# Quantum Physics Lecture

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This lecture discusses two important properties of the quantum world (*).

Its aim is to give you a flavour of the curious behaviour of the quantum world, where 'curious' is an example of the great British understatement! Downright weird and inexplicable is perhaps more appropriate.

The first property is that a quantum object (*) can only exist in a state selected from a set of well-defined defined states.

(*) The terms 'quantum world' and 'quantum object' are given some explanation very shortly.

The second property is that a quantum object actually exists in all of these states until we measure the object's state, at which point we then find it in one and only one member of the set of states.

This second property then leads to a seemingly paradoxical situation that has been repeatedly verified by experiment, but with no satisfactory explanation. Indeed, one might say the whole of quantum mechanics has no satisfactory explanation, except to say we know its rules and we can successfully predict results using its rules, time and time again.

As a very quick example, a quantum object (discussed again shortly) could have a state which I will term black or white, and the first property simply says it can be either black or white - where the 'set of states' is the set comprising just the two colours, black or white. The second property is more bizarre because it says that the object is actually neither black nor white, but rather a combination of black and white, until we measure it that is. Once measured, it is then most definitely either black or white but not both. The very process of measurement causes the combined state to disappear and reduce to a sensible, single known state, black or white. This mechanism of flipping from a combination of black and white to just either black or white is termed 'collapse', and discussed again later.

Before proceeding to more detail, I ought to also define the two aforementioned terms 'quantum world' and 'quantum object'. This is not a rigorous or complete definition, but will hopefully suffice for now, and the reader may acquire greater understanding of quantum behaviour after this and other general lectures on the subject.

The quantum world is basically the world of atoms and sub-atomic particles - it is the region where the laws of quantum physics dominate over those of classical Newtonian physics (good ole Force equals mass times acceleration, i.e. 'F=ma'), and this quantum world is nothing like the world around us.

Acting at the atomic level, the quantum world is truly tiny. For example, a simple hydrogen atom is around one ten thousand millionth of a metre, which is about a million times smaller than a human hair. At this level of size, the properties of atoms and their components do not behave like the Newtonian dynamics of, for example, cars, spacecraft, or any household object built from an immense numbers of atoms. Everyday objects follow Newton's laws (these laws are well over 300 years old now), and these laws are the realm of massive objects like ourselves, comprising millions upon millions of atoms. The atoms themselves follow the laws of quantum physics, but when combined in enormous numbers, the combined objects follow classical Newtonian Physics. At some point there is a transition between quantum and physical behaviour, but it is a blurred boundary, and the subject of many experiments. However, let us not be concerned with this transition region for now.

Just one important point that cannot be omitted, and that it is not to say Newton's laws are wrong in so far as 'F=ma' is wrong, but that this law is borne out when taking averages over a large number of quantum objects, the more objects, the better the average, and the closer nature adheres to Newton's laws. To be truthful, we also need Einstein's relativity - more on that later.

Returning to the quantum world, I shall focus on a specific quantum object; namely the sub-atomic particle called the electron.

An electron is a fundamental sub-atomic particle. It is fundamental because it cannot be further sub-divided into any smaller sub-atomic particles, i.e. it is not made up of any particles. An electron is absolutely tiny and actually appears point like, i.e. with no size at all, or at least none of note. Indeed, it is at least another hundred thousand times smaller than an atom. In fact, an electron generally 'orbits' the nucleus of an atom, just like a planet such as the earth orbits the sun in the solar system. Although this orbital behaviour is not quite the case, the exact details do not matter here. Suffice to say, whereas planets orbit according to Newton's laws, an electron, instead, follows the laws of quantum mechanics, which do at least behave according to the rules of Newtonian mechanics once we look at very large objects, where 'large' actually just means any collection of, say, ten-thousand atoms or more. As usual, there are lots of caveats and fine detail omitted, for which a trained physicist would object to my omission, but we would be here all day discussing these finer points.

As regards the first quantum property (a finite set of states), the electron, as a quantum object, has a property called spin, and it can exist in just one of two spin states (a very small set of states indeed), i.e. the set of well-defined states has two members. As will be explained shortly, Physicists term the two states up and down, but I shall use the colour-coded names black and white in their place, because this suits with an analogy I shall give later.

Just like the earth rotates (spins) about its axis (once a day by the definition of a day), the electron can also spin about its axis, and it is this property of electron spin we shall look at to illustrate the two quantum properties. The property of spin is also the same as the spinning property of, for example, a bicycle wheel, a gyroscope, or any object spinning or rotating about an axis.

Unlike the spin of an electron, which we will discuss soon, the spin speed (or spin rate) of an everyday rotating object in the world around us can take any value from nought (not spinning) to spinning many times a minute. For example, in a washing machine spin cycle, the drum can spin at 1000 revs per minute (rpm). In another example, a bicycle wheel spins at any speed from zero, when the bicycle is stationary, to many times a minute when the bicycle is in motion. The faster you ride, the faster the wheel spins. The only practical limit to the spin speed is how fast you cycle. The point is, in our everyday world, a spinning object can usually spin at a whole continuum of speeds - slow, fast, 1rpm, 5rpm, ten-and-a-half rpm and, indeed, any number of speeds in between or greater for that matter. Just to make this more precise, if you request a spin rate between two close limits, say 10 and 11 rpm, we can make the wheel spin at 10.5 pm. Likewise, it can spin between 10.5 and 10.6 rpm, or, indeed, any spin rate between 10 and 11, only subject to our own mechanical limitations - but these are our limitations, not nature's - except in the quantum world that is. In the quantum world, there are two neighbouring spin rates in-between which there can be no spin rate. For example, a spin of 10 and 11 rpm may well have no in-between value, we can either measure 10 or 11 rpm, but never 10.5 say.

In fact, the electron has a fundamental property that it can only spin at one fixed, non-zero rate. It is not a case of that or zero; it truly has a single non-zero value. However, spinning at this single rate, it can also spin either clockwise or anti-clockwise, which is effectively spinning in two different directions - and this is therefore counted as two speeds. Thus, the set of quantum spin states comprises spin in two different directions, but both with the same spin rate, and it is really this spin direction that we are going to measure.

Perhaps confusingly, the spin direction is actually specified as 'up' or 'down' in the world of Physics, but this is related to a mathematical property of the spin axis, and you needn't concern yourself with it. Alternatively, and hopefully not too confusing, I am going to call the two spin directions 'black' and 'white', instead of up and down, or clockwise and anti-clockwise for that matter, for reasons that will become obvious quite soon - it makes an analogy very straightforward.

Don't get hung up about using two colours to describe the spin state (up/down, clockwise/anti-clockwise). It is merely a convenience for what follows - the key point is that there are essentially just two ways an electron can spin, and this is unlike the real world we see whereby objects can spin at any speeds. Of course, ordinary objects also spin clockwise or anti-clockwise but, as stressed, they can do this at any speed subject to physical limitations such as the maximum motor speed. To reiterate, the electron has one speed and it can be either black or white (up or down, clockwise or anti-clockwise) but always two quantum states, whereby two states is basically the minimum number of states required to make the behaviour non-trivial.

One might well argue that even in the real world objects may only spin at two speeds, e.g. a washing machine may spin at only its maximum speed, or not at all. However, in getting to its maximum it will have to pass through every possible spin rate from zero to the maximum - it is we humans that have artificially imposed a two-speed-only washing machine spin-cycle. An electron's spin is simply not like that, it is always spinning and it spins at the same speed, just in two different directions, which I have rather artificially referred to as black and white.

So, too summarise this first section, we will measure a property of the electron related to its spin, that can be either black or white, but no other value, and this is unlike any real-world spinning object such as a bicycle wheel that can take any spin rate (or spin speed), only subject to how fast you pedal. In between nought and max speed there is a whole continuum of speeds with which the wheel can spin, but not so for the electron, that only has one speed but two different spin directions. If we measure an electron's spin, it will either be measured as spinning 'black' or 'white' but no other value. This two-state affair is a quantum property and unique to the quantum physical behaviour of the electron.

This, then, is the first quantum property - that an object in the quantum world can only take on a certain set of values, also referred to as a discrete number of values or 'states' - in this case there are just two spin states. Because the spin can only take on certain discrete values, it is also said to be 'quantised'.

So, on to measuring the spin of an electron.

We can envisage that we have some lab equipment that can measure the spin of an electron. The technical details of the apparatus need not concern us - the measurement of spin can and is done in physics laboratories worldwide, and this shall be good enough for us.

So, using the spin measuring apparatus, we take an electron and measure it to be either spinning black or white, but nothing else (not red, blue etc.). Physicists say it is either 'spin-up' or 'spin-down' but, as I have said, it suits in my further analogy below to refer to up and down as the colours black and white.

Now, as just presented, measuring this spin property of the electron isn't mysterious or anything different to the classical world (our real world), once we have accepted that the spin can take only one of two values. That it only has two values, and that they are always the same two values, and no other values can be measured, makes it self-evident we will either measure an electron spin as black or white.

Incidentally, note that the electron spin does not slow down - it goes at one speed all the time, but this can be clockwise or anti-clockwise (black or white). In the real world, of course, a spinning object generally slows down due to friction, i.e. friction in the bearing, air resistance and physical intervention, e.g. you manually stop it spinning. But an electron does not do this, it is always spinning, it keeps on spinning without limit. However, whilst it is always spinning, its absolute spin direction (black or white) is not determined until we measure it.

For sure, we don't know the electrons spin until we have done the measurement but, otherwise, it will always be black or white, end of story. And this would not seem to be anything strange.

However, there is a quantum twist to come. Suppose we measure the spin and it is black, and therefore definitely not white! We would conclude the spin immediately before the measurement was also black, and we have just measured it as such. Similarly, if we measured white, we would assume it was white before the measurement and we have just found out this obvious fact for ourselves by doing the measurement. As a trivial classic example, if we look at an object and we see it is red (our eyes have 'measured' it as red), then we know it was red at least for a very short instant before we measured it. Ok, it might be some colour changing object like a chameleon and could be changing its colour over the last few minutes (or even seconds) but, at least at the tiniest instance of time before we measured it, it was red, and we have just confirmed it is red by looking at it, i.e. measuring its colour. Our looking (call it observing or measuring) has not had any effect on the colour, i.e. it was a certain colour before we measured it and it hasn't changed afterward. We have merely noted its colour but, otherwise, not influenced the measurement!

Nevertheless, the aforementioned quantum twist is that, in the quantum world, when we measure an electron's spin and find that it is black, it does NOT mean it was black an instant before we measured it. Neither was it white and flipped its colour to black upon measurement. In fact, the electron spin, right up to the point of measurement, is not defined as either black or white and, instead, it is actually a combination of the two possible states, and is said to be in a 'superposition' of both the black and white state. The electron really does not exist in any specific state until we measure that state; the state here being black or white. This indefiniteness of the state before measurement is a very important point in quantum mechanics; I cannot stress it enough, bar continuing to stress it here.

Just one point - the electron was always spinning and the measurement does not suddenly create spin, i.e. the spin always existed, and measuring it does not suddenly create spin. It is often mistakenly said that in quantum mechanics something doesn't exist until you measure it. However, this is not the case - the spin state, be it black or white', exists for certain - what doesn't exist is the exact state. This exact state, either black or white, is only jumped to when the measurement is made. You can say the spin flips to the measured state at the point of measurement. This is termed the 'collapse' of the spin to one state or the other.

Of course, you might just say this is all unnecessary or even fanciful thinking, i.e. a complication that simply need not be introduced. After all, if the electron is in a definite spin state when we measure it, black or white, then surely there is no need to introduce uncertainty by saying it wasn't either black or white immediately beforehand? What does it matter? When we measure it is in the state as measured. In the classical world, it is true to say that, using the car example, the car was always the colour red (barring some malicious paint job - which I shall exclude), and we just confirmed it was red by looking at it. That is, it was not green beforehand and suddenly change to red when we measured it. However, this is most definitely not the case in the quantum world, the quantum car is neither red nor green until we measure it. It is only in our large (huge, enormous) macroscopic world, where a real car is comprised of million, billion, trillions of atoms, all quantum effects are long gone and the car in our real-world has a fixed paint-job - always was and always is one colour that we measure, disregarding a human-generated paint alteration.

To reiterate, the quantum spin state of an electron, black or white, is indeterminate, and can be thought of as a hybrid of black and white, (but neither one nor the other) until we measure it. The measurement has forced the electron to show either one spin or the other whereas, before the measurement, the electron was quite happy to remain non-committal to its exact spin state.

This odd (bizarre) state of affairs has been confirmed by many ingenious physical experiments, and it really is the case that the electron's spin state is not defined until the measurement is made. It is not simply a case that we are ignorant of the state, and the electron was already in, say, the black state, so that when we look at it (i.e. measure its state), we are merely confirming this. On the contrary, in the quantum world the exact state really does not exist until we measure it. Alternatively expressed, our measurement can be said to have forced the electron's hand; instead of sitting on the fence, showing neither black not white, our measurement (the act of looking at it) forces the electron into one of the two states. The measurement is said to have 'collapsed' the state.

Note that if we measure the spin state a second time, after having already measured it and noted its state, it will not change state again (it could actually change with some further experimental interference but this is just obfuscation). So, if we measure its spin once as black then measure it again, it will be black again and most definitely not white. The first measurement 'collapsed' its state to black, and thereafter it exists in the black state so that any subsequent measurement will see black, and never white. Similarly if we first measured white then it will remain white thereafter.

That the electron has no well-defined spin state until the measurement is made is the second quantum property I wished to explain.

Thus, so far, it has been stated that the electron has only two spin states, black or white (or up and down as the physicists call it), i.e. the electron only has a 'discrete' number of states and not a continuum of states, and, until we measure this state, the electron cannot be said to specifically exist in either one of the spin states, but rather it is said to be in a superposition of the two possible states. When we measure the electron's spin state this superposition collapses the electron's spin to a specific state, either black or white. Note too that it doesn't collapse to any other state.

So, now for an analogy of this behaviour.

Suppose we have a black, drawstring magician's type bag with two balls in it, one black and one white. However, We don't know this fact and we are told the bag contains a single electron. We now wish to measure the spin property of the electron (black or white) by sticking our hand in the bag and drawing out a ball (which we think is an electron). If the ball is black our electron has a spin black; if white then spin white.

Hopefully then, the reader will appreciate that if we draw a ball, i.e. measure the electron's spin, there is a 50% chance it is black, and 50% chance it is white (AKA a 50:50 chance it is black and a 50:50 chance it is white). Before we draw a ball, however, we can think of the electron as being in a combined black/white spin state where the probability of measuring black is the same as that of measuring white, i.e. one half (50% chance) for each state.

Suppose we draw a ball, observe its colour, and then put it back. If we then redraw the ball we still have a 50:50 chance it is white or black, presuming the bag has been 'reshuffled' so to speak. If we do this many times then, on average, 50% of the time we will draw a black and 50% of the time we will draw a white. At each measurement we draw a ball and measure one and only one colour, be it black or white (but never both of course). However, before we draw the ball, the electron (effectively a combination of both the black and white ball), is neither black nor white, but a 50:50 combination of each. This detail is hidden in the bag and we have no knowledge of it. This last sentence has been purposefully worded as it relates to Einstein and others objections to quantum mechanics; the clue is in the word 'hidden'.

Specifically, Einstein's issue is that the electron state is only seemingly in an indefinite superposition of states before our measurement because we do not have all the details. In other words, there is 'hidden' information that we don't know, and may never know, so that we can never say what the electron spin state is until we measure it.

Once again, whilst not explained here, numerous (very ingenious) experiments have so far failed to show this is the case, i.e. all physics experiments so far have verified numerous times that there is no hidden information. The quantum uncertainty in the state is not just our ignorance or lack of information, that is somehow hidden from us, but rather there is no hidden information, period! The electron is really not in a defined spin state prior to measurement. For sure it exists and is spinning, but it is spinning 50% in one state and 50% in the other and, until we measure it, its spin state remains completely undefined.

Using this two-ball, black-bag magician analogy, does this mean, or is it possible that the electron actually exists separately in both states simultaneously? Well, strictly, this is possible, and is known as the 'many worlds' interpretation of quantum physics, i.e. it exists in both states simultaneously and is not just a 50:50 hybrid or 'superposition'. Alternatively, the electron doesn't so much exist in both states but is, indeed, a hybrid superposition of both states, neither one nor the other. Both explanations are actually plausible and the simple truth is we don't know which of the two explanations, if either, is correct. What we do know for sure though is that the electron does not exist in only one state before the measurement, its exact spin state, black or white, is completely undetermined until the measurement is made - get it!

Thus to summarise the two quantum properties:

1) An electron has spin, but it only has two values, which physicists call up and down, and I have called black and white so I can use the 'coloured balls' analogy.

2) The spin state of the electron is not defined until we measure it. It is a combination of black and white, neither one nor the other.

Moving on now to the concept of 'collapse' and its far-reaching consequence.

From what has been said, it seems that when we make a measurement, we force the spin state into one state or another, whereas immediately before the measurement it was a combination of both states. It seems the state has flipped from a hybrid combination of 50% one state, and 50% the other, into an exact, 100% specific spin state. This flipping has been previously referred to as the 'collapse' of the electron's spin state.

I cannot explain the collapse, nor can anyone else, it remains an unresolved problem in quantum physics known as the measurement problem, over which physicists debate interminably. But it does have one very bizarre consequence, which flummoxed Einstein et al. and was responsible for his rejection of QM as ultimately correct.

Finally then, to this bizarre consequence of the undefined spin state and its collapse upon measurement.

Before describing this consequence though, I will give the classical equivalent, for which there is no paradox.

Suppose you draw a ball from the bag but DO NOT look at it. So you are none the wiser about the electron's spin state. The magician holding the bag (not you) gets in an aircraft (carrying the bag), and flies halfway around the world. After the lengthy flight of several hours, he (or she!) then draws a ball from the bag. Suppose he draws a black, then he will also immediately, and correctly, deduce you have a white ball. If you then look at your ball it will, indeed, be white - there were two balls in the bag, one was black and one was white, so if you have white, the magician has black and vice versa. This is all logical, no surprises, no quantum weirdness!

The quantum weirdness though is this, when you draw a ball without looking at it, you are really just taking a copy of the combined 50% black, 50% white electron - your withdrawn ball is really just a copy of the mixed black/white state and, according to quantum mechanics, until you look at it, i.e. measure its spin, it really is not in one or the other of the defined states! That is very important, and not like the classical interpretation given in the previous paragraph whereby, whilst you don't know the balls colour, i.e. the electron spin state, you do know it is definitely one or the other and not a combination.

With this in mind then, that you have drawn a copy of the electrons spin state and you do not know what state it is yet (because you haven't looked) the magician travels away again on a flight.

After several hours he then draws a ball and, likewise, until he looks at it, he too only gets a copy of the combined electron's state, which is neither black nor white, but just a 50:50 combination of both.

At this stage, you have drawn a ball but not looked at it, the magician has flown for a few hours then also drawn the ball and also not looked at it. Both you and the magician have a copy of the electron, but neither of you know what its spin state is. In quantum mechanics then, you each hold an electron where each electron is a hybrid, 50:50 superposition of black and white spin. Yours is not black, and his white, or vice versa. Neither of you have looked yet, and the best either of you can say is that you have a copy of an electron whose spin state is a 50:50 combination of black and white, end of story - until you both take a peek that is.

Now, the really big point is that when the magician measures his electron state, i.e. looks at the ball he has withdrawn, he will see it is either black or white, but not both. Suppose it is black, then absolutely immediately (instantaneously), your ball must be of the white state. Even without you looking, your electron spin must have flipped from a combined 50:50 white/black state to white. You then look at your ball and, surprise-surprise, it is white. Conversely If the magician had a white ball and thus measured the spin state as white, you would see (measure) black. In other words, the magician's collapse of the electron spin state instantaneously forces the collapse of your spin state. His measurement of electron spin has directly affected your electron instantaneously, even though possibly thousands of miles apart. You don't even have to look at it - it will have collapsed immediately following his measurement.

Indeed, even if the magician had travelled many light years across the universe before looking (measuring) the electron spin state, as soon as he measured his electron spin state, your spin state would have collapsed to the opposite state (with or without you actually measuring it). If you then measured it there would be no 50:50 probability - it would be the exact opposite spin state to the magician's measurement. But until the magician measures his electron spin state (and providing you don't peek a look at your ball) your spin state remains a 50:50 combination of black and white, and only upon his measurement does your spin state collapse to the opposite state to his. In other words, this collapse happens instantaneously with no regard to the speed of light nor the time it would take for a possible 'collapse message' to travel from him to you. This collapse is instantaneous; it beats the speed of light.

As an aside, the magician's ball and your ball are said in quantum mechanics to be 'entangled'. The entanglement is a quantum property - they are entangled because their measured states are effectively dependent upon one another.

Returning to the instantaneous collapse: this for Einstein was a no-no, which is not surprising since he put the speed of light into relativity as a pinnacle speed above which nothing can go faster.

Einstein and others argued that the above paradoxical behaviour, i.e. faster than light communication (instantaneous collapse of the magician's and your electron spin state), as nonsense and put it down to ignorance, i.e. missing information in the form of 'hidden variables'.

You can't really blame Einstein for his dismissive attitude - only a few years prior he not only had one fantastic theory, i.e. Special Relativity', he then came up with General Relativity, which just blew physics and gravity out of the water.
Einstein is a true genius, Newton too, all others aren't quite up to their standard.

Maxwell et al are extremely clever, but to have two vindicated, but extremely counter-intuitive theories (Special and General relativity that is), puts Einstein on a pedestal above all others bar Newton, who was just plain ahead of his time. Perhaps we ought to include Gauss to give a podium top three historic geniuses of modern times (post the Egyptians and Greeks). I digress!

The aforementioned paradoxical, faster-than-light case is also known as the Einstein-Podolsky-Rosen 'EPR' paradox - there were other clever physicists in on this, not just Einstein!

Nevertheless, as stated, numerous experiments have shown this paradoxical behaviour to indeed be the case, making Einstein et al wrong on this one.

The EPR paradox is a quantum phenomenon - it has no classical analogue. However, its conclusion has been verified repeatedly in physics laboratories, and it appears to be the unequivocal case with no exceptions. Somehow the collapse occurs instantaneously, no matter how far apart the two measurements are made. It not only breaks the speed of light, it breaks all speed limits and happens instantaneously. The measurement could be made at one end of the universe with the collapse occurring instantaneously at the other end.

Even if the magician and you were a billion light years from each other, which means it would take light 1 billion years to travel from you to him (and vice versa), the collapse would happen instantaneously, it would not even take a second. It would appear to travel 1 billion years in 0 seconds!

It is by far the most bizarre and important concept in quantum physics, and is repeatedly verified as a real phenomenon, yet we have absolutely no physical explanation for it other than we know it is a very real effect. It all comes down to the extremely important fact that an electron's spin state really does not have a defined value until it is measured. Certainly the electron exists regardless of a measurement, but which spin state it is in is undefined up to the point of measurement.

The end.