LECTURE 24

QUANTUM MECHANICS

Most physicists currently believe that they have the basic description of the universe [though they currently admit that 90 to 99% of the universe is in the form of "dark matter" of which they know nothing except that it has gravitational attraction]. You should realize that in all of science there are only descriptions of how things happen and nothing about why they happen. Newton gave us the formula for how gravity worked, and he made no hypotheses as to what gravity really was, nor through what medium it worked, let alone why it worked. Indeed, he did not believe in "action at a distance".

The reasons for discussing quantum mechanics, QM, are that: (1) it is basic physics, (2) it has many intellectual repercussions, and (3) it provides a number of models for how to do things.

At the end of the 1800's and early 1900's physics was faced with a number of troubles. Among them were: (1) classical physics dealt with continuously varying things, and clearly the spectra of atoms came in discrete lines, (2) electric charges, when moving, other than in a straight line, should radiate energy, hence the then current picture of the atom with the electron going around the center should radiate energy rapidly and collapse into the nucleus, but obviously it was stable, (3) the black body radiation measured in the laboratories had one shape, but the theories fitted one end or the other and each gave infinite energy for the opposite end, and (4) many other troubles often centered around the discrete-continuous contradictions.

Max Planck (1858-1949) fitted the black body radiation experimental data with an empirical curve, and it fitted so well that he "knew" that it was "the right formula". He set out to derive it, but had troubles. Finally he used a standard method of breaking up the energy into finite sizes, and then going to the limit. In the calculus course we do the same sort of thing; the integral is approximated by a finite number of small rectangles, these rectangles are summed, and then the limit taken as the largest width approaches zero. Fortunately for Planck, the formula fitted only so long as he avoided the limit, and no matter how he took the limit the formula disappeared. He finally, being a very good, honest physicist, decided that he had to stop short of the limit, and that is what defines Planck's constant!

The result was presented at a meeting, (Dec. 1900), and later published, but was fairly well ignored. Even Planck had little faith in it, until Einstein showed how the finite pieces of energy, called quanta, would also explain the photoelectric effect. This got quantum mechanics going. But it still drifted, even though Bohr devised a model of the atom in which the electrons were confined to definite orbits and emitted energy only when they changed orbits. This model came from the spectral line theory that had been built up based on arithmetical formulas with no known physical basis.

Before going on, let me discuss how this piece of history has affected my behavior in science. Clearly Planck was led to create the theory because the approximating curve fitted so well, and had the proper form. I reasoned, therefore, that if I were to help anyone do a similar thing I had better represent things in terms of functions that they believed would be proper for their field rather than in the standard polynomials. I therefore abandoned the standard polynomial approach to approximation, which numerical analysts and statisticians among others use most of the time, for the harder approach of finding which class of functions I should use. I generally find the class of functions to use by asking the person with the problem, and then use the facts they feel are relevant - all in the hopes that I will thereby, someday, produce a significant insight on their part. Well, I never helped find so large a contribution as QM, but often by fitting the problem to their beliefs I did produce, on their part, smaller pieces of insight.

In 1925 the new QM was started by two people, Heisenberg and Schroedinger. Heisenberg adopted the position that he would refer only to measurable quantities, the spectral lines for example, and was led to the matrix mechanics. Schroedinger adopted a wave type approach based on the earlier work of de Broglie and found a corresponding theory. Both mathematical structures, as you know, admit discrete eigenvalues, to be identified with the discrete energy levels of the spectral lines. It was quickly shown by Schroedinger, Eckart, and others that the two theories, though looking very much different were, in many senses, equivalent to each other.

Moral: there need not be a unique form of a theory to account for a body of observations, instead two rather different looking theories can agree on all the details that are predicted. You cannot go from a body of data to a unique theory! I noted this fact in the last Lecture.

Another story will illustrate this point clearly. Some years ago when I took over a Ph.D. thesis from another professor I soon found they were using random input signals and measuring the corresponding outputs. I also found that it was "well known" - meaning it was known, but almost never mentioned - that quite different internal structures of the black boxes they were studying could give exactly the same outputs, given the same inputs of course. There was no way, using the types of measurements they were using, to distinguish between the two quite different structures. Again, you cannot get a unique theory from a set of data.

The new QM dates from about 1925 and has had great success. It supposes that energy, and many other things in physics, come in discrete chunks, but the chunks are so small that we, who are relatively large objects with respect to the chunks, simply can not perceive them other than with delicate experiments or in peculiar situations.

The situation was, therefore, that classical Newtonian mechanics, which had been very well verified in so many ways and had even successfully predicted the positions of unknown planets, was being replaced by two theories, relativity at high speeds, large masses, and high energies, and QM at small sizes. Both theories were at first found to be nonintuitive, but as time passed they came to be accepted widely, the special theory of relativity being the more so. You may recall that in Newton's time gravity (action at a distance) was not felt to be reasonable.

Newton had inferred that light was particulate in nature, though he also had his "fits" of the parts. Initially light was thought to be made of particles that travelled in straight lines, but Young's wave picture of light, which is the one you have probably been taught in optics courses, came to dominate the particle model. We now have to face the fact that light apparently comes in quanta, and that the quanta appear to be <u>both</u> particles and waves. Almost every professor when teaching QM is forced, one way or the other, to say, "I cannot explain this duality, you will get used to it!"

Again I stop and remark to you the obvious lessons to learn from this wave-particle duality. With almost 70 years, and no decent explanation of the duality, one has to ask, "Is it possible that this is one of those things that we cannot think?" Or possibly it is only that it cannot be put into words. There are smells you can not smell, wave lengths of light that you cannot see, sounds that you cannot hear, all based on the limits of your sense organs, so why do you object to the observation that given the wiring of the brain that you have then there can be thoughts that you cannot think? QM offer a possible example. In almost 70 years and all the clever people who have taught QM, no one has found a widely accepted explanation of the fundamental fact of QM, the wave-particle duality. You simply have to get used to it, so they claim.

This in turn shows that while they were developing the theory they were groping around not really "knowing" what they were doing. When they found an effect in the symbols that they could interpret in the real world they would then claim a step forward. Well along in the process of creating QM Born observed that from the wave function, in the Schroedinger theory, the square of the amplitude is to be interpreted as a probability of observing something. Similarly for the matrix mechanics of Heisenberg. Complex numbers dominated the whole theory from the beginning, hence the need to take the square of the absolute value to get a real probability. Dirac observed that a photon only interfered with itself, hence the probability was to be assigned to the individual photons, hence in QM probability is <u>not</u> an average property of set of all photons, (or electrons from the Davisson-Germer experiment), as many probability books define probability.

Heisenberg derived the uncertainty principle that conjugate variables, meaning Fourier transforms, obeyed a condition that the product of the uncertainties of the two had to exceed a fixed number, involving Planck's constant. I earlier commented, Lecture 17, that this is a theorem in Fourier transforms - that any linear theory must have a corresponding uncertainty principle, but among physicists it is still widely regarded as a physical effect from Nature rather than a mathematical effect of the model.

That the probability of events was all that the theory supplied made many people wonder if below this level of these parts of Nature there might still be a perfectly definite structure, and that we were seeing only the statistical mechanics of it (but see Dirac's observation above). Von Neumann in his classic work on QM proved that there were no <u>hidden variables</u>, meaning there was no lower structure and that Nature was essentially probabilistic - a point that Einstein never would accept. But the proof was found to be fallacious, new proofs found, and in their turn found to be fallacious - the current situation being a toss up as to what you want to believe.

Man is not a rational animal, he is a rationalizing animal.

Hence you will find that often what you believe is what you want to believe rather than being the result of careful thinking.

This probabilistic basis of QM, with nothing definite below it, attracted the attention of many philosophers, and the general subject of <u>free will</u> was bandied about by them. The classical statement on free will is the remark, "You being what you are, the situation being what it is, can you do other than as you do?" There is apparently no way that the question can be settled experimentally, so the arguments go on. Personally, and it is only my belief, I can see no connection between the two - that Nature basically may be probabilistic does not mean that we are able to affect it in anyway, hence we cannot "choose" - that is if you accept that the forces of official physics are all that there are. Back in ancient Greek days, Democritus (about 460 b.c.) said, "All is atoms and void." This still the basic position of most physicists - they believe that they know everything there is (in the sense that there are no unknown forces they have not detected).

It is a religious question to a great extent - you can believe as you wish in this matter. If we have no free will, then the wide spread belief in punishment by God (or gods) for our deeds seems a bit unfair - we must do as we do if you accept the deterministic approach! On the other hand, if it is sensible to believe in justice from our God (or gods) then some sort of free will ought to be around. (Calvinists to the contrary.) And, of course, "infinite mercy" implies being forgiven for everything you ever do; see the Amida Buddha sect in Japan around the year 1000 a.d. for the extreme of such beliefs.

I do not believe that it is reasonable to argue such questions based on QM. I doubt, between you and me, that the physicists know every thing. In my old age I have come to the belief that there are such things as self-awareness, self-consciousness, which cannot be ignored as they are ignored in the "atoms and void" theories. But how such things, if they exist, (and in what senses they do exist), can interact with the real world of atoms is not a bit clear to me. The psycho-physical parallelism theory (the psychical and physical worlds go on independent parallel tracks with no interconnections but they always agree perfectly) that I was taught in an early psychology course, seemed to me, even at that time, to be utterly foolish. So I have nothing to offer you in these matters, except not to depend on QM for much support for your beliefs.

But worse things were to come in QM. Alain Aspect, in Paris, has done some experiments that are bothersome to say the least. Two particles with opposite spins are sent in opposite directions. The polarization of them is not known, but it is believed that when one is measured then the other will be found in exactly the opposite polarization. It is also a basic belief of QM that it is only the act of measurement that puts the wave function into some definite state; before measurement you have only the probability distribution. Thus the orientation of one measuring device at one end of the experiment will immediately - and we apparently mean immediately - affect what is measured at the other, remote end of the experiment - some 12 meters or so away! And this may at first seem to contradict both the special and general theories of relativity! I said "seem" because the theories predict that you can do no useful signaling at faster than the velocity of light. One can swing a bright light beam, as from a light house, so rapidly that a point far out goes faster than the velocity of light; but you can't signal faster according to the two theories. The Aspect experiments apparently force you to accept non-local effects - that what happens at one place is affected by remote things and that the effect which is transmitted does not, in any real sense, pass through the local areas in between but gets there immediately. But apparently you cannot use the effect for useful signaling.

Others have done similar experiments showing the same kind of effect. There are, apparently, non-local effects in QM. Two systems that were once "entangled", as they say, can forever interact - there is no such thing as an isolated object, much as we talk about using them in classical experiments. Einstein could not accept non-local effects, nor can many other people. But the experiments have been around for more than a decade and many hypotheses have been devised to get around the conclusion of non-local effects, but few of them have gotten much acceptance among physicists.

Einstein did not like the idea of non-local effects and he produced the famous Einstein-Podolsky-Rosen paper, (EPR), which showed that there were restraints on what we could observe if there were non-local effects. Bell sharpened this up into the famous "Bell inequalities" on the relationships of apparently independent probability measurements, and this result in now widely accepted. Non-local effects seem to mean that something can happen instantaneously without requiring time to get from cause to effect - similar to the states of polarization of the two particles of the Aspect experiments.

So once more QM has flatly contradicted our beliefs and instincts which are, of course, based on the human scale and not on the microscopic scale of atoms. QM is stranger than we ever believed, and seems to get stranger the longer we study it.

It is important to notice that, while I have indicated that maybe we can never understand QM in the classical sense of "understand", we have never-the-less created a formal mathematical structure that we can use very effectively. Thus, as we go into the future and perhaps meet many more things that we cannot "understand", still we may be able to create formal mathematical structures that enable us to cope with the fields. Unsatisfactory? Yes! But it is amazing how you get used to QM after you work with it long enough. It is much the same story as your handling complex numbers - all the professor's words about complex arithmetic, being equivalent to ordered pairs of real numbers with a peculiar rule for multiplication, meant little to you; your faith in the "reality" of complex numbers came from using them for a long time and seeing that they often gave reasonable, useful predictions. Faith in Newton's gravitation (action at a distance) came the same way.

I do not pretend to know in any detail what the future will reveal, but I believe that since at every stage of advance we tend to attack the easier problems the future will include more and more things that our brains, being wired as they are, cannot "understand" in the classical sense of understand. Still the future is not hopeless. I suspect that we will need many different mathematical models to help us, and I do not think that this is only a prejudice of a mathematician. Thus the future should be full of interesting opportunities for those who have the intellectual courage to think hard and use mathematical models as a basis for "understanding" Nature. Creating and using new, and different kinds of mathematics seems to me, to be one of the things you can expect to have to do if you are to get the "understanding" you would like to have. The mathematics of the past was designed to fit the obvious situations, and as just mentioned we have tended to examine them first. As we explore new areas we can expect to need new kinds of mathematics - and even to merely follow the frontier you will have to learn them as they arise!

I have put the word "understand" in quotes because I do not even pretend to know what I mean by it. We all know what we mean by "understand" until we try to say explicitly just what it means - and then it sort of fades away! St. Augustine (died 604 a.d.) observed that he knew what "time" was until you asked him about it, and then he didn't know! I leave it to you in the future to try to explain (better than I can) what <u>you</u> mean by the word "understand".

This brings me to another theme of this course; progress is making us face ourselves in many ways, and computers are very central in this process. Not only do they ask us questions never asked before, but they also give us new ways of answering them. Not just in giving numerical answers, but in providing a tool to create models, simulations if you prefer, to help us cope with the future. We are not at the end of the Computer Revolution, we are at the start, or possibly near the middle, of it.

I must make caveats if I am to be honest in these matters. It is traditional, and almost always assumed in Quantum Mechanics, that the probability distribution belongs to the particle. Long ago Lande' suggested that in the two slit experiment the probability distribution belonged to the apparatus, not the photon, or the electron. This makes much of the mysticism, including Feynman's assertion that the wave particle duality is fundamentally a paradox, seem to disappear. Lande' has been almost uniformly ignored, but experiments now planned, or already done, may revive his opinion. We are currently successfully confining single atoms for long periods so we think we know what we have, we are able to "tag" a single atom by putting it in an excited state and recognize it later, and hence the old statistics that assumed that particles were indistinguishable is coming under scrutiny. Long ago Davisson and Germer showed that electrons also reveal an interference pattern, and there is not a fundamental difference between photons and electrons in this matter. We are now able to do the two slit experiment with some of the lighter atoms, with, of course, much finer interference patterns. There is a proposal to "tag" an atom in the two slit experiment, and set things up so that in going through a slit a photon will be emitted, and hence we will know which path the atom took through the apparatus. Such experiments make the uncertainty principle a subject for experimental verification rather than just a theoretical claim. Modern technology is making possible many such experimental refinements, hence, broadly speaking, what was once pure theory becomes subject to experimental verification. It seems to me that as a result we will probably have to revise a lot of our beliefs, though it seems likely that much of QM will remain.

I can only speculate that a result of this deeper experimental probing of our theories will, in the long run, produce fundamentally new things to be adapted for human use, though the experiments themselves involve only the tiniest of particles. Certainly, past history suggest this, so you cannot afford to remain totally ignorant of this exciting frontier of human knowledge.