On the Interpretation of Quantum Mechanics

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I. Introduction

"I think I can safely say that nobody understands quantum mechanics." There is a great deal of truth to this quote by one of the greatest physicists of our time, Richard Feynman (*The Character of Physical Law, 1965*). In fact, the prevailing interpretation of quantum mechanics forbids even seeking to understand the nature of quantum mechanics. It is a theory that works as well or better than any theory in the history of physics, so we should just "shut up and calculate!" In this paper, we will explore the interpretation of quantum mechanics – summarizing what people think they know about quantum mechanics, and speculating what we can know, and finally concluding that maybe we know more than we think we know. Interested? Shut up and read!

In order to avoid excessive infiltration of my opinion where objectivity is required, I will begin by briefly summarizing the major families of interpretation: probabilistic, deterministic, and "other." Because I do not intend to get into the details of each method, nor elaborate on the finer points of the methods, I will generalize these ideas respectively as "The Copenhagen Interpretation," the pilot wave interpretation, and as an example of "other" I will mention the Many Worlds interpretation, as this is gaining interest in recent years.

After reviewing the major interpretations, I think it is necessary for us to step back and ask some more fundamental questions about the theory of quantum mechanics and what that theory needs to look like. Specifically I will present some oft-overlooked (at least in recent decades) theological arguments, as well as a more common argument (though still overlooked): Occam's razor. Finally I will tie together what we know along with my opinions with the standard, basic example: double-slit interference.

II. The Copenhagen Interpretation

By far, the probabilistic interpretation – here referred to loosely as the Copenhagen Interpretation – is the prevailing interpretation of quantum mechanics, and has been since the 1930's. R. Shankar's book "Principles of Quantum Mechanics"[4] follows this interpretation and presents the four basic postulates of the theory (pg 115). Of particular interest here are the first and third postulates:

i. The state of a particle is represented by a vector $|\psi>$ in a Hilbert Space.

iii. If a particle is in a state $|\psi>$, an ideal measurement of a variable Ω will yield one of the eigenvalues ω with probability $P(\omega) \sim |<\omega|\psi>|^2$. The state of the system will change from $|\psi>$ to $|\omega>$ as a result of the measurement.

The first postulate implies that the wavefunction is the only thing necessary to describe a particle, so there is not a particle and a wave. There is only the wave. Postulate three implies that the "particle" exists only by "collapsing" the wavefunction. If, for example, we measure the position of the particle in state $|\psi>$, the wavefunction collapses to a point and the position is now known. However, the term collapse implies that the wavefunction is changing as a result of the measurement, and so measurement of the position of a particle does not imply the location of the particle before the measurement. In fact, the question "where is the particle before the measurement?" is frowned upon in the Copenhagen interpretation. Because there is no particle –

there is only the wavefunction $|\psi>$ – there is no answer to the question where is the particle as we think of it in classical terms.

The natural question following this introduction is "what is the wavefunction $|\psi>$?" Or, "what is waving?" In this interpretation, the only allowed answer is that the (properly normalized) squared amplitude of the wavefunction - $<\psi|\psi>$ - is the probability density. That is, $<\psi|\psi>$ as a function of position is the probability of finding the particle at that position if one takes a measurement. The probability wave also allows for computation of the probability of seeing any event or property of the particle Ω as $<\psi| \Omega |\psi>$. No further explanation of the wave is available, or in fact allowed, in the Copenhagen Interpretation. This is the origin of the phrase "shut up and calculate"; this interpretation of quantum mechanics works remarkably well and has stood the test of time over the past century, but does not yield any insights into the physical nature of the quantum world (if there is one as we know it).

Neils Bohr presented the idea of "complementarity" to address the ambiguities of wave/particle duality in the Copenhagen interpretation. Unfortunately there appears in the literature a multitude of insufficient explanations of what Bohr actually meant by this. J. Bell[1] thinks that most people (Einstein included) in fact don't understand what Bohr really meant. Bell asserts that by using the common definition of the word (e.g. your shirt and shoes complement each other nicely to form an outfit, or, the wave and particle complement each other nicely to form real objects) most people miss the mark and that Bohr may have enjoyed using the familiar word with a different meaning. Bell thinks that Bohr "seems to insist rather that we must use in our analysis elements which *contradict* one another, which do not add up to, or derive from, a whole. By 'complementarity' he meant, it seems to me, the reverse: contradictoriness."[1] Bell's analysis summarizes Bohr's theory: not an assertion that the wave and particle natures add up and make sense together, but that they do not make sense together based on our classical notions of physics, and we should not try to apply our classical understandings to the wave/particle duality problem.

III. Pilot Wave

The pilot wave theory is the prevailing interpretation for "classicists:" those who insist on a classical interpretation of quantum mechanics. The idea is simple: experiments clearly show that there is both a wave and particle nature of light and matter. Rather than asking "is it a particle or a wave?" one obvious solution is that light and matter consist of a wave AND a particle. The particle "rides" along the pilot wave, and it is favorable for the particle to be in a location where the wave has strongest amplitude, and thus, we are most likely to find the particle there. However, even though we still obtain the probabilities that we are familiar with, this interpretation is completely deterministic. That is, the wavefunction obeys Schrodinger's equation, and can be determined, and the particle exists in a classical, corpuscular state (position, momentum) somewhere on the wave. If we know the initial conditions of the system, we can completely determine the future position of the system. We see the appearance of probability and indeterminism because simply speaking, there is no way for us to know the precise initial location of a particle. However, in the pilot wave interpretation it is theoretically possible to know this, whereas in the probabilistic interpretations it is not.

Albert Einstein was a firm believer in the determinism of physics[2], and tried to create a viable, deterministic description of quantum mechanics. In 1927 he introduced the "hidden-variable" formulation, so-called because the wavefunction contains information about hidden variables such as particle position and momentum. Einstein abandoned the theory because to him it violated a more fundamental notion that for a system of non-interacting particles, solution of the wavefunction and subsequent hidden variables (velocities) yields results that are dependent on other particles. Einstein firmly believed that if a system Hamiltonian is the sum of the individual particle's Hamiltonians, then the velocities should be only functions of the individual particles' properties. In Einstein's paper he notes that Grommer suggested to him a slight re-formulation that would solve the inter-dependency problem, but Einstein did not pursue it and abandoned the idea. Recently, Peter Holland of Oxford University revisited Grommer's idea and showed that in fact, one can formulate the hidden-variable interpretation such that the properties of independent particles and indeed independent[3].

IV. Many Worlds

The many worlds interpretation (MWI) is a popular interpretation of quantum mechanics originally presented in 1957 by H. Everett, a Princeton graduate student. The theory begins as similar to the Copenhagen Interpretation in that the wavefunction completely describes a particle: if the wavefunction is known then everything about the particle is known. The interpretations differ when considering what happens in an experiment such as the double-slit experiment. In the Copenhagen Interpretation, as we mentioned, the wavefunction describes a probability that the particle will appear at different locations on the screen. There is no way to predict at which location it will actually appear. In MWI, the idea is that the particle appears in all possible locations. For each possibility, a "new world" is created. Thus, we live in one universe in which the photon appeared at location x, and there is another world in which the photon appeared in location y. According to J.S. Bell[1], the largest appeal of this interpretation is with quantum cosmologists, who like to view the universe as a self-contained quantum system. The idea of classical boundary conditions do not settle well with these physicists, and this theory allows for the universe to be a consistent quantum system without classical boundary conditions.

Frank Tipler[5] elaborates on this notion by noting that the Copenhagen interpretation usually necessitates that the world be "observed" for things to actually happen. Further, the interpretation of the wavefunction amplitude as a probability amplitude is formulated based on performing repeated experiments to develop the appropriate statistics. But, what happens to the universal system, in which there is only one system? There are no outside observers, and repeated experiments cannot be conducted. Quantum cosmologists, who are worried by this, find solace* in the notion that the only way for ensemble averages and proper statistics to be built up is if different results actually do happen, and in MWI we can assume that all events occur in an infinite number of universes.

V. Theology

After briefly presenting the three basic classes of interpretations of quantum mechanics, I now wish to turn to some fundamental notions which we all use for better or worse to develop our interpretations. In today's world, it's not "politically correct" to talk about God, especially in science. However, if God created the world (and the physical laws that the world follows), then how can we ignore Him? The most famous example of using theology to explain quantum mechanics is Einstein's belief that "God does not roll dice." Einstein had a difficult time believing that God would allow the world to evolve at random, and this belief was a strong

*Yes, I violated my own rule of objectivity.

motivation for him to find a deterministic interpretation. I have not come across any opposing argument, for why God would want probability to be central to quantum mechanics, but I believe there is a valid argument for this as well.

The argument in favor of probability boils down to "how does God perform miracles?" In the Bible we read about many of the miracles that God performs, which are impossible by the laws of deterministic physics (as we know them). Does this mean that for God to perform his miracles, He must be constantly breaking the laws of physics which He himself created? I do not want to claim that we can fully understand Him, but it does seem logical that if you knew you would be working miracles, you would build the physics of the world to accommodate that. If the quantum world (and thus, the whole world) is set to run on the laws of probability, it might be *possible* for miracles to occur without violating the laws of physics. This is not to say that miracles happen at random: they still need divine intervention, as the probabilities associated with these events make them impossibilities without God's intervention.

Let's take a case study: more than once, God parted the sea for the Isrealites (both when crossing the Red Sea out of Egypt, and crossing the river Jordan into Isreal). If we believe that particles are truly represented by probability waves, then those waves extend off spatially to infinity with infinitesimal probability, but non-zero probability. For example, a particle in a well (in our case, a water particle confined between two other water particles) has a wave function that drops off exponentially outside the well. The probabilities of the particle appearing very far from the well are so small that, in all the particles in all the wells in the universe for all time, there may not be an observed occurrence. But, if God can take over when he wants to, or to deterministically decide that the particles will behave differently than the standard probability to which He has set them, then He could make miracles occur without violating the laws of the physical world which He created.

Of course these arguments are rather un-scientific, and in fact have seen from Einstein and myself opposing viewpoints of theology in the Copenhagen interpretation. I do think that both arguments are valid. I have a difficult time, however, finding two sides of theology in the many worlds interpretation. The Many Words Interpretation ought to be unsettling to just about anyone, and is terribly inconsistent with the monotheistic religions. Imagine for example that you are presented a situation in which you can do right or you can do wrong. Of course, you choose the right decision and try your best to live a good life. But, you also do the wrong thing in a parallel world! Which is the real you? Either there are infinite "yous" or, if all beings take all actions, then all beings are in fact the same (we have all done everything possible – all infinite possibilities – so I am the same as you! Disturbing, isn't it?). If all things happen all the time, then the meaning of right and wrong vanishes; this is not consistent with my knowledge of God.

VI. Occam's Razor

Occam's Razor is a well known principle that says when presented with a set of solutions, the simplest one is the best. This is of course not always going to be necessarily true, but indeed it is wise to not add complexity to an already complicated situation. An interesting example is in astronomy: it was believed for a long time that circles are the most perfect shapes, and so orbits should be in circles. Well, once it was seen that orbits are not circles, it was explained by considering epicycles – circular orbits around circular orbits. A highly complicated set of epicycles could be used to describe the actual orbit: an ellipse. Today, no one would challenge the notion that we should describe an ellipse as an ellipse (2 parameters) rather than a set of epicycles (>>2 parameters in general). I'll refrain from using more recent examples from astronomy.

For quantum mechanics, the Copenhagen Interpretation is in fact the simplest interpretation available, which is probably the reason it has been the preeminent interpretation since the formulation of wave mechanics in the early 20th century. The Copenhagen Interpretation has the benefit of relying solely on the wavefunction – we do not need to know about the wave and the particle (added parameters!). Additionally, we do not need to sweep away the ideas we don't like into higher dimensions (string theory, which I have not mentioned in this paper, as I have concentrated on "classical" ideas of quantum mechanics!) or alternate universes – common places to sweep the garbage of complicated physical theories. Occam's razor tells us that we should first accept the answer that has the fewest parameters, and that solutions which put the full answer in place where we cannot ever find it should be avoided.

VII. The particle and the wave

We have oft been introduced to the double slit interference experiment (most interestingly the single-photon version) as a clear example of the complexity of the quantum world and of wave/particle duality. This is indeed a fascinating experiment, unquestionably showing characteristics of light (or particles, since the experiment has been done with objects as large as C_{60} fullerines) that cannot be explained as a wave or as a particle alone. This leads naturally to questions such as "how can it be a particle and a wave?" and "what determines where the photon strikes on the screen?"

Before we get too caught up in the notion of wave/particle duality, we should be careful to ask the question: “what is a particle?” I think that there is a large enough body of evidence that the answer is not that a particles is “a little rigid sphere.” For example, if electrons are little rigid spheres, then we need to use the Bohr model of the hydrogen atom, which leaves a lot of explaining to do about radiation from accelerated charges. Based on our current knowledge f quantum mechanics, the only possible way for there to be a separate particle and wave is if the particle disappears until we measure it, whereupon it reappears so that we can look at it and interact with it. During nominal conditions when we aren’t interacting with a particle directly, the body of evidence suggests that the particle is a delocalized wave. The separate particle and wave violates the principle of Occam’s razor on two points: 1) it adds parameters by needing to know about both the particle and the wave, and 2) it wills away the unanswered questions by making the particle “do something special” (i.e. violate all the laws we think we know about physics) while we’re not looking at it.

The other question about having both a particle and a wave is the question of energy. We know the energy of a particle is contained within the particle (mass-energy equivalence). But what creates the wave? Where is the connection between our classical world and the wave? There are two possibilities to explain this: 1) either the wave does not require energy, or 2) there is a special “wave-energy” that only interacts with other “wave-energy” and we can never interact with it in our classical world of particles. Both of these options are unsettling to me. The first means that we can get something for nothing. This violates all of the tenets we have established about our physical world throughout history. The second is feasible but violates the complexity rule (Occam’s razor), and sweeps the problem to where we cannot see it or answer it.

Therefore, because we know there is a wave, there must not be a particle also. There is only the wave. The answer to the riddle of particulate behavior is simple: a particle is nothing more than a highly localized (in space) wavefunction. Now, we must be careful at this point to not jump to conclusions that because there is not a particle and a wave, there is just a wave, then the Copenhagen Interpretation must be the only possible interpretation. J.S. Bell brings up what I believe is the most-overlooked, completely unanswered, fundamental question of quantum mechanics: in the double-slit experiment, what causes the wave to suddenly collapse to a point on the screen, and at which point does it appear? Nothing about the wavefunction or Schrodinger's wave equation give us a hint that the wavefunction is going to suddenly collapse. Of course, when we disturb a delocalized wave, we change the boundary conditions on the wavefunction and cause the wavefunction to collapse, so mathematically it is consistent, it just doesn't answer the question of why.

For example, imagine the single-photon double-slit experiment. The Schrodinger wave equation tells us exactly the probability of the photon scintillating at any point on the screen. Of course, in this description of the system, for an analytical answer we necessarily approximate the environment (screens, slits) as a classical boundary. But on the microscopic (nanoscopic?) level, the scintillation screen is a set of vibrating atoms, with orbiting electron wavefunctions extending out in space back toward the photon. Certainly, the scintillation location must be affected by this "random" thermal motion of the atoms, such that at the instant the photon is about to strike the screen, the probability density must be spiking locally at the atoms vibrating toward the photon. Therefore, the boundary conditions for the wavefunction, which appear to be a classical flat boundary when the photon is released from a distance of about 10^0 meters away, will be an oscillating mess (certainly not a flat wall) once the photon is about 100 atomic distances away (when the photon is 10^{-7} m from the screen, the time to the screen is about 1 femtosecond, which is also an appropriate timescale for atomic vibration). This local, changing boundary MUST play an important role in the local determination of where the scintillation occurs by continuously changing the photon wavefunction's boundary conditions as it approaches the screen. So, could small fluctuations and thermal motions of the target atoms completely account for the distribution on the screen, making the wave-mechanics completely deterministic? It might be possible to explain much of the probabilities with determinism in this fashion. I have in fact not seen any attempts to explain the wave-only theory in this deterministic way. The point is, even though I think we must think wave-only, this does not necessarily force us to follow the Copenhagen school.

VIII. Conclusions

I hope that I was unable to hide my disdain for the many worlds interpretation of quantum mechanics. Not only for theological reasons which cannot be ignored, but because of the violation of Occam's razor and what I perceive as sweeping your problems under the rug of other universes. I sympathize with those who want to believe the pilot-wave theory for its classical interpretation of the particle, but I do not think that it is necessary to force particles to be little rigid objects. The wave-only interpretation is this simplest (and thus, best!) interpretation, and we only need to adopt the definition of a particle as any wavefunction that is "highly localized." I don't think that this should alter our classical notions of particles in any significant way, just make it easier for us to grasp the physics of the quantum world. Luckily for those still unhappy with the present unknowns, this does not mean "Copenhagen or bust." Wave-only still has a lot left unanswered, and in fact, I think there is still a possibility that the probabilistic nature of where the wavefunction collapses might be explained deterministically. This might make many of the deterministic interpretation's proponents such as Einstein happy, but I think that his argument the "God does not roll dice" is a dangerous one, as God might choose to make particles behave randomly because it works! Who are we to argue with what works?

IX. References

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