Philosophy of Quantum Mechanics for Everyone

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April 4, 2003

1 Introduction

Quantum mechanics is one of the most successful scientific theories ever. Thought up in the first half of the 20^{th} century, it revolutionised physics. Its predictions have been confirmed by experiment upon experiment and no serious scientist nowadays doubts the validity of the quantum mechanical theory. It offers us a generally accepted description of the microscopical world of atoms and elementary particles such as electrons or photons. Technical applications of this knowledge include great inventions like the laser, and not so great inventions like the nuclear bomb.

But when we pry deeper into the meaning of this theory, we'll discover that different people have very different ideas. Some claim that quantum mechanics proves that the world is indeterministic, while others deny this. We might hear that the theory entails that there are many parallel worlds; that cats can be both alive and dead at the same time; that elementary particles are sometimes particles and sometimes waves; and the list goes on. We might feel bewildered, and wonder how much of this is true.

This document is intended as a short introduction to the philosophy, or foundations, of quantum mechanics. Unlike most discussions of this subject matter, it doesn't assume any knowledge of physics or mathematics, and is therefore useful for the interested layman. Those who wish to read a more rigourous introduction are referred to the 'suggested readings' at the end of this document.

2 Indeterminism or hidden variables?

2.1 Quantum mechanics and probability

Physical theories tell us about physical systems. A 'system' can be anything, from a glass of water to the solar system, and from a single electron to a complex molecular structure. With every system, certain properties, or physical quantities, are associated. Thus, we say that the glass of water has a certain 'temperature', or that the earth and all the other planets have a 'position' and a 'velocity'. In classical physics – a term denoting all physical theories independent of quantum mechanics – a physical system is completely described by the values of all quantities associated with it. For instance, in classical mechanics all we need to know are the mass, position and velocity of every object. This tells us all there is to know, and allows us to predict what the system will do in the future.

In quantum mechanics, things aren't so simple. A system is no longer described by the values of physical quantities, but by what is technically called 'a vector in a Hilbert space'. This is an abstract mathematical concept, which is related to physical quantities through the rules of the theory. What is so special about quantum mechanics, however, is that it does not do this in a straightforward fashion. In general we cannot assign a precise value to a physical quantity; all we can say is that there is a certain *probability* of finding a value when we measure a quantity.

Suppose, for instance, that we have a quantum mechanical description of an electron. This description is a vector in a Hilbert space, but fortunately we have rules to calculate, say, the position of the electron from this vector. The result of our calculation, however, will generally not be a specific position. Instead, it will be the probability of finding the electron at a certain position! Quantum mechanics does not tell us where the electron *is*, it tells us merely how *probable* it is that we *find* it at a certain place when we measure its position.

As an even simpler example, let's focus on the rather nonintuitive property 'spin', which is possessed by elementary particles. When we measure the spin of an electron in a certain direction, we can find only two values, which we call 'spin up' and 'spin down'. Suppose we have a machine which sends electrons to a measuring device, one after the other, in such a way that they are all described by the same vector in Hilbert space. Quantum mechanics now tells us that for every electron we have a chance a of measuring spin up, and a chance b of measuring spin down, obviously with $a + b = 1$, since these are the only two possibilities.[1] We can test this empirically by measuring the spin of lots of electrons; in the end, we'll find that we measured spin up in a fraction a of the measurements, and spin down in the other cases.

Thus it seems that quantum mechanics gives us empirically testable predictions about the probabilities of finding certain outcomes in experiments.

2.2 Incompleteness and hidden variables

This immediately leads us to question the *completeness* of the theory. Does quantum mechanics tell us all there is to know, or is it an incomplete description of reality? Two electrons with the *same* quantum mechanical description can lead to *different* experimental outcomes. Many claim that this shows that the world is not ruled by determinism; what happens is dependent on chance. If two systems that are identical can bring about different results, it becomes impossible to make predictions with certainty – even if one were infinitely intelligent and knowledgable. Thus, quantum mechanics proves that the world is indeterministic.

But others suggest that maybe the electrons weren't in identical states after all. There must have been differences between them to account for the different experimental outcomes. These differences were not visible in their quantum mechanical description, simply because it's incomplete. Beneath the quantum

[1] In mathematics and physics, it is customary to let chances ranges from 0 to 1, not from 0% to 100%. A chance of 1 thus corresponds to a chance of 100%.

phenomena lies the deeper reality of *hidden variables*. These hidden variables can be different for systems with the same quantum mechanical description, and they account for the differences between such systems.

A hidden variable theory is deterministic: everything happens according to strict laws that leave nothing to chance.[2] In general, we will not be able to directly measure the hidden variables; their existence and their values can only be inferred from experiments measuring ordinary properties of systems, such as position or spin. Is it possible to create such a deterministic theory?

Indeed it is. In 1952 David Bohm published a set of two papers in which he described exactly such a theory. Bohm assigned to every particle a definite, non-probabilistic place, one of his hidden variables, and introduced a 'quantum potential' to account for the peculiar predictions of quantum mechanics. Although Bohm's particles are classical in the sense that they have precisely defined values for all physical quantities, their behaviour is distinctly non-classical due to the quantum potential. His theory predicts, as far as we know, exactly the same experimental results as orthodox quantum mechanics. Thus, a hidden variable version of quantum mechanics has been shown to be possible. Yet, as we shall see later, it has consequences that many believe are even worse than the problems it tried to solve.

2.3 The Einstein-Podolsky-Rosen paradox

In 1935, almost two decades before Bohm thought up the first consistent version of a hidden variable theory, Einstein, Podolsky and Rosen published an article called 'Can Quantum-Mechanical Description of Physical Reality be Considered Complete?' Their goal was to prove that quantum mechanics was indeed incomplete, and hidden variables were necessary. In order to understand their basic argument, we need to take a closer look at the property called 'spin'. We can measure it in any direction we wish, and the chances of the results 'up' and 'down' are dependent on the direction we choose. Suppose we label one direction x and another y, with the directions chosen such that they are orthogonal. There exists a quantum state for a particle such that when we measure the spin in the x-direction we are certain to find 'up'. However, in this state, when we measure the spin in the y-direction, we have chances 0.5 of finding 'up' and 0.5 of finding 'down'. Similarly, there exists a state in which the particle could be where it is certain we find that the spin in the y-direction is 'up', but the chances in the x-direction are exactly fifty-fifty. There is no state where it is certain both what we will find when we measure in the x-direction and in the y-direction.

It is possible to create two particles, electrons say, in such a way that their spins are exactly opposite. This means that if we measure the spin of both electrons in the same direction, we will always find that one of them is 'up', and one of them is 'down'. As long as we measure in the same direction, we'll never find that both are 'up' or both are 'down'.

With this background knowledge, we can start describing the Einstein-Podolsky-Rosen paradox, commonly abbreviated as the EPR-paradox. In their article, they make two fundamental assumptions:

[2] There are in fact non-deterministic hidden variable theories, but these will not be discussed in this introduction.

- If, without in any way disturbing a system, we can predict with certainty (i.e., with a probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.[3]
- Two systems cannot influence each other instantaneously when they are a large distance apart. Speaking more technically, all interactions are *local*.

Both of these assumptions seem very reasonable. It seems extremely counterintuitive to drop the requirement of locality, as that would entail that what I'm doing here on earth can influence what happens at this very moment on a planet orbiting a far-away star. And surely, if we are certain to find that an electron has spin 'up' in the x-direction were we to measure it, there must be an element of physical reality corresponding to 'spin up in the x-direction'. This ought to be an objective property of the electron.

Suppose now that we prepare two electrons in such a way that their spins are exactly opposite. We send them in different directions, and wait until they are very, very far apart. Now we can measure the spin in the x-direction of the first electron; suppose we find 'up'. We can now predict with absolute certainty that were we to measure the spin in the x-direction of the second electron, we would find 'down'. Thus, there must be an element of physical reality corresponding to 'the second electron has spin down in the x-direction'. In fact, since the electrons are very far apart, my measurement of the first electron cannot have influenced the second electron. Therefore, there must already have been an element of physical reality corresponding to 'the second electron has spin down in the x-direction' *before* I made the measurement.

But in exactly the same way I can prove that there must have been an element of physical reality corresponding to 'the second electron has spin down in the y-direction' (or spin up, depending on my measurement of the first electron) before I made any hypothetical measurement of the first electron's spin in that direction. Thus, the second electron must already have definite spin in both the x-direction and the y-direction before I make any measurement at all. But, as we have already seen, quantum mechanics does not allow this! Whenever a particle has a definite spin in one direction, it *cannot* have a definite spin in the other direction.

We can now see, Einstein, Podolsky and Rosen claimed, that quantum mechanics is incomplete. A particle can have definite spin in two orthogonal directions, but quantum mechanics does not allow us to say this. There must be a more complete theory beneath the quantum phenomena that does allow us to speak of these things.

2.4 The Bell inequalities

Unfortunately, things weren't that simple. In a paper published in 1964 J.S. Bell showed that any hidden variable theory which satisfied the requirements of Einstein, Podolsky and Rosen is not empirically equivalent to orthodox quantum mechanics. Looking at the thought-experiment from the EPR-paradox, Bell

[3] Einstein, Podolsky & Rosen, 'Can Quantum-Mechanical Description of Physical Reality be Considered Complete?', *Physical Review*, 47, 777-80 (1935); the quotation was taken from the reprint in Salmon, Earman, *et al.* (1992), 'Introduction to the Philosophy of Science'.

showed that any local, deterministic hidden variable theory predicted results that differed from those of quantum mechanics. If these hidden variable theories were true, a set of inequalities known as the 'Bell-inequalities' would hold; if ordinary quantum mechanics were true, they would not.

This was revolutionary. Hidden variables were no longer simply a matter of philosophical debate, they had entered the realm of experimental testing. Experiments were performed, and the Bell-inequalities were shown to be violated. In other words, local, deterministic hidden variable theories were shown to be untrue.[4]

Since the necessity for such theories was a consequence of the two assumptions made by Einstein, Podolsky and Rosen, at least one of these had to be untrue. Thus, physicists were confronted with a difficult choice: either the postulate about 'elements of physical reality', or the postulate about locality had to go. Most physicists were loath to give up locality, and abandoned hidden variables and intuitions about the nature of physical properties. A few chose to abandon locality, and followed non-local hidden variable theories.

The remark that Bohm's theory was empirically equivalent to quantum mechanics, combined with this section, may have led the discerning reader to the conclusion that Bohm's theory must be non-local. And indeed, it is. His quantum potential allows for instantaneous influence of one particle on another over arbitrarily large distances.

Further research showed that hidden variable theories had to be not only non-local, but also *contextual* in order to escape the Bell inequalities. A contextual theory is one in which the results of a measurement can depend on what kind of measurements have been made on other systems. Thus, in the EPR-experiment, the result of a measurement on the second electron may depend on which measurement (in the x-direction, the y-direction, or some other direction) has in fact been made on the first electron. Bohm's theory is contextual, in addition to being non-local. Non-locality and contextuality were judged by most to be too high a price to pay for determinism, but Bohm's hidden variable theory still enjoys a modest popularity today.

The debate about determinism, locality and hidden variables still continues. Obviously, it touches on some of the most important issues concerning our view of nature. It is often linked with such subjects as free will and holism. In the following section, we'll look at the way in which people handle the vagueness of properties implied by the rejection of hidden variables.

3 Uncertainty and complementarity

3.1 Some quantum mechanical experiments

Let's take a look at some experiments that will give us greater insight into the strange features of quantum mechanics. Once again we consider electrons, and we measure their spin in the x-direction and the y-direction. Our measurement devices are such that all electrons with spin up are allowed to pass through the device in a straight line, whereas all electrons with spin down are emitted at the

[4]In fact, even local non-deterministic hidden variable theories fall prey to the Bell-inequalities, but as before we do not consider them.

side of the apparatus. In this way, we can split a beam of electrons into those that have spin up, and those that have spin down.

We consider a beam of electrons in some arbitrary state and a measurement device that measures spin in the x-direction. The beam is split into two. We take a second measurement apparatus and put it after the first in such a way that only the beam with spin up enters it. If this second device also measures spin in the x-direction, we'll find that all of the electrons entering it have spin up. There is no surprise here. If the second device measures spin in the y-direction instead, we will find that exactly half of the electrons entering it have spin up (in the y-direction), and half have spin down. This too is no surprise.

However, suppose we put a third measuring device after the second, which again measures spin in the x-direction. Summarising, we have one apparatus that measures spin in the x-direction; the electrons with spin up are sent to the second device which measures spin in the y-direction; and the electrons with spin up are sent to the third device which again measures spin in the x-direction. What will we find? Do all electrons have spin up? No. We'll find that half have spin up and half have spin down, even though they all had spin up when we measured the spin in the x-direction for the first time. Surprisingly enough, our second measurement has destroyed all information about spin in this direction.

How can we understand this? We saw before that any state in which an electron has a precise value of spin in the y-direction is a state in which there is a maximum uncertainty about spin in the x-direction, where 'maximum uncertainty' means that we have exactly chance 0.5 of finding spin up and 0.5 of finding spin down. So what seems to happen when we make a measurement is this: if we measure spin in a certain direction, the electron will be put into a state in which that quantity has a precise value. Therefore, the spin in all directions orthogonal to this will be completely uncertain. This is a general feature of quantum mechanics: before we make a measurement, the value of the measured quantity does not have to be certain. We only have probabilities of finding outcomes. But once we have measured the quantity, the system has been changed in such a way that it is now in a state where this quantity has a precisely defined value - namely, the value just measured. As a consequence, some other quantities are now utterly uncertain. A measurement in quantum mechanics seems to disturb the measured system in a fundamental way.

3.2 Heisenberg's uncertainty relations

Among the most famous results of quantum mechanics are Heisenberg's *uncertainty relations*, yet no consensus concerning their interpretation has been reached. In fact, two distinct and different sets of inequalities are both known as Heisenberg's uncertainty relations, due to unfortunate misinterpretations.

The first uncertainty relation was derived by Heisenberg in 1925: it stated that the uncertainty in a particle's position times the uncertainty in its momentum[5] could never be smaller than a certain numerical constant. Similar relations hold for other quantities, such as time and energy. The more certain we can be about the value of one of the quantities, the less certain we can be about the other – but what do we mean when we use the word 'certainty'? Are we talking about an objective feature of the particle, about outcomes of repeated

[5] The momentum of a particle is its velocity times its mass.

measurements, or about the state of our knowledge?

In his original derivation, Heisenberg looked at ways to measure the position of an electron. To observe the place where the particle is, we must illuminate it and detect the reflected light. In quantum mechanics, light consists of particles, called photons, so we must always use at least one photon to do our measurement. Furthermore, the accuracy of our observation depends on the energy of the photon: the higher its energy, the more precise our measurement. By making the photon's energy arbitrarily high, we can make our measurement of the electron's position arbitrarily accurate. However, when a high-energy photon 'hits' the electron – which must happen for it to reflect and thus show us the electron's position – it changes the momentum of the electron. In fact, the higher the energy, the more the momentum is changed. We thus see that if we want to make a very precise measurement of a particle's position, we greatly disturb its momentum. This also works the other way around: if we make a very accurate measurement of a particle's momentum, we greatly disturb its position. The uncertainty relations, then, seem to place a limit on our *knowledge*: we can never measure two quantities for which Heisenberg's relations hold up to an arbitrary precision. There is always some uncertainty in the value of at least one of them.

Heisenberg elaborates on this interpretation using his so-called *'measurement = meaning' principle*, which states that a term like 'the position of the particle' has meaning only if there is an experiment we can use to measure it. This seems to imply that if there exists an experiment which can measure a quantity, but only with a limited accuracy, we cannot say that this quantity is precisely defined. Thus, it is not only our possible *knowledge* that is limited by the uncertainty relations, but in fact even the *definiteness* of physical quantities. A particle's position and momentum cannot, according to Heisenberg, be simultaneously well-defined. This is a pretty radical claim.

Yet Heisenberg goes even further, and invokes something called the *'measurement = creation' principle*. According to this principle, a measurement creates a value for a quantity; an electron only has a position *because* we measure it. On this view the uncertainty relations show us that a particle cannot *have* a position and a momentum at the same time. They limit our possible knowledge (the *epistemic* consequence), the definiteness of our concepts (the *semantical* consequence), and the amount of properties a particle can be said to have at any one time (the *ontological* consequence). It is important to note at this point that it is not necessary to accept Heisenberg's two principles, so one does not have to accept his conclusions. In particular, many people do not wish to accept the ontological consequence.

We saw in the preceding sections that some quantities, spin in two orthogonal directions for instance, cannot both have a precise value at the same time. In fact, in any quantum mechanical state where one of them has a precise value, the other is completely uncertain. Such quantities are called 'non-commuting', a mathematical term we will not worry about. Another famous example of non-commuting quantities is the pair 'position' and 'momentum'. Historically, a lot of confusion resulted from the fact that Heisenberg's relations were nearly identical to a set of uncertainty relations proven by Kennard in 1927. He proved a mathematical theorem, which is a precise formulation of what was described above: two non-commuting quantities cannot both have a completely certain value; the more certain one of them is, the more probabilistic and uncertain is the other. The analogy with Heisenberg's relations is obvious, and most often, they are identified with each other – in fact, both Kennard and Heisenberg thought that they were the same. However, this is untrue. Where Heisenberg's uncertainty relations are a result of the fact that measurements influence the systems on which they are performed, Kennard's are not. Heisenberg tells us that our measurements of one quantity will disturb other quantities, and hence we can never know them at the same time. Kennard tells us that the more certain the outcome of a measurement of one quantity is, the less certain is the outcome of certain others. These two things are not identical.

3.3 Wave-particle duality

In the seventeenth century, there was an extensive debate on the nature of light. Some physicists, like Newton, held that light consists of particles, in the same way that matter consists of particles. Others, most notably Christiaan Huygens, contended that light consists of waves, like sound. Historically, Newton's side initially dominated, but in the 19^{th} century the wave-theory of light was revitalised by scientists such as Thomas Young, Augustin Fresnel and James Maxwell. This was mostly due to the observation of interference phenomena.

Suppose we have a black screen with two parallel slits in it. Some distance behind it we place a white screen, and we take a light source and let it shine on the black screen. What will we see on the white screen? If light consists of particles, we'll just see two light bands corresponding to the two slits. But if light consists of waves, we ought to see a *diffraction pattern*. Waves will propagate from the two slits, and these will amplify each other is some places, and extinguish each other in others. This phenomenon is familiar in the case of sound: if you put two speakers in a room and let them produce the same tone, there will be places in the room were the resulting sound is very loud, and other places where it is almost silent. If light consists of waves, we will see numerous alternating light and dark bands on our white screen. And this is in fact what we see when we do the experiment.

This seems to solve the issue: light definitely consists of waves. However, in the last decades of the 19^{th} century and the first of the 20^{th}, a number of experiments were performed which proved that light consists of particles, which were dubbed 'photons'. For instance, a beam of light of very low intensity colours a photographic sheet one spot at a time. If light consists of waves, the sheet ought to colour slowly over the entire area; but instead the colouring is seen to be a succession of discrete photographic grains becoming black. These discoveries led to a paradoxical situation: some experiments proved that light consists of particles, and others proved that it consists of waves!

Things were only made worse when it was shown that tiny particles such as electrons create interference patterns when they are used in the double-split experiment too. Photons, electrons, etcetera seem to behave like waves in one situation and like particles in another. This strange aspect of reality is called 'wave-particle duality'. Can we conclude that photons and electrons are *both* particles and waves? Or are they *neither* particles, *nor* waves? Or maybe they are *sometimes* particles and *sometimes* waves? There is no easy answer to these questions, but it will be instructive to look at the most influential thought concerning this phenomenon: the principle of complementarity.

3.4 Bohr's complementarity principle

The combination of wave-particle duality and Heisenberg's uncertainty relations led the Danish physicist Niels Bohr, one of the founding fathers of quantum mechanics, to postulate what is known as his 'complementarity principle'. It is hard to overestimate Bohr's influence on the philosophy of quantum mechanics. He is the main thinker within the so called 'Copenhagen' school of thought, which was the most influential philosophy of quantum mechanics for decades and is still the one implicitly assumed in most textbooks on quantum theory.

According to Bohr, we cannot give a description of the quantum world - and in fact, it is not the aim of physics to do so. The only concepts we can meaningfully use to describe the world are those that describe our normal, macroscopic world. These concepts were formalised in classical mechanics, like 'position' and 'momentum'. When we do an experiment, what we see will always be describable using these concepts: we see, for instance, the position of a needle on a dial. Any description of nature must use these classical concepts, as they are the only ones we can get experimental knowledge about.

However, quantum mechanics shows us that we cannot describe elementary particles in terms of classical physics: this leads to such absurdities as particles being both waves and particles, or not having a position and a momentum at the same time. Hence, it is not possible to give a meaningful description of the quantum world. Elementary particles never have a momentum or a position, not even sometimes – those terms simply cannot be used to describe them.

What we *can* describe using classical concepts are phenomena. A phenomenon is the result of a measurement, something which we can check in our laboratory and which is always well-defined. Thus, which concepts we can use to describe a situation depends on the experimental context – we can only use a concept if the experiment measures the corresponding quantity. Since some quantities, for instance position and momentum, or spin in two orthogonal directions, cannot be measured simultaneously, these quantities are *complementary*. Complementary quantities cannot be measured in the same experiment, yet they are both needed to give a complete description of the object under investigation.

Concerning wave-particle duality, this means that we need both the wave-nature and the particle-nature of quantum objects in order to describe their behaviour in experiments; yet these two descriptions can never be applied at the same time. Physics does not tell us what the quantum world is like – that is something we can never know.

Thus, Bohr's solution to the strange aspects of quantum mechanical experiments is a denial of the possibility that a clear picture of the quantum world can ever be drawn. Many physicists and philosophers have seen this as a weak move, and started searching for ways to explain the quantum world in a way that makes its strange features more acceptable to the human mind. This is a search that continues to this very day, and no consensus has been reached.

4 The problem of measurement

4.1 Superpositions and measurement

Perhaps the greatest problem in the interpretation of quantum mechanics is the 'problem of measurement'. Before we can understand this problem, we have to take a look at superpositions. We saw in the preceding paragraphs that a particle can be in a state such that there is exactly 50% chance of measuring spin up in the x-direction, and 50% chance of measuring spin down. Mathematically, we can describe such a state as a 'superposition' of the state in which the particle has definite spin up, and the state in which it has definite spin down. In a way, we just add 0.5 times the up-state to 0.5 times the down-state to obtain the new state. We claim that the particle is 'in a superposition' of the two states.

Suppose we have a particle in such a superposition, and we send it through a measuring device which measures its spin. What we would like to see is that quantum mechanics tells us that after this is done, the measuring device either points to 'up' or to 'down'. Unfortunately, quantum theory predicts that after the measurement, the measurement device is in a superposition of the states 'pointing to up' and 'pointing to down'. But what is this supposed to mean? We never see a device showing us 0.5 times one result and 0.5 times another – that is impossible. We only see measurement devices that point either to one outcome or to the other. Quantum mechanics predicts that measurement devices will be in superpositions after measuring, but we only see them in perfectly well-defined states. This discrepancy is the problem of measurement.

4.2 Schrödinger's Cat

To make the problem more dramatic, Erwin Schrödinger devised his famous thought experiment involving a cat. Suppose, he said, that we have a cat placed in a hermetically sealed box. The box also contains a diabolical device, consisting of a radioactive atom, a measuring device, a hammer and a flask of poisonous gas. When the radioactive atom decays, the measurement apparatus notices this and the hammer smashes the flask – much to the detriment of the cat's health. The decay of a radioactive atom is a quantum mechanical process, where the atom is in a superposition of 'already decayed' and 'not yet decayed', with the 'chance' of already being decayed increasing as times goes by.

But now, according to quantum mechanics, we should say that the cat is also in a superposition; a superposition, in fact, of the states 'being alive' and 'being dead'. But that is surely preposterous, for how could a cat be both alive and dead? All our intuitions scream that at any time the cat ought to be either alive or dead, and not in some strange superposition of them.

There are two ways out of this problem. The first is to claim that quantum mechanics is essentially incomplete, that there are hidden variables which determine at any given moment whether the cat is alive or dead. This approach, and its weaknesses, were discussed earlier. The second, and more common, is to try and solve the problem of measurement. A plethora of solutions has been proposed, and the discussion is still going on. We will now take a look at some of the better known attempts to solve the problem of measurement.

4.3 The projection postulate

The earliest and most-followed approach was that adopted by the brilliant mathematician John von Neumann. In 1932, he published a book in which he axiomatically defined the mathematical structure of quantum mechanics and proved numerous results. It was to be the foundation for quantum theory ever after. Von Neumann based his account on five postulates, the first four of which are relatively unproblematic. But the fifth postulate was his 'solution' to the problem of measurement, and is known as the 'projection postulate'. It states that whenever a measurement is performed on a system (such as a particle), the system is taken from a superposition to a new state wherein the measured value has a precisely defined value. Thus, according to von Neumann, there are two distinct types of evolution. Most of the time, a quantum mechanical system evolves according to the normal laws of quantum mechanics. But whenever a measurement is performed, there is a sudden change in the system's state which is contrary to these normal laws.

Some people will be quite happy with this. But von Neumann's approach has two problems. First, isn't it strange that there are two distinct types of evolution? Wouldn't it be much more beautiful if measurements weren't something special, but could be described using normal physical laws? The special status of measurements has been unacceptable to many people. Secondly, and more acutely problematic, what exactly *is* a measurement? Presumably, when we measure something, this is just a physical interaction like any other. What makes a measurement a measurement? It has proved to be very hard to make this clear, which is a weakness that many solutions to the problem of measurement have in common. One radical attempt to define 'measurement' was made by Eugene Wigner.

4.4 Wigner's friend

I can be sure that my own mind is never in a superposition, Wigner claimed. Whenever I myself do a direct measurement, I am sure to find one and only one definite outcome. It isn't impossible to assume that a particle can be in a superposition, and it isn't impossible to assume that a measurement device can be in a superposition. But it is surely impossible that my own mind is in a superposition. So whenever I directly observe something, a measurement takes place and the projection postulate describes what happens.

But assume, continues Wigner, that I have a friend, who does a quantum experiment. When I ask him what he has found, I do a measurement, and supposedly reduce him from a superposition to a state in which it is clear and unambiguous what he has found. But is it plausible to believe that my friend, another conscious being, was in a superposition until I made a measurement? Surely not. All conscious beings are, according to Wigner, able to do measurements. This is true because a consciousness is the only thing in the universe which can measure itself.

Thus Wigner wishes to give consciousness a central role in quantum theory to solve the problem of measurement. Most people, however, think his ideas are too far-fetched, and only a few are willing to attribute a special place to consciousness. But the fact that this idea has been given serious attention by physicists shows the severeness of the conceptual problems.

4.5 Spontaneous collapse

In an attempt to solve the measurement problem without using two different types of evolution – one for normal situations, one for measurements – Ghirardi, Rimini and Weber thought up the collapse theories. In these proposals, there is only one type of evolution, but it is slightly different from that of normal quantum mechanics. Instead of always evolving due to the standard equations, each particle has a very small chance of being reduced from a superposition to a state where the particle's position is well-defined. This chance is truly tiny; a particle will generally have to wait for 10^{10} years before such a reduction occurs. However, if particles form an object together, the object's state is reduced whenever that of one of the particles is. Since all visible objects consist of enormous amounts of particles, they would be reduced many times per second. So if we do a quantum experiment in which we measure a property of a particle, our measurement apparatus – which is in general pretty big – will be reduced from a superposition to a state with a well-defined position within a fraction of a second. This obviously solves the measurement problem, at the cost of adding a somewhat non-intuitive element of chance to the evolution of systems. An interesting fact about these theories is that their truth should be empirically testable, but as yet experiments have not been sufficiently precise to do so.

4.6 Many worlds

Another, better known and more spectacular option is the many-worlds interpretation of Everett, Wheeler and DeWitt. They reject the projection postulate, and claim that the normal evolution from quantum theory perfectly describes the way the world works. Whenever a measurement takes place on a particle in a superposition, the measurement device will be in a superposition too. But the different parts of this superposition correspond to different alternate worlds! If we measure the spin of a particle, the universe splits in two: in one world we find spin up, in the other spin down.

If this already sounds bizarre, I'll make it even stranger. To ensure that the predictions of quantum mechanics hold good, we must actually postulate not that the world splits into two worlds when we measure a particle's spin, but that it splits into an infinite number of worlds, in a fraction a of which we find spin up – where a exactly corresponds to the chance of finding spin up. Thus every time a measurement is made at any place in the universe, the universe splits into a infinitude of alternate universes.

Intriguing as it may be, most physicists and philosophers think it is too strange to be true. In addition, the many-worlds interpretation only removes the need for two kinds of evolution, but leaves intact the problem of defining 'measurement'. Many other attempts to solve the measurement problem have been made, but they are often quite technical and one needs a firm grasp of quantum mechanics and its mathematical structure to understand them. We'll leave the topic now, and end our voyage through the philosophy of quantum mechanics with a short conclusion.

5 Conclusion

Quantum mechanics is a very rich field for philosophers of physics. It has far reaching implications for such issues as determinism, holism and locality. It raises questions about the kind of properties elementary particles can be said to have, and about the possibility of ever getting a coherent picture of the microscopic world. It has huge unsolved interpretational problems, which are linked with issues such as the existence of parallel worlds and the role of consciousness. When one enters the quantum world, one enters a colourful realm of intriguing puzzles, beautiful ideas and profound philosophy.

Hopefully this essay has given you an idea of what that realm is like.

6 Suggested readings

For anyone interested in the philosophy of quantum mechanics, or indeed philosophy in general, the *Stanford Encyclopedia of Philosophy* is a great resource. Located at `http://plato.stanford.edu/`, it is an excellent site containing articles written by professional philosophers. Relevant to our present subject are, among others, the following articles.

- *Quantum mechanics* is a moderately difficult introduction into the mathematical formalism of quantum mechanics, explaining such concepts as 'operator' and 'Hilbert space'.
- *Quantum mechanics - Bohmian mechanics* explains the basic concepts of hidden variables and the ideas and consequences of Bohm's theory. The article avoids extensive use of mathematics.
- *Quantum mechanics - Copenhagen interpretation* is an introduction to the Copenhagen interpretation of quantum theory, focussing on ideas like complementarity. It does not contain any mathematics.
- *Quantum mechanics - Everett's relative-state formulation* and *Quantum mechanics - many-worlds interpretation* look into the many worlds interpretation, in all of its forms.
- *Quantum theory - measurement* is a short description of the problem of measurement, but it is rather technical.
- *Uncertainty Principle*, finally, is a thorough historical introduction to both the derivations of the different uncertainty relations, and the ideas of Heisenberg and Bohr concerning their interpretations.

I have been told that David Z. Albert's 1992 book, 'Quantum Mechanics and Experience' (Cambridge, Mass.: Harvard University Press), is also a good introduction to the philosophy of quantum mechanics for non-physicists. I have not yet had the pleasure of reading the book, but nevertheless take the liberty of mentioning it here.

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