Quantum Mechanics and Theology

There have been many connections claimed between quantum mechanics and theology. Perhaps we could summarize them all by saying that quantum mechanics and theology are both weird. If scientists, being generally level-headed people, can believe in quantum mechanics then they shouldn't have so much trouble with theology! See if we can sharpen that up a bit.

I will try to explain quantum mechanics. I think I can do that without using any mathematics. On the other hand, you won't understand it -- for the simple reason that no one understands it. Richard Feynman used to joke that if he caught any of his graduate students actually *thinkin*g about quantum mechanics, he would have them thrown out of the department. Now Feynman is dead and beside none of us is a Cal Tech student, so I suggest that we fly in the face of authority and actually think about quantum mechanics.

The first thing I should say is that quantum mechanics is a theory of things that are very small and in some sense, very simple. QM is essential in thinking about atoms; but most chemists never think of it at all. Nonetheless, the laws that determine how atoms combine to produce molecules are quantum mechanical in origin. In principle, all chemistry could be derived from quantum mechanics. On the other hand, if one just knew about atoms and quantum mechanics, one could never predict or even anticipate, for example, a strand of DNA. In this sense the world of molecules is an emergent level of reality. I will have more to say about emergence in a later lecture. There are two quantum mechanical phenomena that are macroscopic: superfluidity and superconductivity. These are also emergent levels of reality that were discovered long before they were understood.

The world of atoms is so remote from our world, or so it seems. So is this spooky world of quantum mechanics directly relevant in any way to our own world; or for our purposes, does God interact with the world at the level of quantum mechanics? Let's come back to that question after we have mastered some theory.

Every explanation of QM begins with the two-slit interference experiment. Imagine passing a beam of light through an opaque screen with two small holes in it. We would expect that some light would go through each hole, so that on the other side of the screen there would be two separate beams of light. This is indeed what you would see unless the holes were very small and very close together. In that case the light spreads out as it passes through the holes, and so there will be a region where the light coming through one hole overlaps with the light coming through the other. In that region you will find a complicated pattern of light and dark spots. This is easy to understand if you remember that light is like a wave with very small wavelength. Depending on how the waves overlap you will find regions where the two waves reinforce one another and regions were they cancel one another. We say that the two waves *interfere* with one another. You could see the same sort of thing with ocean waves. Suppose there are waves coming through two holes in a dike. The waves that come through the holes get mixed up a make interesting patterns. There is nothing surprising about this. This has been known for almost 200 years and was the first absolute proof that light consists of waves.

Now here's the mind-blowing, inexplicable thing. Repeat the experiment with a beam of electrons. Make the holes really small. You will see the same phenomenon! It seems that electrons that we always thought were very, very tiny particles are really waves. Or are they? I said carelessly, "You will *see* the same phenomenon," but of course you can't see electrons. To make this more precise, suppose we had some very high-tech photographic film, such that every time an electron hit it, it would make a tiny dark spot. We let the electrons stream through the holes for a while and then go develop the film. Spots on the film where many electrons have hit are dark. Surrounding regions are light. The patterns of light and dark are exactly what we saw in the case of light except very much smaller. Now here's the paradox. When the electrons passed through the holes, they behaved like waves. But when they hit the film they produced spots, which is what we expect of particles! It seems that when we do something with the electrons that encourages them to act like waves, like passing them through holes, they obligingly act like waves. When we explore their particle nature, we find particles.

I'm sure you have all silently come up with a scheme to settle this paradox once and for all. We will just send the electrons through the holes one at a time. That way there can be no interference and thus no wave-like behavior. You have all heard the Zen koan, "What is the sound of one hand clapping?" We all know the answer. There is no sound. One hand by itself can't clap. One electron by itself can't interfere. The Zen master get's the last laugh though. After many electrons have passed through we develop our film, and – there are the dark and light regions. We have just heard the sound of one hand clapping, and it sounds just like two hands clapping, or for that matter, a thousand hands. Put it another way, the *possibility* that the electron *might* have gone through hole A interferes with the *possibility* that it *might* have gone through hole B.

Philosophers divide things up into ontology and epistemology. Epistemology is all about explaining, describing, and predicting things. Ontology deals with questions of existence. What *really* exists and what is its nature? Physicists are good at epistemology. We can make measurements, draw diagrams, do calculations, and assign homework. We are very nervous about ontology. If you ask the typical physicist what an electron is really like, she will respond, “I don’t know and I don’t care. In fact the question makes no sense. We only have experiments and models that explain the experiments. We sometimes speak as if the models were reality, but we all know better.” I quoted earlier Feynman’s famous remark about not thinking about quantum mechanics. Now you see what it means – don’t waste your time with ontology.

Feynman not withstanding, many physicists and philosophers have thought about the ontology of QM and have come with many different conclusions. I will follow as closely as possible the majority view, which is called the Copenhagen interpretation. I don’t necessarily subscribe to it. It raises some profound problems as you will see.

The quantum-mechanical world is ruled by a mathematical object called the wave function. It’s a complex-valued function; that is, it has real and imaginary parts. It’s a function on space and time coordinates, so that at every point in space at every instant of time the wave function has some complex value. We can calculate these values using an equation discovered in 1922, the so-called Schrodinger equation. This function, however, is unlike anything in physics up to that time. All the other physics equations dealt with real properties: pressure, temperature, force, speed, etc. Things that can be measured. Things you have some intuitive understanding of. The wave function cannot be measured or detected except very indirectly. Its connection with the so-called real world is that it enables us to calculate probabilities. This brings us to the next puzzling thing about QM, it is a theory of probabilities.

Physics up to this time was completely deterministic. The Newtonian paradigm works like this. Suppose you have a system of particles interacting with one another. If you know the positions and velocities of all the particles at one moment of time, then in principle you can calculate the subsequent behavior of the system for all time. Our solar system works like this. If you have the right software, you can calculate the phases of the moon a thousand years in the future. You can also calculate what the phases of the moon were a thousand years in the past. Quantum mechanics doesn't work like this. Let me give you a simple example. Radioactive isotopes emit radiation by spontaneously changing into lighter isotopes. The energy released thereby is converted into one of several forms of radiation. We say that the nucleus decays. This all takes place inside the nucleus; that is to say, in the domain of QM. As a consequence, it's not possible to predict when this will occur. I can say that a given atom has a 50% probability of decaying in some specified period of time. In principle it is possible to predict what that time is, *but I have no way of knowing when it actually will decay*. Suppose there is a 50% chance it will decay in the next minute. It is possible that it will still be around 10 years from now; and if it is, there will be a 50% probability that it will decay in the next minute. The point is that in the quantum realm things happen *randomly and unpredictably*. This is not a shortcoming in our knowledge. Things in the quantum realm do not follow the usual rules of cause and effect. We can calculate probabilities, *but that's all*.

Now let's get back to this mysterious, metaphysical thing, the wave function. We use it to calculate probabilities. We do that by calculating its absolute magnitude. In doing this we throw away some hidden information. We don't know what, if anything, this hidden information means.

Here's a summary of the plot so far.

- Under some circumstances particles can act as if they were waves. The converse is true. Light and other electromagnetic radiation which we usually think of as being composed of waves can, under some circumstances, act like a stream of particles. In this case we call the particles photons.
- QM gives us a strange ontology in which possibilities are in some sense "real."
- When things happen in QM they happen randomly and unpredictably.
- The ultimate level of reality in QM is a mathematical function that cannot be measured or observed directly and contains hidden information of uncertain significance.

This is a partial list of quantum weirdness. There is much more to come.

There are certain privileged conditions in QM called quantum states or eigenstates. The definition is rather technical but I can give you a feel for what the term means by giving some examples. Take any atom; a hydrogen atom for example. Don't do anything to it. Just leave it sit. It will remain in the same state indefinitely as would any other hydrogen atom. If you measure the energy of its electron you are guaranteed to get 13.6 eV. So long as you don't disturb it, it is identical to every other hydrogen atom in the universe. We say that it is in an energy eigenstate because its energy has a precisely defined value. Suppose you measure the position of a particle. Immediately after the measurement the particle is in a position eigenstate because its position has a precisely defined value.
Now here is a trick question. What was the position of the particle *before* you measured it? According to the usual interpretation of QM, the question is meaningless. It doesn't have a position. I don't mean that it has a position and we just don't know it. It doesn't have a position. Position is not an attribute at this point. You create position by performing an experiment that measures it!

This is maybe the second weirdest thing about QM. (I will get to the all-time weirdest thing in a minute.) You create properties by observing them. There is one radical interpretation here, (by no means undisputed) that things have no real existence until we observe them. We bring the universe into existence by observing it!! That is such a wild idea that I don't want to lean on it too hard, but let's go back to something more prosaic – the two-slit interference experiment. There was a paradox. It seemed like the electron should be going through one hole or the other, in which case there could be no interference effects. Which hole did it go through, we want to know. Well, if you knew that it was going through hole A, then you would know its position; and it doesn't have a position. Not only that, if you placed some sly piece of apparatus by the holes to see just where the electron went, then all the quantum effects would disappear, because by measuring it you would have given it a position. This is not speculation. It's just as fact.

You have probably heard of the sad story of Scrhodinger's cat. No discussion of QM would be complete without reference to this poor animal. Before I tell you the story I have two cautions. The first is that this is only a thought experiment. No one to the best of my knowledge has performed it; and in fact, doing the experiment would serve no purpose. You would simply wind up with a dead cat. The second caution is that Schrodinger was one of the fathers of QM, but he never liked his offspring. This thought experiment was intended to prove that there was something wrong with it. Exactly what that is has been endlessly discussed. Anyhow, a cat is placed in a box with some diabolic apparatus that will kill the cat when triggered by the decay of a radioactive atom. The argument goes that since radioactive decay is a quantum mechanical process and since this decay is indirectly responsible for killing the cat, the entire apparatus including the cat must be treated with the formalism of QM. The next part of the argument is that the life state of the cat is a precisely measurable quantity. The cat is either precisely alive or precisely dead. Therefore when we determine that the cat is alive, then the cat is in the "live cat" eigenstate; and when we determine the cat is dead, then it is in the "dead cat" eigenstate.

What happens when you are not looking? As I explained before, its life status is not defined. It is neither alive nor dead. This is described mathematically by saying the cat is in a "mixed state." Its wave function is just the sum of the live-cat and dead-cat eigenstates. Now if you look at the cat and find it dead, the live-cat eigenstate instantly disappears. You have killed the cat by looking at it. If you find the cat alive, the dead-cat eigenstate vanishes. You have brought the cat back to life!

This story might be misleading for several reasons, but there is a genuine mystery here. The wave function changes instantly in a way that seems to have nothing to do with cause and effect. My eye intercepts some light coming from the box and as a consequence some mathematical thing of uncertain significance changes instantaneously. In our jargon, this is called "the collapse of the wave function." It's was a mystery to Schrodinger and it's still a mystery today.

You should be thinking just now that the whole discussion is meaningless. The cat is either alive or dead and that's the end of it. The rest is just mathematical flapdoodle. Now I will tell you the strangest thing about QM, and I hope you will yield to astonishment. It's called the EPR paradox. It requires a lot of explanation, but the punch line is easy to understand.

Electrons have a quantum mechanical property called spin. Think of a baseball thrown by a good pitcher. It goes fast and spins around some axis. Electrons are something like this. Fortunately I don't have to go into details except to say the following. All the electrons in the universe have the same spin. This is one of many things we don't understand. They just do. They are all spinning about some axis. We call that the direction of their spin. We can measure something about this direction, but our ability to do this is limited in a strange way. We can choose an axis, say the direction my pencil is pointing, and measure the direction of spin relative to that axis. According to the rules of QM, we will only get one of two possible answers. Either the spin is exactly aligned with the axis or it's exactly aligned in the opposite direction. We say the spin is either "up" or "down." If we perform a subsequent measurement about some other axis, we will get the same result; either "up" or "down." Now it's possible to build a device that emits two electrons simultaneously such that if we measure the spin direction of one and find that it is "up," then the spin of the other must be and will be "down," and vice versa. Suppose we set up this device in Kansas, measure one electron in San Francisco and the other in New York. Before we make any measurements, the electrons don't have spin directions as I explained before. Like the cat, they are a mixture of "up" and "down." So we measure the spin in San Francisco and get the result "down" then instantaneously in New York the "down" part of the wave function vanishes. Something in San Francisco instantaneously has an effect in New York. According the Einstein, signals can't travel than the speed of light, but these do. The effect is instantaneous.

Einstein thought this disproved QM. To explain why he thought so, I will tell you a parable. There was a small village located on a long desolate road. Because of some genetic peculiarity all the children in this town are twins. And when they grow up they all leave the town in separate directions to seek their fortune. The elders of the village know that in both directions the road forks, and for reasons that I won't go into, the twins must take opposite directions. If one turns left the other must turn right and vice versa. This is easy to arrange. Each set of twins is given a set of instructions they must carry at all times. When one twin comes to a fork, he or she must consult the instructions to see whether to turn left or right. The other twin who has received a complementary set of instructions will then turn right or left. If, as Einstein argued, the twins are analogous to the electrons, they must carry some hidden information that will tell them to be "spin up" or "spin down." QM as we understand cannot allow such hidden information. Therefore QM is wrong.

The matter rested here for many years. As in the cat experiment, there is nothing you can do to test it. If you perform the experiment you will get what you must get.

All you can do is argue. Then a theorist named John Bell came up with a great idea. He said in effect that the elders of the village had it easy because they knew what was on the road. Suppose we changed the configuration of the road in some random way that the elders couldn't anticipate. They could send along with the twins some general-purpose instruction set, but the kinds of instructions they could write in this way are limited. Bell showed how we could design an experiment such that all possible instruction sets could be enumerated. We could then do the experiment and see if the electrons followed one of these hypothetical instruction sets – or did something else.

The matter rested here for some more years because the technology didn't exist to do the experiment. Finally it was performed with photons rather than electrons, and the result – the photons did something else. QM is right. Einstein is wrong. The experiment has since been performed over large distances. The most recent version I am aware of was done with one detector in France and the other in Switzerland. The photons were sent through ordinary fiber-optics communication lines.

By now you may be lost in the technical details, so let me return to my parable of the twins. Here is the quantum mechanical version of the twin's journey. The twins leave home without any idea of what they will encounter on the road. They each encounter a fork in the road. Each twin chooses left or right in a completely spontaneous, unpredictable way without any explicit knowledge of what the other twin is doing. Years later they come back for a class reunion. They get together to talk about their lives. It transpires that in every case the two twins turned in opposite directions. Thousands of twins have made this journey. There have been no exceptions.

How are we to understand this? The typical physicist would not try. Why? Because it is not possible to discuss this result without using the language of mysticism. The two twins are not separate entities. They are part of some implicit order. They participate in some all-encompassing reality that "decides," if that's the right word, whether it will be right-left or left-right. It is possible theoretically to consider more complicated versions of this experiment with three or more particles. The results are surprising. The more particles, the more profound the correlation among their various choices. The conclusion is inescapable; at the quantum mechanical level at least, the entire universe is bound up in this implicit wholeness.

I definitely want to get back to the issue of mysticism. First I need to tell you two more strange facts. I mentioned previously that one might measure the precise position of a particle. In doing so, however, one would have to interact with it in a way that would transfer energy in some uncontrollable way. This would in turn give it some unpredictable velocity. It seems that you can't measure the position and speed of a particle simultaneously with arbitrary accuracy. A lot of ingenuity has gone into finding some way around this fact, but it's a fundamental limitation built into the laws of QM; not just a limit of our technology. We call this the uncertainty principle. The combined accuracy with which we can measure momentum and position is limited by a small fundamental number called Planck's constant. Moreover, the rule in QM is that what can't be measured doesn't exist except in the realm of possibilities. As a consequence, quantum processes that occur over a very small region of space and a brief instant in time can violate the law of conservation of energy; for after all, energy is not all that well defined. And that means that something can be created out of nothing! It works this way. Here I have nothing. Out of this nothing appear an electron and a positron. An instant later they annihilate one another, and I am left with – nothing! This happens all the time. The void is not empty. It is full of this cosmic dance of creation and annihilation. I should add that this is not just speculation. The effect can be observed. It's a difficult experiment, but it has been done and the results are consistent with theory.

It's a curious fact that the total energy of the universe is exactly zero. This has led to some speculation that the universe might have emerged from nothing via some sort of similar quantum process. I will return to this when we study cosmology.

Finally, I said that particles can act like waves. If that is so, what's waving? This question came up in the 19^{th} century in connection with light. It was imagined that space was filled with a medium called the ether that propagated light ways mechanically in much the same way that sound waves are propagated through air. In order to obtain the speed of light, however, this ether had to have some bizarre properties. There were other things wrong with the theory, and it was eventually discredited by a classic experiment that all physics majors learn about. That was before the days of QM, however. The idea is now back in quantum mechanical terms. It's called the "field." Or more properly, the fields, since there is a different kind of field for each kind of particle. These fields are like wave functions in the sense that they are mathematical object that are imagined to fill all space. In this view, particles are not fundamental. At the deepest level, reality consists of fields; and what we think of are particles are just bunches of energy carried by the fields.

I have told you things that just cannot be understood in terms every-day logic. We can still assign the homework problems and do the calculations – that's epistemology. But I would like to know about ontology. What really exists. There are several directions we could go here. There is a book, "Wholeness and the implicit order" by one of our gurus, David Bohm, who takes this on at a technical level. I will pass over that in favor of a cult classic, "The Tao of Physics," by Fritjof Capra. Capra was a physicist back in the 1960's who became interested in Eastern mysticism. By his own account he had some sort of mystical revelation and started to pursue the connections between quantum physics and the teachings of Hinduism, Buddhism, and Taoism. The book was a best seller, and Capra went on to become something of a new-age guru. The book was written in 1974, and since then some of the physics on which he based his argument has been thoroughly discredited. I am not very sympathetic to his entire approach, but I think his basic ideas are worth a bit of our time. Let's start with a quote from J. A. Wheeler.

"Nothing is more important about the quantum principle that this, that it destroys the concept of the world as sitting 'out there.' … the measurement changes the state of the electron. The universe will never afterwards be the same. To describe what has happened, one has to cross out that old word 'observer' and put in its place the new word 'participator.' In some strange sense the universe is a participatory universe."

Or a quote from Heisenberg

"What we observe is not nature itself, but nature exposed to our method of questioning."

The Eastern mystics have pushed this notion to the extreme, to a point where observer and observed, subject and object, are not only inseparable but also become indistinguishable. Here's a line from the *Upanishads*.

"Where there is a duality, as it were, there one sees another; there one smells another; there one tastes another … But where everything has become just one's own self, then whereby and whom would one see? Then whereby and whom would one smell? Then whereby and whom would one taste?"

I offer one more comparison out of many in Capra's book: the similarity of our notion of the quantum field with the Neo-Confucian notion of *ch'i*. Like the quantum field, *ch'i* is conceived as a tenuous and non-perceptible form of matter which is present throughout space and can condense into solid material objects. In the words of Chang Tsai:

"When the *ch'i* condenses, its visibility becomes apparent so that there are then the shapes of individual things. When it disperses, its visibility is no longer apparent and there are no shapes. At the time of its condensation, can one say otherwise than that this is but temporary? But at the time of its dispersing, can one hastily say that it is then non-existent?"

And further

"The Great Void cannot but consist of *ch'i*; this *ch'i* cannot but condense to form all things; and these things cannot but become dispersed so as to form (once again) the Great Void."

What if anything does this have to do with Christian theology? I would like to throw out three ideas and discuss them briefly. The first point is that physicists can talk unblushingly of an underlying level of reality that can only be referenced indirectly and which cannot be understood in terms of our normal modes of thought. Perhaps this particular level of reality has nothing to do with the supernatural as Christians normally understand it, but the very fact that it makes good scientific sense to talk about alternate levels of reality should encourage us to think that the notion of a supernatural realm cannot be simply ruled out by the success of science.

The second point has to do with free will. In the Newtonian paradigm all subsequent behavior of a system is determined by its initial state. If this is true our entire future has been determined by physical law. Both QM and chaos theory teach us that many things happen by blind chance and so are inherently unpredictable. Neither picture leaves any room for God to act in the real physical world. But suppose God acts through the indeterminacy of QM; events that seem to us completely random are in fact channeled toward specific ends through the will of God. The difficulty with this is that QM acts in the realm of the very small – atoms, electrons and such. It's hard to see how events on this scale could influence things in our world, but perhaps they do.

The final point is that even if QM and Christian theology have nothing directly to do with one another, they are similar in the sense that they try to understand a level of reality not directly accessible to our senses. So at least their methodologies should be similar. John Polkinghorne has recently written *Quantum Physics and Theology: An Unexpected Kinship*. He points out four interesting parallels.

- Understanding in physics comes from the interplay of experiment, observation and data on one hand and theory on the other. In Christianity the data consists of events in the life of Jesus and the personal experiences of subsequent Christians. Theology plays the role of theory in this context.
- Progress is made when critical questions are explored. Polkinghorne gives as an example: how could one prove that protons and neutrons were in fact made up of constituent particles, i.e. quarks? On the theological side he lists: (i) Was Jesus indeed resurrected on the third day, and if so, why was Jesus, alone among all humanity, raised from the dead within history to live an everlasting life of glory beyond history? (ii) Why did the first Christians feel driven to use divine-sounding language about the man Jesus? (iii) What was the basis for the assurance felt by the first disciples that through the risen Christ they had been given a power that was transforming their lives in a new and unprecedented way?
- Sometimes a discovery is made that radically transforms and expands our horizon. Polkinghorne gives the example of superconductivity – profoundly puzzling when it was discovered in 1913. It required the development of quantum theory many years later to fully explain. Polkinghorne suggests that miracles may play a similar role.
- Finally there are critical events that transform their subject immediately. I was actually present in the counting room at SLAC when the first direct evidence of quarks appeared on the computer monitor. We all looked at the peak in the distribution and realized our field would never be the same. Of course, the one singular event that changed all of western faith history was the resurrection of Christ.

Even if none of these points appeal to you, you can still take QM as metaphor. There is an underlying level of reality to which we have only indirect access. Everything in the universe is entangled in a mysterious way that defies the usual rules of cause and effect. And finally, we live in a participatory universe. That should be enough for one evening's reflection.