Chapter 7

The Collapse of the Wave Function

At this point, it's worth taking a step back and reviewing where we are. We started with some observations about how electron spins function, and how it's very different from what you'd expect for little spinning balls operating under the laws of classical physics. These observations are:

- Every single electron has exactly the same total angular momentum $(\sqrt{3}/2)\hbar$. In contrast, classical spinning balls can be spinning at pretty much any rate (limited only by the speed of light for very fast rotation rates).

- Every time you measure the component of angular momentum along a given axis (for example, the z axis), you get one of only two values: $+\hbar/2$ and $-\hbar/2$. This is different from classical spinning balls in that even if they all have exactly the same rate of rotation, you could still orient them so that the z component of angular momentum is anything between the total (if the angular momentum is pointing in the $+z$ direction), on down to 0 (if the angular momentum is pointing in the $x-y$ plane), on down to minus the total (if the angular momentum is in the $-z$ direction).

- You can only know one component of angular momentum at a time. That is, if you measure the z spin of an electron and it comes out $+\hbar/2$, next time you measure it you will still get $+\hbar/2$. If you then measure x spin, you have an even chance of $+\hbar/2$ or $-\hbar/2$. This may not be surprising, as you hadn't measured the x component yet, so you didn't now anything about it. However, after measuring the x spin, if you go on to measure the z spin again, you have an even chance of measuring $+\hbar/2$ or $-\hbar/2$. Electrons *can not have a definite angular component of angular momentum along more than one axis at a time.* From a classical point of view, this is extremely bizarre. In classical physics, angular momentum is a vector. Thus, a spinning ball has an x, a y, and a z

component of angular momentum, and you can in principle measure all of them at once.

In order to explain this observed behavior, we've been constructing a mathematical model that operates on state vectors. We've been using Dirac notation, with objects written similar to $|\psi\rangle$ used to represent this state vector. These are abstract mathematical objects, different from algebraic variables, different from (but with some similarities to) vectors in 3-d space.

7.1 Summary of Rules for Manipulating Ket Vectors

As with algebraic variables or vectors in 3-d space, there are rules for manipulating ket vectors. It's important to remember that these rules exist, and that they are specific to ket vectors. Some of them look and behave exactly like the rules for manipulating algebraic objects, and indeed, you use ket vectors in algebraic equations. However, this does not mean that you can do everything with a ket vector that you can do with algebraic objects. For instance, there is no way you can *divide* by a ket vector; that's just not a defined operation. Also, multiplication with ket vectors does not match terribly well to the algebraic counterpart, except when you're multiplying a ket vector by a scalar (i.e. something that represents just a plain complex number).

The two most basic things you can do with a ket vector are summing them together and multiplying them by a scalar. These are also things that you can do with vectors in 3-d space, or with any other vector for that matter. If you multiply a ket vector by a constant, you get another ket vector. if you add together two ket vectors, you get a third ket vector. This rule can be summarized by:

$$|\xi\rangle \ = \ a\,|\psi\rangle \ + \ b\,|\phi\rangle$$

where $|\xi\rangle$, $|\psi\rangle$, and $|\phi\rangle$ are all state vectors, and a and b are scalars (i.e. something that could just be a complex number). All of the usual rules for scalars still apply to multiplying *scalars*. Thus, for example, you can use the distributive property, $a(|\psi\rangle + |\phi\rangle) = a\,|\psi\rangle + a\,|\phi\rangle$.

You can turn any ket vector $|\psi\rangle$ into a corresponding bra vector $\langle\psi|$. The detailed rules for how you do that will depend on how you represent a ket vector. In general, if a ket vector is built from other ket vectors

$$|\xi\rangle \ = \ a\,|\psi\rangle \ + \ b\,|\phi\rangle$$

then the corresponding bra vector is

$$\langle\xi| \ = \ a^*\,\langle\psi| \ + \ b^*\,\langle\phi|$$

where a^* represents the complex conjugate of a (i.e. replace all instances of i with $-i$). Notice what we did here on the right: replace all scalars with their complex conjugates, and replace all ket vectors with their corresponding bra vectors.

You can take an *inner product* between a bra vector $\langle\phi|$ and a ket vector $|\psi\rangle$, which is notated as

$$\langle\phi\,|\,\psi\rangle$$

The notation is meant to suggest this; you can "stick these vectors together on their straight sides." The result of this inner product is a *scalar*. While you can't divide by a ket vector, if you have something that's closed off (i.e. an inner product), it becomes just a scalar, so you can do anything with it in equations that you can do with scalars (including divide by it).

The meaning of an = sign is the same as always. That means that if you have, for example, $|\psi\rangle$ in one expression, and you have an equation that sets $|\psi\rangle$ equal to something else, you can substitute what $|\psi\rangle$ is equal to back into the first expression. You will usually want to make sure to put parentheses around what you're substituting in, to make sure that you don't (for instance) multiply by just a *piece* of $|\psi\rangle$ when you mean to multiply by all of $|\psi\rangle$. As an example, suppose you wanted to evaluate $\langle\psi\,|+z\rangle$, and you know:

$$|\psi\rangle \;=\; \frac{i}{\sqrt{3}}\,|+z\rangle \;+\; \sqrt{\frac{2}{3}}\,|-z\rangle$$

Well, first, we know how to build $\langle\psi|$

$$\langle\psi| \;=\; -\frac{i}{\sqrt{3}}\,\langle+z| \;+\; \sqrt{\frac{2}{3}}\,\langle-z|$$

and now we can substitute that into $\langle\psi\,|+z\rangle$:

$$\langle\psi\,|+z\rangle \;=\; \left(-\frac{i}{\sqrt{3}}\,\langle+z| \;+\; \sqrt{\frac{2}{3}}\,\langle-z|\right)\,|+z\rangle$$

If we wanted to reduce this further, we could distribute the $|+z\rangle$ to the left through the parentheses, and then substitute the known results $\langle+z\,|+z\rangle = 1$ and $\langle-z\,|+z = 0\rangle$ to get out just a single number.

There is one important thing to realize about = signs, however: an equation is only meaningful if you have the same types of objects on both sides of the equation. You've actually seen this before, with dimensionalities. It doesn't make sense to set a certain number of meters equal to another numbers of kilograms. Meters and kilograms are different sorts of things (one is length, the other is mass), and so they can't be equal. Similarly, you can't set different kinds of mathematical objects equal to each other. Bras, kets, and scalars are all different kinds of mathematical objects. You can't add a scalar to a ket vector, and you can't set a ket vector equal to a scalar. Nor can you set a ket vector to a bra vector. (Remember, however, that a scalar times a ket vector is a ket vector, and so forth. Thus, you *can* set a ket vector equal to a scalar times another ket vector, because the latter is just a ket vector itself. This is similar to saying that you can set a speed equal to a number of meters divided by a number of seconds, because when you divide length by time you get speed.)

One thing that you can **not** do with inner products is change the order of them. The *commutative* property of multiplication applies to scalars, but does not apply necessarily in general to other kinds of mathematical objects. So, while $ab = ba$, it's important to remember that $\langle\psi\,|\,\phi\rangle \neq \langle\phi\,|\,\psi\rangle$. (In fact, it turns out here that $\langle\psi\,|\,\phi\rangle = \langle\phi\,|\,\psi\rangle^*$. That works for bras and kets, but also is not going to be generally true for other mathematical objects.) You *can* change the order when you're multiplying by a scalar, however. Therefore, if you have:

$$\langle\psi|\,\frac{1}{\sqrt{2}}\,|\phi\rangle$$

it is the same as

$$\frac{1}{\sqrt{2}}\,\langle\psi\,|\,\phi\rangle\,.$$

Here, we didn't reorder any bras and kets; we just moved a scalar around.

For any given set of ket vectors (e.g. the set of all ket vectors that could potentially represent an electron spin state), you can identify a set of *basis vectors* from which all the other vectors can be built. For vectors in 3d space, the unit vectors $\vec{e}_x$, $\vec{e}_y$, and $\vec{e}_z$ form the basis vectors. For electron spins, $|{+z}\rangle$ and $|{-z}\rangle$ form the basis vectors. These two basis vectors represent, respectively, a particle whose z component of angular momentum is $+\hbar/2$ and a particle whose z component of angular momentum is $-\hbar/2$.

7.1.1 Calculating Experimental Predictions

Because quantum mechanics is stochastic rather than deterministic, often the results we expect from our theoretical calculations are probabilities of certain observations. We interpret the inner product

$$\langle\phi\,|\,\psi\rangle$$

as the *amplitude* (sometimes called "probability amplitude" to distinguish it from other sorts of amplitudes) for a particle in state $|\psi\rangle$ to be found in state $|\phi\rangle$ given a measurement of the observable for which $|\phi\rangle$ is a definite state. To calculate the probability, you take the absolute square of the amplitude, i.e.:

$$Pr \;=\; |\langle\phi\,|\,\psi\rangle|^2 \;=\; \langle\phi\,|\,\psi\rangle^*\,\langle\phi\,|\,\psi\rangle$$

If you want to calculate the overall probability for a particle to go through two different subsets of a path (e.g. if that particle is going through two different SG machines), you multiply the *amplitudes* for each subset of the path to get the overall amplitude for that path. When two possible paths for a particle to have traversed are combined together, you add the states of the particle at the end of each path, multiplied by their respective amplitudes. You only take the absolute square of amplitudes to find a probability when an actual measurement is made. More about that in Section 7.2.1.

We say that a ket vector describing a quantum state is *properly normalized* if $\langle \psi \mid \psi \rangle = 1$. Additionally, we generally want to choose basis states that are orthogonal, i.e $\langle +z \mid -z \rangle = 0$. If you square these two amplitudes to get probabilities, you see that this makes sense with the interpretation. If the electron is in state $|\psi\rangle$, the probability of finding it in state $|\psi\rangle$ is obviously 1. If the electron is in state $|-z\rangle$, then the probability of subsequently finding it in state $|+z\rangle$ is 0.

7.2 The "Collapse" Rule

There is another important more rule for manipulation of ket vectors in order to represent quantum systems. We've been using this all along, but haven't explicitly identified it yet. That rule is that when a *measurement* is made of an observable, the state of the system being measured *changes* to become a state that corresponds to a definite value of that observable. *Which* value of that observable the state adopts is random. It will be one of the ones that are possible, and quantum mechanics allows us to calculate the probabilities for each state to be adopted, but it does not allow us to predict with certainty which specific state the system will fall into. For example, if an electron is in state

$$|\psi\rangle = \frac{1}{\sqrt{2}}\,|+z\rangle \;+\; \frac{1}{\sqrt{2}}\,|-z\rangle$$

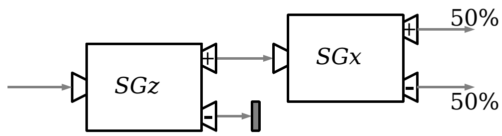
then after a measurement of the z component of angular momentum, it will either switch into the state $|+z\rangle$ or $|-z\rangle$. The *amplitude* for it to switch into $|+z\rangle$ is $\langle +z \mid \psi \rangle$ (in this case, $\frac{1}{\sqrt{2}}$), and thus the probability is $|\langle +z \mid \psi \rangle|^2$ (in this case, $\frac{1}{2}$).

This process of the state of a particle changing from an indeterminate state into a state that has a definite value for a given observable is often described as "collapse". The state vector of the system "collapses" to one of the definite state for that observable. Sometimes (although not always) you can use a function (e.g. a function of position $[x, y, z]$) to represent a quantum state $|\psi\rangle$. In quantum mechanics, these functions are called "wave functions" because the equations that govern their evolution are very similar to standard wave equations. As such, you will hear the term "the collapse of the wave function" to describe what happens to a quantum state when a measurement is made on it.

7.2.1 What is a measurement?

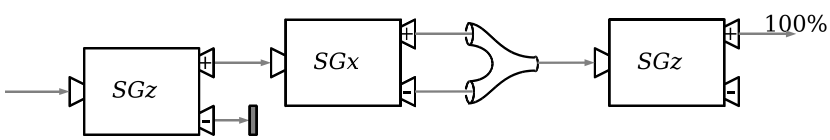
When you start to dig into exactly how to decide what happens with a particle going through various parts of a system, it turns out that it's not exactly obvious what it means to "make a measurement." This is the source of a lot of debate within the scientific community, and has led to various different (often bizarre) interpretations of quantum mechanics. It's also the source of a lot of the dubious and downright wrong things that are said about quantum mechanics, including much of "quantum mysticism". As such, it's worth putting some thought into the measurement problem.

Consider the following sequence of Stern-Gerlach machines:



The particle going into the second machine is in state $|+z\rangle$. While this is a definite state for the z component of angular momentum, it's *not* a definite state for the x component of angular momentum, which is what the second SG machine measures. Thus, we would say that upon the making of the measurement the quantum state collapses into either $|+x\rangle$ or $|-x\rangle$, each with a probability of 0.5. Evidently, the SGx machine has performed this process of "making a measurement," whatever that is.

However, now consider this sequence of SG machines:



In the previous example, when the electron goes through the SGx machine, its state changes. It changes into either $|+x\rangle$ or $|-x\rangle$. Both of those x states do not have a determined value of the z spin. In both cases, if you subsequently measure the z spin, you find an 0.5 probability for measuring the z spin as either positive or negative. Because that's true for both $|+x\rangle$ and $|-x\rangle$, you would then expect that if you combined paths together each that represented one of those two states, you'd still have a 0.5 probability of either $|+z\rangle$ or $|-z\rangle$. That is, if the electron follows the top path, it collapses into state $|+x\rangle$, and thus you'd think it has a 50/50 chance of being measured with either positive or negative z-spin. Likewise, if it follows the bottom path, it collapses into state $|-x\rangle$, and thus you'd think it has a 50/50 chance of being measured with either positive or negative z-spin. However, that's not what's observed! Somehow, when the two paths are recombined, the state $|+z\rangle$ that the electron was in before it entered the second SG machine is reconstructed. We have said previously that when you make a measurement, the state of the system changes. We have also said that x spin and z spin can't be known at the same time, so if you've measured x spin, the particle can't have a definite value of z spin. And, we saw previously that evidently an SGx machine makes this measurement of x spin, because you can figure out the x spin of the electron by seeing which output of the SGx machine the electron emerges from. Yet, here, it looks like a measurement of x spin wasn't made after all!

So how do you know what to do? Does the state vector collapse, or doesn't it? How do you know if you've made a measurement?

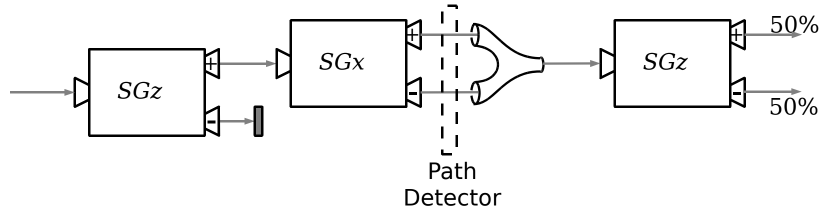
The mathematics of quantum mechanics are clear. Despite the interpretational difficulty, it's very important to realize that the *predictive power* of quantum mechanics is strong. If you followed the rules for propagating amplitudes through the series of *SG* machines above, what you'd find is that all of the amplitudes on the $|-z\rangle$ parts of the x states coming out of the SGx machine subtract out when you combine the two beams at the recombiner. So, while there is an *interpretive* mystery as to exactly what's going on here, there's no mystery as to what the result of either set of SG machines is. Too many of those who want to argue for some form of quantum mysticism seem to lose track of this distinction. Too many seem to say that because of debates about the interpretation of quantum mechanics, there are debates about what quantum mechanics says can happen. While you may find some *qualitative* and *interpretive* similarities between some sorts of radical post-modernist philosophies and the uncertain interpretations of quantum mechanics, it's simply wrong to say or imply that quantum mechanics tells us that we can't know the results of experiments. Those results may be *probabilities*, but even in that case they are rigid probabilities defined by the nature of physical reality. It's incorrect to claim that quantum mechanics points to a physical reality that doesn't fully exist without our own perception of it, and that reality itself can somehow be a "social construction". Rather, the success of quantum mechanics simply tells us that on the smallest scales, physical reality is simply something that is deeply unintuitive to us with our brains that evolved to deal with huge numbers of atoms at one time, where the laws of quantum mechanics in bulk give rise to the much more deterministic laws of classical physics.

Cautions aside, let's return to the interpretive difficulties that this whole notion of collapse gives us. The physical observation is that we experience the world in definite states. Sure, there is always *measurement* uncertainty, meaning that we don't know things perfectly. (For example, when you measure your height, do you know it to the millimeter? To the micrometer? If your ruler is marked to centimeters, and perhaps millimeters, you probably haven't measured your height to better than a few millimeters.) But while we do measure things with experimental uncertainty, we *never* directly observe something to be both something to be two different ways at the same time, we never see this "mixture of states" that quantum mechanics tells us particles can be in.[1] Our devices that measure spin will measure a value of angular momentum, with some experimental uncertainty, they will not return a "maybe" for two different discrete values for the measurement on a given particle. It is from this observation that we know *something* like the collapse of the state vector happens. But what is it that makes something into a measurement? The answer is not obvious, and has led to various different interpretations of quantum mechanics (see Section 7.3). Some even suggest that it must require a conscious observer to cause this collapse. After all, the argument goes, if it is *our* experience of the world that tells us that things are found in definite states for observables, then it must be something in *our act of observation* that causes the wave function to collapse. The unthinking SGx machine in the example above wasn't able to fully and irrevocably collapse the state vector; however, if an experimentalist looks at the output of the SGx machine, if that experimentalist figures out which output an electron came out of, then the state vector does change.

Many physicists, however, are very uncomfortable with requiring a conscious observer to change the state of the system, for it is not obvious exactly what "consciousness" is in this context. Indeed, modern neuroscience models all the thought processes of our brain as the material interaction of atoms and ions in our neurons, which are themselves ultimately governed by the laws of quantum mechanics. Where, and how, then, does this different "consciousness" manage to arise? Or is it an illusion, something that looks like it's there to us the same way a liquid appears to have a temperature even though what we call temperature is really just a measurement of the average speed at which the molecules in that liquid are bouncing about? The whole notion of temperature doesn't then feed back and somehow affect the molecules in ways that couldn't be derived from the laws governing the direct molecular interaction. If "consciousness", whatever that is, arises just as a property of a whole lot of neurons working together, then there is nothing particularly special there from a physics point of view that could somehow cause the collapse of the wave vector. So how does it happen? The question is not fully answered.

It is worth revising the SG machine one more time. Consider the sequence of SG machines we looked at last, but add one wrinkle. We aren't going to *capture* the electron out of the second machine; we'll let it go on into the recombiner unhindered. However, we are going to put some sort of detector that allows us to figure out *which* of the two outputs of the second machine the electron came out of before it goes into the beam recombiner.

[1] Greg Egan's science fiction novel *Quarantine* plays with the notion that there might be creatures who can, somehow, directly perceive these mixtures of states.



In this case, if you *could* tell which of the two outputs of the SGx machine the electron emerged from, you do *not* reconstruct the $|+z\rangle$ state after the recombiner. Without the path detector, effectively a measurement has not been made. If there is no way that you could know which path the electron went through, effectively it goes sort of goes through both, and the two paths *interfere*. Mathematically, what happens is that when you combine together the amplitudes, the amplitudes on the $|-z\rangle$ state from the expansion of the $|+x\rangle$ and $|-x\rangle$ states cancel each other out, just leaving you with $|+z\rangle$. But, if the path detector is there, if somewhere data is recorded that somebody *could* look at and see which path the electron took, then the electron takes *only* that path.

7.2.2 Schrödinger's Cat

In the sequence of SG machines without the path detector, in a very real sense each individual electron goes through *both* the $+x$ and $-x$ paths in the SGx machine. This is one example of a particle acting more like a wave. You can divide a wave up and recombine it (adding together amplitudes), but a particle is either *here* or *there*. The notion that particles like electrons could somehow follow both paths if you don't measure exactly which path it takes— even though, if you do measure the path, you never see that happen— seems absurd. Yet, that's what quantum mechanics tells us happens, and the predictions of quantum mechanics have been confirmed by countless experiments.

Schrödinger's cat is a thought experiment that tries to point out the absurdity of what quantum mechanics seems to be saying. Put a cat in a closed box. With the cat, put in a single radioactive nucleus, that is attached to a thread holding a hammer over a vial of poison. If the radioactive nucleus decays, the thread will break, releasing the hammer, breaking the vial, releasing the poison, and killing the cat. (Poor kitty!)

Put the cat and everything else in the box. Then wait enough time that there is a 50% chance that the radioactive nucleus has decayed. Is the cat still alive or is it dead? You don't know, because it's completely random exactly when any individual radioactive nucleus will decay. You can predict probabilities, but you can't predict anything about an individual decay. Indeed, we've now seen that if you don't make the measurement as to whether the nucleus is still there or not, in a very real sense it's neither decayed nor undecayed, but just like an electron whose z spin hasn't been measured, it's in an indeterminate quantum state, in a state that is a mixture of the decayed state and the undecayed state.

However, whether or not the state is decayed determines whether or not the cat is still alive. Is the cat still alive? Or is it dead? It's not just that you don't know, the argument goes. In fact, the cat is in a sense *both* alive and dead. It's in an indeterminate state. The jargon we use is to say that the cat's state has become entangled with the radioactive nucleus' state, since whether or not the nucleus has decayed determines whether the cat has died. But the cat doesn't take on a determinate state, being either just alive or just dead, until you open the box and make the observation to find out whether it's alive or dead.

Most physicists would argue that in reality a cat would function as an observer, and as such the cat makes the "observation" of the nucleus' decay by dying (or by its failure to decay by staying alive). Indeed, the vial of poison is itself a macroscopic enough system that once the radioactive nucleus becomes entangled with the states of the huge numbers of particles in the vial, wave function collapse has already happened; you don't even need the cat. However, Schrödinger's cat remains as a thought experiment that points out the very non-intuitive nature of quantum measurement and quantum mixtures of states.

The largest objects for which quantum interference has been directly observed is C-60 molecules, or buckyballs (Arndt et al., 1999). Physicists refer to hypothetical states where the interference of amplitudes of quantum states for macroscopic objects can be observed as "Schrödinger's Cat States." While these show up in science fiction (such as in some stories by Greg Bear and Greg Egan), they have yet to be observed in reality.

7.3 Interpretations of Quantum Mechanics

Does the wave function *really* collapse? What does it mean to say that? And what really is a measurement? Quantum mechanics is a great physical theory. It gives us a mathematical model that allows us to predict results for a wide range of experiments. It explains phenomena that could not be explained with classical physics. Quantum mechanics explains the structure of chemistry's periodic table of the elements. Practically speaking, it provided the understanding of nature that allowed us to develop, among other things, the laser and the solid-state transistor. All of today's digital technology is based on an understanding of semiconductors given to us by quantum mechanics. It is a tremendous misrepresentation of quantum mechanics to say that it brings mysticism into science, to say that it shows us that nothing is real and nothing is tangible or definite. The reality of today's human society would bear absolutely no resemblance to what we all know without the reality of quantum mechanics and our understanding of it.

However, while quantum mechanics provides us for clear rules for manipulating its mathematical model of atomic and subatomic reality, some questions it leaves unanswered have led to numerous “interpretations” of quantum mechanics. By and large, these interpretations struggle with the measurement problem. Practically speaking, the measurement problem is not a serious problem. We know when we’ve made a measurement. Whether or not consciousness is really involved (something, again, that most physicists are extremely uncomfortable including in their models), we’re able to design things based on quantum mechanics with the knowledge that once macroscopic things are affected by the results of quantum processes, measurements effectively have been made. However, if you want to understand what it really means, what quantum mechanics is saying about the nature of reality, then you have to grapple with the various different interpretations.

These interpretations include the standard Copenhagen interpretation, which says the wave function does in fact collapse. Practically speaking, however, most physicists go through their days behaving as they accepted the instrumentalist interpretation, which N. David Mermin summarized as “shut up and calculate!” (citation needed). This is the interpretation described above: practically speaking, we know ☑ how it works. So, just accept that it’s a mathematical model that is useful and don’t worry too much about what it means beyond what it tells you about the outcome of experiments.

A second variety of the instrumentalist interpretation is the statistical interpretation. This interpretation is based on the fact that in order to actually measure real probabilities, you have to perform experiments a large number of times. Otherwise, the statistics of counting random events tells you that you cannot make all but the roughest estimates of what your experiment tells you those probabilities are. In the statistical interpretation, quantum mechanics ultimately only talks about ensembles, groups of particles in enough numbers that you could compare the results of experiments to the predictions of quantum mechanics. In this interpretation, it’s over-interpreting the theory to talk about what it says about the behavior of individual particles. The author of this text thinks that the statistical interpretation doesn’t hold water. In the various quantum systems where different paths interfere and give us results that would be surprising to a classical physicist, yes, it’s true that we can’t practically compare those results to the numerical predictions of quantum mechanics until we’ve put multiple particles through the system. However, quantum interference happens even if you send only one particle *at a time* through the system; therefore, individual particles do in some way interfere *with themselves.*

Perhaps the most interesting interpretation of quantum mechanics is the Many Worlds interpretation, sometimes called (in an attempt, perhaps, to make it sound less outlandish) the “relative states” formulation of quantum mechanics. Before an electron spin is measured, it's in a state that is in a sense half up and half down. When you measure that state, you see the electron as being (say) spin up. What happened to the spin downness? In the Copenhagen interpretation, it's just gone; the wave function has collapsed. In the Many Worlds interpretation, the universe splits, and thereafter there are two universes. In one, you measured spin up; in the other, you measured spin down. Every time a measurement of a quantum system happens that requires that system to take on a definite value, and there are multiple possibilities for that value, the universe splits, one universe for each possibility of the value.

An interpretation that has been gaining a lot of favor recently is decoherence (Schlosshauer, 2004). As quantum particles interact with other quantum particles, there states become entangled. In reality, it's difficult (or impossible) to so isolate a system that you can do much for long without that system interacting, and thus having its state become entangled with other systems. Indeed, the act of measurement itself represents a quantum state becoming entangled with the state of the measuring device (or, perhaps more properly, with the quantum states of all of the particles in the measuring device). The decoherence idea states that as particles become entangled with more and more other particles— effectively, as the system becomes more and more macroscopic— interference terms become highly suppressed, leading to the practical appearance of wave function collapse. However, while decoherence indisputably happens, it's not clear that the decoherence paradigm actually addresses the measurement problem or not. (Only Schrödinger's cat can probably answer for sure!)

As you consider interpretations of quantum mechanics, it is important to remember that none of the valid interpretations of quantum mechanics lead to quantum mysticism. Much quantum mysticism— unfortunate parts of popular culture such as the movie *What The #$*! Do We Know?* or the book *The Secret*— is based on a misreading of the measurement problem. Two things are true: first, that quantum particles can be in a mixture of states, where multiple outcomes are possible and consistent with the laws of physics. Second, when *we* make a measurement, somehow that act of measurement causes one of the outcomes to be realized. This leads many people to conclude that we are affecting the state of the system, and that therefore somehow we can influence these outcomes. This is not the case. The probabilities for the outcomes are rigidly dictated by the probabilities that you can calculate from the mathematical model that we call quantum mechanics. Countless experiments have given us extremely good confidence that this is a good mathematical model. Nowhere in that model is there anything that allows the observer to *influence* or *choose* which particular outcome will be observed when an experiment with multiple probable outcomes is observed. Nowhere has a valid, reproducible quantum experiment been performed to demonstrate this effect (despite what you will hear in things such as the aforementioned movie).