15 but what does it mean??

You have now paid your dues - you've got some proficiency with USING quantum mechanics. so now we can stop and ask what it all means!!

15.1 probability versus determinism

we looked at how waves were tricky things - we couldn't know both position and wavelength. and for particle waves that means we can't know position and momentum simultaneously. we looked at superposition of multiple waves to try to handle this, and it gave us a great way to quantify this lack of precision in the heisenburg uncertainty principle.

but the is something deeper here. in the double slit experiment, the particle is clearly wave-like as it produces interference. if we turn down the rate so that only 1 particles goes through the slit at once we get the SAME interference pattern, so the wavey property belongs to a single particle not just to particles interfereing with each other.

the wavefunctions give us the probability that the particle ends up at some point on the screen, but its only a probability. we don't know where it is till it hits (as a nice localised single particle hit!)

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....

but if I measure the particle again after the first measurement then everyone agrees I'll get C. The wavefunction collapses on measurement to a spike at point C. it will spread out again given time - the gaussian wavefunction spreading we did last lecture, so we have to redo the measurement quickly. but if we do, we'll get C.

so wavefunctions evolve with time as given by the time dependent schroedinger equation, but can also suddenly and discontinuously collapse on measurement!

15.2 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. However, 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

$$\psi = \frac{1}{\sqrt{2}}(|alive> + |dead>)$$

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 called 'collapsing' the wave function. The 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 'take a stand', 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.

The realist position holds that if you get a measurement from a system described by a probability distribution then the system has actually been in that state from the beginning. So when you look in the box and see a dead cat then the cat was that way prior to your checking the box. The sampled decayed at some point prior to looking in the box and the cat has been dead since that time. This belief that the system has been in the state prior to the measurement removes the importance of the act of measurement.

The final stance is the agnostic response. People with this belief avoid the question completely on the basis that it does not matter. The equations work and the philosophical implications are of no consequence. This is the most practical of approaches but not very interesting.

Schroedinger regarded this all this as patent nonsense!! there is something absurd in a macroscopic object being in a linear combination of 2 different states. an electron can be, but not a cat! the way around this in 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 consious mind observer. However its still not entirely satisfactory. There is a still a superposition state, which collapses instantaneously on measurement.

there is also another caveat here - a cat is a macroscopic thing, not a single atom, and we know (Ehrenfest theorem) that quantum mechanics has to give the same answers in the end as classical mechanics when we go from quantum scales to macroscopic scales. and we have seen how a wavepacket spreads out - we localise it at the start and it quickly spreads. so while we could prepare a a superposition state, but it decoheres very quickly due to the multiple interactions between multiple atoms in the cat!

and indeed, the refuge of the nutters: multiworlds. the entire universe splits into two copies, one where the cat is alive and a copy where the cat is dead.... (anyone ever heard of energy conservation???)

Bells theorm gave a way to TEST between realists and orthodox - and merely the fact that its an experimental question means that the agnostic position is not tenable!!! and its doing it on single particles not on a macroscopic article so its not a feature of decoherence. it really tests the fundamental wierdness of quantum mechanics. there are subtle differences between true indeterminancy and hidden variables - true indeterminancy produces odd correlations (entangled quantum states) across particles that are so widely separated as to be not in causal connection. 2 photons formed by decay of a particle - opposite direction and SPIN. according to QM then they both have equal chance to be $m_s = \pm 1/2$ and they are in an entagled state. but when you measure one the other is INSTANTLY known to be the opposite spin to the one you measured. The real experiment is more subtle as it uses different components of $\underline{S}$ and results in Bells inequality. they did the experiment.

and the EXPERIMENTS support true indeterminancy, or rather, the experiements show that nature is non-local. and after that, noone really cared much for hidden variables as they had bigger problems!!

15.3 Quantisation - bound particles again

For a free particle then the wavelength i.e. k could take any value. But as we start to trap a particle in some potential V i.e. it has energy $E = \hbar^2 k^2/2m < V$ then the multiple reflections set up interference so the only waves which fit are those with some integer wavelength condition and hence some quantisation of energy.

This is very different from classical physics. we have multiple solutions of the Schroedinger equation ψ_n, each with energy with energy E_n. The observable energy only has a deterministic value if the system is in one of these eigenstates ψ_n, at which point the energy is E_n. If its not one of the eigenstates, if it has instead some arbitrarily shaped wavefunction ψ, then this can be expanded out as a sum of all the different eigenstates so $\psi = \sum_n a_n \psi_n$. But then the outcome is NOT deterministic. the systems can only be on ONE of the states. we don't know which one, we only know the probability as we know the average energy is

$$< E >= \int \psi^* H \psi dV = \int \sum_n a_n^* \psi_n^* H (\sum_m a_m \psi_m) dV = \sum_n a_n^* \sum_m a_m \int \psi_n^* E_m \psi_m^* dV$$

$$= \sum_n a_n^* \sum_m a_m E_m \delta_{nm} = \sum_n (a_n)^2 E_n$$

the only way this works is if each state n has probablity of a_n^2 of being observed.

If we prepare many identical copies of the system, i.e. all having the same initial state wavefunctions ψ then the probability we measure the energy is E_n is a_n^2 but we can't tell WHICH system will give us which energy.

Probability is at the heart of quantum mechanics. It is inherently non-deterministic, a statistical theory.

16 Conclusions

the wavefunction represent the state of a particle or system. particles do not in general posses specific dynamical propoerties (position, momentum energy etc) until the act of measurement intervenes. the probability of getting a particular value of a specific proerty is determined by the statistcial interpretation of the wavefunction. the wavefunction collapses on measurement so an immediately repeated measurement is certain to yield the same result.