that some agent gains additional information, i.e. is a purely subjective matter.

5.4 Observation, objectivity and the mind

Quantum mechanics is often thought to tell us something significant about observation: the idea is that in quantum mechanics, it is not possible to observe something without changing it. This is based on the widespread idea that, in quantum mechanics, quantities only gain an exact value through measurement (which does not hold strictly, given that e.g. the ionization energy of hydrogen can be predicted exactly independently of any measurement; moreover, as we will see, also this depends on interpretation). The idea that what we observe partly depends on our presence as observers has implications for philosophical debates on whether it is possible for us to have knowledge of the world as it really is, independently of us. Quantum mechanics is sometimes taken to imply an extreme view: It is sometimes claimed that *consciousness* plays an essential role in the measurement process, and that quantum systems only gain well-defined properties when they are observed by a conscious being. Although there are indeed well-known physicists who have made this claim, it is certainly not a generally accepted view. First, it is widely acknowledged that the term “measurement” in quantum mechanics is an awkward expression: if observables indeed only gain an exact value through the process of measurement, this means that the measurement does not inform us about a property that was already there: rather, the measurement *brings about* the measured outcome, and this process is rather more a process of “creating” than of “measuring”. But this creation does not have to be explained through the “mind” or “consciousness” of the observer: it is far more plausible that the interaction between the measurement instrument and the observed system plays an essential role here. A measurement is then a process of intervention, rather than a passive observation.

But secondly, also in this case, different interpretations offer significantly different views on the matter. The picture we have just discussed agrees with the Copenhagen interpretation, according to which the interaction between the quantum system and the “classical” measurement device brings about the observed outcome. However, in the many-worlds interpretation, a measurement does not have a single definite outcome, but rather all outcomes are realized in some “world”, and the observer shares in this multiplicity. According to the de Broglie-Bohm view the outcome of any measurement is uniquely determined; however, for measurements of variables other than position, the values are determined by the whole context of measuring apparatus, wave function and configuration of particles (which implies a specific meaning to the claim that measurements “create” their outcome).

5.5 Quantum non-locality and holism

A physical theory is called “local” if any action can only affect nearby regions in space (more technically: actions propagate slower than the speed of light in the vacuum). Given that the wave function for an N-particle state is defined on the 3N-dimensional configuration space, it is rather apparent that “being nearby in (3D) position-space” has no immediate significance within quantum theory. This feature supports the idea that there is some kind of “holism” or “non-locality” in quantum physics. In 1964, John Bell published a result which is often taken to mean there are exactly such non-local effects in quantum physics, that is, what happens at one location can have an instant effect on a distant location. His argument was based on the famous Einstein-Podolsky-Rosen (EPR) thought experiment, suggested already in 1935. If a two-particle system is in a specific superposition (called “entangled”), you can construct situations in which the particles are far apart, but measurement outcomes of experiments on each particle separately show correlations (this can be verified experimentally). Technically, one speaks of Bell’s inequality being violated by quantum physics. If such entangled states could be used to communicate faster than light, this would violate a basic postulate of special relativity. However, this is not possible because the corresponding correlations are between “random numbers” (i.e. you cannot deliberately generate one of the two possible states on either side of the coupled system) and can be checked only with the help of a “classical” (that is local) communication line, after the experiment has been done. Still, according to many, these correlations beg for an explanation and compromise the relation between quantum physics and special relativity. On a different reading the EPR-correlations indicate no superluminal exchange of an effect, but rather the non-locality of the corresponding state (see e.g. Friebe et al. 2018: chapter 4). However, either way, some locality assumptions are compromised.

But also here the assessment depends on the interpretational choice: Due to the vague definition of the “Copenhagen interpretation”, it is debated whether non-locality is present there. Ballentine, the vocal proponent of the ensemble interpretation, accepts the conclusion that the violation of Bell’s inequality implies some sort of non-locality (see Ballentine 1998: chapter 20 for an extremely readable introduction to the whole subject). The de Broglie-Bohm theory fully endorses non-locality since it accounts for this violation of Bell’s inequality by an explicitly non-local mechanism. Within the many-world interpretation, however, it has been argued that one may avoid any non-locality (see e.g. Bacciagaluppi 2002). The same holds with quantum Bayesianism: given that this interpretation deals with personal judgments of individual (i.e. local) agents, it also can avoid the threat of non-locality (Fuchs et al. 2014).

6. Concluding remarks

We have seen that quantum mechanics indeed has remarkable features, which seem to have implications for our understanding of nature. However, we have also seen that there are a variety of interpretations of quantum mechanics, and that what quantum mechanics shows us about various issues in the philosophy of nature is highly dependent upon the interpretation. This raises an awkward question: if quantum mechanics can give us so few definite answers about what the world is like, is it from a philosophical point of view worth learning about quantum mechanics?

In answer to this question, we first have to say: Although the different interpretations do yield very different pictures of physical reality, this does not mean that all options remain open. Quantum mechanics does not force us to accept extreme conclusions such as the claim that things only come into being when we look at them. However, in each interpretation, some common-sense assumption is given up, and it is therefore clear that somehow or other, the world is different than it was imagined before, at least on the quantum scale. In any case, if ‘billiard ball’ or ‘clockwork’ conceptions of physical reality, in which everything is reducible to simple mechanisms, were ever plausible, they definitely have to be given up in the light of quantum mechanics.

A further issue which is relevant to the philosophy of nature relates to the question of part-whole relations (i.e. mereology). We tend to think of matter as being composed of some fundamental building blocks, be it atoms or subatomic particles. Quantum mechanics indicates – rather independent of any choice in the interpretational debate – that on the quantum scale the part-whole relation is not aggregation (as in the simple picture of "fundamental building blocks") but superposition (Healey 2013).

Furthermore, the very plurality of interpretations is itself philosophically interesting. It is remarkable that such a successful and well-established theory as quantum mechanics can fail to give us a definite account of what the world is like, and that it allows for such a variety of interpretations which paint very different pictures of physical reality. As we have seen in section 4., some of these interpretations should perhaps rather be viewed as alternative *theories* of quantum mechanics, and since these theories yield the same predictions as the standard theory, this would provide a strong example of underdetermination of scientific theories by empirical data. At the same time, it highlights that the choice of a theory (or interpretation) depends on non-empirical criteria like simplicity, symmetry, or its ability of being generalizable.[2]

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