10 Interpretation of Quantum Mechanics

10.1 Superposition

We saw on our way to getting the wavefunctions for bound electrons that we were setting up standing waves from waves reflecting in the potential. so we had $\psi(x) = Ae^{ikx} + Be^{-ikx}$ i.e. the wavefunction is a sum of a wave going from left to right with momentum $p = \hbar k$ and one going from right to left with momentum $p = -\hbar k$.

For a particle picture, having momentum which was equally positive and negative would be describing a particle that for half the time was going left to right, and the other half bouncing off the wall of the box and going from right to left. So it would always only have one of the two possible momentum values.

THAT IS NOT HOW QUANTUM MECHANICS WORKS!!!

In our current standard interpretation of quantum mechanics, the particle is in a true superposition of states - thats what we need to get the standing wave as we need these two momentum components to be present SIMULTANEOUSLY in order to get the interference which sets up the standing wave.

Its also what we needed to get interference patterns in the double slit experiment. We need a single electron going through both slits simultaneously! The electron is in a superposition of states - for the double slit, some of its wavefunction goes through one slit, and some through the other so it can produce an interference pattern, whereas for the bound electron its some of the wavefunction is going left to right, and some is going right to left.

Yet when we MEASURE something - position on a screen for the double slit electron or momentum of a particle in an infinite well - we get a SINGLE number. The double slit electron is detected as a particle on the screen in a single place, the electron in the inifinite well has momentum EITHER $p = \hbar k$ or $p = -\hbar k$.

But then measurement takes on a strange role in the system. without measurement, the wavefunction evolves smoothly according to the time dependent schroedinger equation. Quantum mechanics then looks ordinary, like classical electrodynamics which is also governed by a wave equation, and in fact its simpler as there is only 1 field rather than 2 (E and B) and its scalar not vector!

Some part of measurement changing things makes a bit of sense - we measure using e.g. photons to bounce off the electron. And so we do touch it, so we can change its properties (you've just done Compton scattering in Collisions, Conservation and Fields! a photon gives momentum and energy to an electron when it bounces off it) But this isn't all the story as there are SOME things that measurement doesn't change e.g. ENERGY for an electron in one of the standing wave states - momentum is EITHER $p = \hbar k$ or $p = -\hbar k$ but energy is $\hbar^2 k^2/2m$ which is the same for either.

So the act of measurement only disrupts the system if the system was in a superposition state for the thing that is being measured! e.g. for the infinite potential well we could put the system in a superposition state for energy - we could have a wavefunction $\psi(x) = A\psi_1(x) + B\psi_2(x)$. But this is now TIME DEPENDENT as

$$\Psi(x,t) = A\psi_1(x)e^{-i\omega_1 t} + B\psi_2(x)e^{-i\omega_2 t}$$

where $\hbar\omega_n = E_n = n^2 E_1$ and $E_1 = \hbar^2\pi^2/(2mL^2)$. And then when we measure, we ONLY get either E_1 or E_2, with some probability which is set by the amplitudes A and B.

But then after that measurement, we ALWAYS get the same value if we measure energy again This is called collapse of the wavefunction. It is no longer in a superposition state, we have forced the system into ONE single state of this variable - energy in this example or position for the double slit electron on the screen.

This is what is so very odd about Quantum Mechanics - there are two entirely different physical processes depending on whether we measure something (when the wavefunction collapses) or not! If we DON'T measure, then a system in a superposition state continues to evolve with wave interference, and the outcome of measuring any quantity is probabilitisic. If we measure something then the wavefunction collapses, and the particle now has a SINGLE well defined value of that quantity and the interference patterns stop.

e.g. in the double slit experiment, if we set up a detector at the slits to figure out which slit the electron 'really' goes through, we get back to the pattern on the screen which we expect from particles he orthodox position is to say that actually its the TRIGGERING of the geiger counter which constitutes the measurement, which gets you out of the necessity for a consious mind observer. However its still not entirely satisfactory. There is a still a superposition state, which collapses instantaneously on measurement. as billiard balls, not waves.

OK, so suppose I don't try to figure out which slit the particle went through, and I get the interference pattern on the screen built up from individual electron detection events. And I detect an electron at some point x.

so, just before the electron got to point C the screen, where was it?? where was it just before I measured it?

realist it was just before C - in which case QM is incomplete becasue it couldn't tell us this! the position of the particle was never indeterminte, just unknown to the experimentor! ψ is not the whole story - there is some additional information (hidden variables) which we don;t know which is needed to provide a complete descrition of the particle.

orthodox (Copenhagen) the particle wasn't really anywhere, it was truely indeterminate. but the act of measurement forced the particle to somehow take a stand at some specific position. 'observations not only disturb what is to be measured, they produce it!' but then there is something very peculiar about the act of measurement.

agnostic refuse to answer. - not quite as daft as it seems. the only way to know the position of the particle before the measurement is to measure it....

10.2 Schroedingers cat

the best way to illustrate these different positions is the 'infamous' schroedinger cat experiment. A cat is placed in a box containing a radioactive sample, a Geiger counter connected to a hammer, and a vial of cyanide. If an atom in the sample decays, the Geiger counter will activate the hammer and smash open the vial of cyanide, and the cat dies.

A radioactive sample with a known decay rate is chosen. After a period of time where the sample is equally likely to have decayed as not, we look in the box and check the health of the cat. We will find that the cat is dead or alive.

According to the orthodox view, the cat is BOTH alive and dead until the box is checked. The system is in a superposition of equally likely states and will remain that way until a measurement is taken i.e. the system can be represented by the wavefunction

$$\psi = A(\psi_{alive} + \psi_{dead})$$

The measurement will also influence future measurements of the systems. That is, if you look in the box and see a dead cat then the chances are extremely high that when you look in the box five minutes later the cat will still be dead. This is 'collapsing' the wave function. The 'alive + dead' wave function is no longer a good description of the system now that our measurement has forced a state upon it. This puts a great deal of importance on the act of measurement. Without the act of 'looking in the box' all systems that can be described by a quantum mechanical interpretation exist in a perpetual limbo of superposition states, according to the orthodox viewpoint. It is the measurement that forces the system to 'make up its mind', to choose between live cat or dead cat. And if you look in the box and find the cat is dead it is YOU who killed it by looking in the window.

so then you get into all sorts of ridiculous stuff about conscious observers! or the even more untestable multiworlds hypothesis where the entire universe splits into two copies, one where the cat is alive and a copy where the cat is dead.... !!

Schroedinger regarded this all this as patent nonsense!! The orthodox position is to say that actually its the triggering of the Geiger counter which constitutes the measurement, which gets you out of the necessity for a conscious mind observer (though the cat would also do!).

However this still is not entirely satisfactory. We are still talking about superposition states, though the states are whether or not the radioactive nucleus has decayed in quantum tunnelling which is at least about a tiny particle rather than a macroscopic object like a cat!

11 Conclusions

So I hope that this course has enabled you to start to appreciate just how strange quantum mechanics is, and to build your interest in it. Physics students will study it much more in the comming years, but often we focus so much on the maths, in giving you the tools to calculate what matter does, that we don't stop to think about how odd it all is. My top tip for physics and life - every so often, have a think about the things that are important - and especially right now!