Interpreting Quantum Mechanics

Kieren O'Neil, T00238338

Thompson Rivers University Physics

Kamloops, BC, Canada

oneilk112@mytru.ca

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Instructor: Dr. Robin Kleiv

I. Why quantum mechanics need interpreting

Quantum mechanics is one of the most successful theories ever created. It explains the behavior of atomic and smaller scale systems. The fundamental element of quantum mechanics is the wavefunction Ψ, it describes how a system evolves, it can be found using the Schrodinger equation,

$$-\frac{\hbar^2}{2m}\frac{\partial^2\Psi}{\partial x^2}+V\Psi=i\hbar\frac{\partial\Psi}{\partial t}.$$

Given initial conditions the Schrodinger equation can be solved to find the wavefunction. The wavefunction cannot be directly measured. By the statistical interpretation of quantum mechanics $\int_a^b |\Psi(x,t)|^2\,dx$ gives the probability of finding a system in the range of states between a and b. It is from the statistical interpretation the problem of interpreting quantum mechanics arises. If a system is in some state

$$\Psi=\frac{1}{\sqrt{2}}|0>+\frac{1}{\sqrt{2}}|1>,$$

the probability that it will be found in state $|0>$ is 0.5, and the probability is 0.5 for the $|1>$ state. Even though you know the wavefunction which is everything you can know about the system by quantum mechanics, you cannot know if it will be found in $|1>$ or $|0>$ when the system is measured. If the system was found in the $|1>$ state after a measurement the question arises, was it always in the $|1>$ state? Did the measurement force the system to "choose" between $|0>$ and $|1>$? Or is the question invalid? These are the classic realist, orthodox, and agnostic positions on this problem respectively [1] [2].

II. The Bohr-Einstein debates

The orthodox or Copenhagen interpretation was argued for by Bohr. In the above example this takes the position that the particle was not in any state before it was measured in $|1>$, and the act of measurement forced it into the state. The act of observation does not disturb the system to determine the state, it creates what was measured when a measurement is made. This measurement is irreversible and is how a quantum system can influence our classical world. Bohr and his supporters contested classical conservation laws and locality, arguing that the new quantum theory was entirely new and not dependant upon such classical phenomena [1] [3] [4].

The hidden variables interpretation or the realist position takes the idea that the particle was in $|1>$ before the measurement was made, the observer simply did not know it was there. Einstein took this position, he believed that there was some deeper theory that could explain where the particle was always. Quantum mechanics was incomplete and a component of deeper theory which would eliminate the issues he perceived with quantum mechanics specifically locality violation, and the issue of the probabilistic description rather than a deterministic one. There is nothing special about the measurement, nor is there any divide between a classical and quantum world, the measurement simply reveals a state that already existed to the measurer [1] [4].

The debates in popular conception occurred over the 1927 Slovay conference, however Einstein and Bohr continued a correspondence on this topic for many years, and both were deeply interested in it from the development of quantum theory. Einstein's greatest argument against quantum mechanics as a complete theory is the 1935 EPR paper discussed in section III. The primary arguments of both Einstein and Bohr continued to largely be the same with most of Einstein's coming from locality and conservation laws and dealing with apparent ways in which quantum mechanics violated them. Bohr's tended to consist of insistence that quantum mechanics was not classical and could not follow the same principles as classical theories [4].

Einstein's argument at the 1927 conference consisted of a double slit experiment, of the kind where single particles are emitted; by quantum mechanics pass through both slits and have a position probabilistically determined by their wavefunction creating the standard double slit interference pattern. Einstein said that you could detect by conservation of momentum from the emitter which slit a particle passed though. Bohr's counterargument for this was to apply the uncertainty principle to the emitter arguing that its momentum could not be determined to enough precision to determine which slit the particle passed through. The two continued discussing this at the 1930 conference, Einstein proposed a mirrored box containing some amount of radiation, a shutter could open to release some amount of radiation; the box could then be weighed before and after determining the energy of the emitted radiation. Bohr again disproved this with the uncertainty principle, the displacement of the box in the gravitational field needed to weigh it disturbed the frequency of the emitted photon enough for the uncertainty principle to be satisfied [4].

III. Evolution to modern quantum theory

The EPR paradox was proposed in a 1935 paper by Einstein, Podolsky, and Rosen for whom it is named. The intention was to prove the realist or hidden variables interpretation. In which they propose a system in a state

$$\frac{1}{\sqrt{2}}(|10> + |01>),$$

where two qubits are entangled together so that if one is measured in one state the other is forced into the other state. Such a state can be created using conservation laws, if a spin 0 system decays into two spin ½ particles by conservation of momentum one of those must be spin up and the other must be spin down even though you do not know the spin direction of either once one is known the other is also known

$$\frac{1}{\sqrt{2}}(|\uparrow\downarrow> + |\downarrow\uparrow>),$$

which is the EPRB system proposed by Bohm. Experimentally it has been tested, such a state is constructed, and the two components are separated, then one of them is measured. Even when the other is measured faster than a lightspeed signal could have reached it from the other their states are always opposite, if one is measured in $|0>$, the other will always be measured in $|1>$. This is the "spooky action at a distance" or quantum entanglement that famously troubled Einstein [1] [2].

The fundamental assumption of EPR was nothing can propagate faster than light, the principle of locality. If the influence of the wavefunction collapse propagates at the speed of light, this would violate the conservation laws we used to create our system initially, if each part was measured independently, in EPRB if one was in $|\uparrow>$, there is a 50% chance of finding the other in $|\uparrow>$, and violating the conservation of angular momentum. Since this does not occur experimentally, the component states are always opposite; then the final state is either determined by a hidden variable from its creation, or that the influence of wavefunction collapse propagates faster than light. The EPR authors concluded, based on locality wavefunction collapse cannot propagate faster than light, and must occur when the state is created and be determined by a hidden variable unknowable by quantum mechanics, and that quantum mechanics is incomplete [1].

Bell proposed a generalization of the EPR experiment which could detect the impact of hidden variables on the result of a measurement. For the EPR state he suggested that if the two measurements are carried out in different bases angled with respect to each other; one at θ_1 and the other at θ_2 with respect to vertical. By measuring with both detectors, quantum mechanics say the probability that the result will be correlated is

$$P(\theta_1, \theta_2) = -cos(\theta_1 - \theta_2),$$

when $\theta_1 = \theta_2$, $P = -1$ a perfect anticorrelation; if they aligned oppositely aligned, $\theta_1 = -\theta_2$, $P = 1$ a perfect correlation. If the result of each is determined by some hidden variable λ then,

$$P(\theta_1, \theta_2) = \int \rho(\lambda) A(\theta_1, \lambda) B(\theta_2, \lambda) d\lambda$$

is the probability of a correlation. Where $A(\theta_1, \lambda)$ and $B(\theta_2, \lambda)$ are respectively the responses of the first and second detectors given the angle of each and the hidden variable. If we have that $\theta_1 = a$, and we allow the experimenter to choose θ_2 to be either b or c. By completing the above for this situation, difference in correlation between b and c must satisfy Bell's inequality

$$|P(a,b) - P(a,c)| \leq 1 + P(b,c).$$

Choosing a and b to be at 90° to each other and with c in between them gives

$$|P(0°, c)| \leq 1 + P(90°, c).$$

This is trivial to disprove with the quantum mechanical prediction above, if $c = 45°$ then

$$\frac{1}{\sqrt{2}} \not\leq 1 - \frac{1}{\sqrt{2}},$$

and Bell’s inequality does not hold for a local hidden variable [1] [2] [5].

This means if EPR is true quantum mechanics is wrong, and if quantum mechanics is true then locality cannot be. Experiments on Bell’s theorem have been conducted with a variety of systems and they have been inconsistent with Bell’s inequality, and thus have ruled local hidden variable theories out, and proved that the universe is fundamentally nonlocal. Quantum mechanics does not seem to respect relativity, when a wavefunction collapses somewhere it collapses everywhere at once. Such collapses cannot be used to transmit information, the measurement of one component influences the result of measuring the other, since the result of this measurement cannot be controlled no information can be sent, and causality is preserved [1] [5].

The measurement problem is most famously known in the Schrodinger’s cat thought experiment. Schrodinger based this on the EPR paper to illustrate the absurdity of superpositions with a cat in a superposition of alive and dead, as he proposed in 1935, quoted in [1]:

> A cat is placed in a steel chamber, together with the following hellish contraption.... In a Geiger counter there is a tiny amount of radioactive substance, so tiny that maybe within an hour one of the atoms decays, but equally probably none of them decays. If one decays then the counter triggers and via a relay activates a little hammer which breaks a container of cyanide. If one has left this entire system for an hour, then one would say the cat is living if no atom has decayed. The first decay would have poisoned it. The wave function of the entire system would express this by containing equal parts of the living and dead cat.

After an hour, the cat would be in the superposition:

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

According to the Copenhagen interpretation the cat is in a superposition of alive and dead until a measurement is made, and the wavefunction collapses forcing the cat into either the alive or dead state. When does the wavefunction collapse occur? When the box is opened, when the atom decays, or somewhere else entirely? This is the measurement problem which is used to compare the interpretations discussed below; when and where does the wavefunction collapse occur in the system [1]?

The problem can partially be explained by the introduction of decoherence, a crucial development in the modern understanding of quantum theory; and a relevant one when placing a large-scale object, like a cat, in a quantum state. A standard domestic cat with a mass of 5 kg made of mostly water would have on the order of 10^{26} constituent particles [6]. When such a cat is placed in a superposition as above the wavefunction involves the large component particles of the cat. Because there are so many component particles it is likely for them to interact in a way that can broadcast the state to the outside world destroying which is called decoherence. The quantum system of Schrodinger’s cat would quickly interact with many particles rendering it untenable and decohering the wavefunction into a classical state of either a living or dead cat [1].

IV. Contemporary views

Contemporarily the Copenhagen interpretation is still the most popular, however many proponents of other views argue this is because the Copenhagen is what is taught to physicists, and they stick with it. However, even enthusiastic proponents of other interpretations want to discover what lies beneath quantum mechanics and will switch their position if new evidence comes to light supporting other interpretations. The modern views are of nonlocal theories due to Bell's theorem disproving locality. Many incorporate the idea of decoherence on a fundamental level to explain wavefunction collapse [7].

There are of course other interpretations, of which in this paper I will explore the Copenhagen, pilot wave, many worlds, and quantum information interpretations.

The Copenhagen interpretation remains the most popular [7]. The modern form is largely unchanged from the time of Bohr. However, it involves the concept of decoherence to explain the measurement problem, it is also nonlocal in accordance with Bell's theorem. By the Copenhagen interpretation our entangled state could be created, and a measurement made of it, when the measurement occurred the measuring apparatus made of many particles and their wavefunctions became entangled with the wavefunction measured, due to the large number of particles needed to broadcast this state up to our classical world causes the wavefunction to decohere and collapse. This argues that the state gradually lose the quantum properties and decohere into a definite state as the measurement is carried out which lessens the 'quantumness' of the system and creates the classical states we are more familiar with [1] [3].

The pilot wave interpretation is a nonlocal hidden variable theory rather than a local one, it arose from answering the question of whether the worlds is described in terms of particles or waves with, 'why not both,' (to oversimplify slightly). It argues that both the particle and the wavefunction are real; like a drop of oil on a rippling pond the particle rides the wavefunction which determines where it will be found. This has the advantage of not needing to divide the quantum and classical descriptions of the world; the particles exist, and when many are viewed from a large scale they act classically. It is a deterministic interpretation the system will evolve in accordance with the wavefunction, the uncertainty comes from the wavefunction being unknowable [3]. In the survey this received no votes, however the authors state that could have to do with limited sample size [7].

The many worlds interpretation argues that the wavefunction never collapses, it escapes the measurement problem by arguing that it does not occur. This extends to the idea the entire universe a universal wavefunction. For example, when the wavefunction

$$\frac{1}{\sqrt{2}}(|1> +|0>),$$

is measured and the superposition decoheres both parts of the continue to exist. If $|1>$ is measured it is one 'world' and the $|0>$ result creates another of these 'worlds.' When the measurement and decoherence occurred these two parts of the wavefunction ceased to be entangled with each other and could no longer interact with each other. In the many worlds interpretation only the wavefunction exists. When the system is measured it splits, with both parts still existing, decoherence occurs when the parts of the wavefunction can no longer interact with each other [5] [3]. This interpretation is the second to Copenhagen in the survey [7].

Quantum information is the theory that the universe can be broken down into binary questions, as John A. Wheeler famously summarized it, “it from bit.” 1989 quoted in [8]. The theory relies upon the that when we question the universe, we learn more about it. This could be seen as an extension of the Copenhagen interpretation where a measurement creates what is measured. Quantum information’s most exciting ideas are that information is the fundamental thing from which everything arises; and that it can explain issues with quantum mechanics, specifically what is a measurement. This theory is one of the more recent developments in interpreting quantum mechanics and it presents exciting implications both on its own and when combined with other interpretations, specifically many worlds [5] [8]. In the survey quantum information was largely responded to as a new and exciting development in quantum interpretations [7].

Interpretations of quantum mechanics are a fascinating area; these are ideas of what may lie deeper explaining the issues with the theory and even going deeper to areas like as quantum gravity and the origin of spacetime. There are many more interpretations than the ones discussed above, and this is still an active area of some research and lots of speculation. These areas are much divorced from our day to day understanding of the world and even many of the existing experiments on quantum theory. Interpretation presents many exciting philosophical implications, and experiments like testing gravity on progressively smaller scales and quantum mechanics on larger ones there will hopefully be exciting experimental implications as well [1] [5] [7].

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