A Realist view of Quantum Mechanics

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Until the advent of Quantum mechanics, the realm of science was a fairly straightforward realm. The scientific realist view of what science is and does was very successful, and had limited opposition. Scientific realism being the view that when scientists have scientific theories to describe how some class of objects behave, those theories have literal meaning. If a theory describes some theoretical, or unobservable process to explain a particular behavior, the theory is actually describing some unobservable object or process. This is opposed to a philosophical view of science under which scientific theories only actually mean the set of observable consequences the theory would predict. With scientific realism, we hold the view that science is looking for complete descriptions of how the world actually works, as opposed to only models that will provide for us satisfactory predictions about what we will see. We want to be accurate in our understanding of what we cannot see as well. With quantum mechanics, however, the most successful scientific theory to date, much of the theory seems inherently inconsistent with a realist view of the world. We have a scientific theory that not only fails to provide any more than probabilistic expectations of what results we will get from experimentation, but claims this is the best we can possibly do. The theory claims that the limits on prediction are fundamental, and not based on a lack of knowledge or understanding. Not only is this the case, but even the behavior predicted leaves us with some fundamental questions about when things happen, questions which tend to be must successfully answered by “It does not matter.” A very non-realist position. Thus the
question remains, how do we rescue scientific realism from quantum mechanics?

In order to answer this question, the first thing we must do is have an understanding of the bizarre nature of quantum mechanics, and how these problems for the scientific realist manifest themselves. The basic example that we will continue to return to is that of x-spin and z-spin of a spin 1/2 particle. As Classical Quantum Mechanics describes, an electron (or other spin 1/2 particle) which is measured to be in a state of x-spin up, has this state as a determinate property. The electron has x-spin up. However, if we were to then measure that same electron’s z-spin, we would find that fifty percent of the time, we find the electron to have z-spin up, and fifty percent of the time, we find the electron to have z-spin down. We are of course assuming a perfect measurement device. If the first measurement of z-spin finds the particle in a spin up state, then every successive measurement of z-spin will find the particle in a spin up state, and likewise for spin down. In other words, the particle now has a determinate z-spin state. Now we take this electron which had first been measured to have x-spin up, and let us say that we measure the electron to have z-spin down, when we again measure the x-spin, we find that fifty percent of the time, the electron has x-spin up, and fifty percent of the time it has x-spin down. We get the same results if we had measured the electron to have z-spin up. It appears as though a measure of x-spin randomizes z-spin, and likewise as though measurement of z-spin randomizes x-spin.

Classical Quantum Mechanics explains this by saying that x-spin is a linear superposition of z-spin states, and z-spin is a linear superposition of x-spin states. In addition to getting the measurements described above correct, this superposition model also accurately predicts various interference phenomena that produce even stranger behavior. In the mathematical formalism, we use vectors to denote these states, and operators to denote measurement of an observable. If a particle is in a superposition of states, then the operator gives us the amplitude of finding the particle in each of the states. Amplitude is a more fundamental property than probability, the probability being the square
of the amplitude. With this formalism, the equivalence of z-spin with a linear superposition of x-spin states for an electron S is written as follows.

\[ |\uparrow_z\rangle_S = \frac{1}{\sqrt{2}}(|\uparrow_x\rangle_S + |\downarrow_x\rangle_S) \]

and

\[ |\downarrow_z\rangle_S = \frac{1}{\sqrt{2}}(|\uparrow_x\rangle_S - |\downarrow_x\rangle_S) \]

A particle in either of these states is said to be in an eigenstate of z-spin, that is when we operate on this vector by the z-spin operator, the output we get is the z-spin times the original vector we put in. Mathematically we would write this as \( \hat{Z} |\uparrow_z\rangle_S = \frac{1}{2} |\uparrow_z\rangle_S \). Since this is a spin 1/2 particle, spin +1/2 is equivalent to spin up and spin −1/2 is equivalent to spin down. With this understanding, we can see that z-spin and x-spin form two different bases for the vector space of spin states. This formalism will be very important in describing the shortcomings of classical quantum mechanics, as well as the advantages of an alternative view.

The \( \frac{1}{\sqrt{2}} \) in the equation above corresponds to the amplitude of the particle being in an x-spin down state or an x-spin up state. The squared amplitude tells us that if we were to measure the x-spin of this particle, we would have a probability 1/2 to find the particle with x-spin up, and probability 1/2 to find the particle with x-spin down. Not only is this the case, but Classical Quantum mechanics also tells us that preforming this measurement causes the wavefunction to collapse into whichever state of x-spin we find it to be. Thus if before measurement of x-spin the particle has the wavefunction

\[ \psi = \frac{1}{\sqrt{2}}(|\uparrow_x\rangle_S + |\downarrow_x\rangle_S) \]

after measurement, supposing we found the particle to have x-spin up, the wave function would collapse to be

\[ \psi = |\uparrow_x\rangle_S \]
which is now an eigenstate of x-spin, and no longer an eigenstate of z-spin.

This formulation has been wildly successful, in fact is has been the most successful scientific theory to date. However, it seems to pose problems for those who wish to hold onto a realist view of science. Up until quantum, it seemed perfectly acceptable to claim scientific theories give us a definitive view of the world, describing both the observables that we see, and the unobservables whose existence we must posit. The Classical theory of quantum mechanics however, does not tell us what will happen, namely how the wavefunction will collapse, or any way to predict beyond a measure of probability whether our measurement of x-spin on the particle above will yield a particle that is x-spin up or a particle that is x-spin down. The theory also does not tell us why this is what will happen. As Feynman put it “you won’t understand why Nature works that way. But you see, nobody understands that. ...The theory ... describes Nature as absurd from the point of view of common sense” [2, p. 10]. On top of this, the rules that tell us when a wavefunction collapses state that the collapse happens when we perform a measurement, however the rules say nothing about what constitutes a measurement. Does the existence of a device capable of providing measurement information qualify, or does there need to be some sort of sentient soul present in order for a measurement to take place and collapse the wavefunction? Many physicists have offered that it does not matter when the measurement takes place, the equations work out the same way, and we get the same predictive results, so it is not an issue. As scientific realists, this is an unsatisfactory answer, we need to be able to describe exactly what happens when. This is known as the quantum measurement problem, and it is very troubling for the scientific realist.

As has been offered before, we will present here a different, very deterministic view of quantum mechanics, which while simpler than the classical theory, is even more bizarre. Consider the following experimental setup, similar to several such experiments that Barrett presents. We have a system consisting of an electron, S, with z-spin up, and a physical self-contained measuring device, M,
capable of measuring x-spin, in a state ready to make a measurement. This system is completely isolated from us, the observer, so that we cannot be made aware of the results of the measurement. The device will record its measurement so the information is there, just not available to us. This system can be described by the wavefunction

$$\psi = \frac{1}{\sqrt{2}}|\text{ready}\rangle_M (|\uparrow_x\rangle_S + |\downarrow_x\rangle_S)$$

The measurement device is in an eigenstate of being ready to take a measurement of x-spin, and the particle is in a linear superposition of x-spin up and x-spin down. According to classical quantum mechanics, the system will evolve into the state

$$\psi = \frac{1}{\sqrt{2}}(|\text{up}\rangle_M |\uparrow_x\rangle_S + |\text{down}\rangle_M |\downarrow_x\rangle_S)$$

This is a linear superposition of the measuring device recording x-spin up and the measuring device recording x-spin down. The logical question is, how come this physical measuring device is any different from us as a more complex, macroscopic measuring device? Classical quantum mechanics says that as soon as we look to see what M recorded, the wavefunction will collapse into either $|\text{up}\rangle_M |\uparrow_x\rangle$ or $|\text{down}\rangle_M |\downarrow_x\rangle$ with equal probabilities of collapsing into each one. Alternatively, what if we as the observer went into a superposition correlated with the x-spin of the particle and the result that M stored? The waveform would be exactly as it is above, except instead of M recording up or down, it would be us. In order to make this a plausible explanation, we must make sure we can deduce all of the empirical observations that classical quantum mechanics gets right. This has been attempted in a variety of methods, including postulating many parallel worlds, and many parallel minds in order to better describe this no-collapse theory.

One of the most significant appeals of the no-collapse theory of quantum mechanics is its simplicity. There is only one rule in determining the future state of a certain system, and that rule is the linear evolution of the wavefunction.
If $|a\rangle$ would evolve to $|a'\rangle$ and $|b\rangle$ would evolve to $|b'\rangle$ then $\psi = \alpha |a\rangle + \beta |b\rangle$ would evolve to $\psi = \alpha |a'\rangle + \beta |b'\rangle$. There is no collapse of the wavefunction, there is no quantum measurement problem. The wavefunction is a complete description of system, there is no question as to how or when the waveform collapses because it does not collapse at all, and we are not restricted to probabilistic predictions.

The difficult part of presenting this theory is demonstrating empirical adequacy. Classical quantum mechanics gets all of our observations right, at least to the extent that it claims our observations can be predicted. Statistically speaking, we get the same probabilities of various wavefunction collapses as we would predict given the rules of classical quantum mechanics. On top of this, it appears very much as though when we preform a measurement, we are getting one particular result, not a superposition of different results. We need to be able to explain these experiences too.

The most important issue is that of our experiences. In order to explain this, we will provide a story of what happens when a human observer preforms a perfect measurement of x-spin on a particle with z-spin up. The description of events that we would like to defend is that our observer O, who makes a measurement of x-spin on a particle with z-spin up will end up in a superposition of having found the particle to have x-spin up and x-spin down. That is given the system of our observer and particle initially in the state

$$\psi = |\text{ready}\rangle_O |\uparrow_z\rangle_S = 1/\sqrt{2} |\text{ready}\rangle_O (|\uparrow_x\rangle_S + |\downarrow_x\rangle_S)$$

the system will evolve into the state

$$\psi = 1/\sqrt{2} (|\text{up}\rangle_O |\uparrow_x\rangle_S + |\text{down}\rangle_O |\downarrow_x\rangle_S)$$

Physicists have made x-spin measurements on particles with z-spin up, and they consistently report that they get exactly one of either x-spin up or x-spin down as a result. On one such particular measurement, the physicist will report getting x-spin up, and on another, he or she might report getting x-spin down.
Statistically, they report getting each of these results with probability one half. At first, it appears that this would not make sense given the evolution of the wavefunction above. But notice the following details that Barrett points out. If an observer measures x-spin up, he will be in a state to answer the question “Did you get a single result for x-spin?” in the affirmative. Similarly, if the observer measures x-spin down, he will answer the same question the same way. Thus, if this question were to be represented as an operator, then the system is in a linear combination of two different eigenstates with respect to this operator, two different eigenstates with the same eigenvalue. So the linear combination of these two states is also an eigenstate of the question. So even though the observer is in a superposition of states, O will always believe that he or she got a single result from the measurement of x-spin.

Unfortunately, the situation is indeed more complicated than this. A human observer is a macroscopic system capable of introspection, or in the case of quantum mechanics it would be more appropriate to consider it as automatically preforming measurements on oneself and keeping a record of the results. Thus, when we ask O what category of result came from the x-spin measurement, we immediately become entangled ourselves into the quantum mechanical system, and ourselves enter into a superposition of states along with O and the particle. We now have

\[ \psi = \frac{1}{\sqrt{2}}(O \text{-got-a-single-result}_u|\text{up}\rangle_O |\uparrow_x\rangle_S + O \text{-got-a-single-result}_d|\text{down}\rangle_O |\downarrow_x\rangle_S) \]

It is important to notice that this is very different from

\[ \psi = \frac{1}{\sqrt{2}}(O \text{-got-a-single-result}_u|\text{up}\rangle_O |\uparrow_x\rangle_S + |\text{down}\rangle_O |\downarrow_x\rangle_S) \]

which would be the case if we could ask the question of O without becoming entangled with the system. Another way of describing this difference, is the
state after asking the question might as well be

\[ \psi = \frac{1}{\sqrt{2}} (|O - \text{got a single result - up}_O \rangle \uparrow_S + |O - \text{got a single result - down}_O \rangle \downarrow_S) \]

One way of thinking about this is that the observer will remember which result he got. Thus there is a difference between him getting an x-spin up result and getting an x-spin down result. As macroscopic, introspective objects, any sort of interaction will now immediately entangle our state with the observer's state, and we will share any superposition that O is in. It would be AS IF we had asked O whether he got up or down as a result for his x-spin measurement. As such, the macroscopic world that we all inhabit, that seems to be THE WORLD is all in a shared entangled state. So when one physicist makes one measurement of the x-spin of an electron in an eigenstate of z-spin, the entire world enters a superposition of the physicist having found the electron to have x-spin up and the physicist having found the electron to have x-spin down. As our linear rule for the evolution of the wavefunction describes, the world would stay in a superposition of the physicist having measured x-spin up and the physicist having measured x-spin down, and would evolve according to whatever consequences would exist for a measurement of x-spin up or x-spin down respectively. The question however remains, how come then when the physicist reports that his electron has x-spin up does this not entail some sort of wavefunction collapse? What happened to the x-spin down portion of the wavefunction?

Consider this, your physicist friend has an electron in an eigenstate of z-spin. It has z-spin up. He preforms a measurement of x-spin and the two of you enter a linear superposition of finding the electron to have x-spin up and have x-spin down. Each portion of the wavefunction describes a pseudo independent, completely consistent state, which is only accessible to that state. Think of this as the world being in a linear superposition of two states, \(|a\rangle\) and \(|b\rangle\). \(|a\rangle\) describes a complete and consistent state, such as the electron having x-spin down, and the physicist reporting x-spin down, and talking with his friends.
about how the electron definitely has x-spin down and then deciding to go out for coffee. $|b\rangle$ describes similarly a complete and consistent state, such as the electron having x-spin up, and the physicist reporting x-spin up, and going out for donuts with his friends to talk about how the electron definitely has x-spin up. These are two states, correlated with the x-spin of the electron, and by preforming the right measurement of the electron’s x-spin, the physicist is entangling the world’s wavefunction with that of the electron, putting the world into a linear superposition. It is important to see that within each state, the x-spin of the electron is an absolute, and any mental process corresponding to only one of the states will be accurate in its description of the electron in that definite state. The various descriptions within each state must be thought of as local, they are not global properties. Local in the sense of only corresponding to the state from within which they exist, in this case either $|a\rangle$ or $|b\rangle$, and not global in the sense of the overall wavefunction, the linear combination of $|a\rangle$ and $|b\rangle$.

With this understanding, we can address the issue of empirical incoherence that Barrett brings up. At first glance, it might seem as when an observer makes a measurement of x-spin on an electron in a state of z-spin up, and claims to have a completely determinate result with respect to x-spin that he or she is in error, and is holding a false belief. For as we have described, the electron does not have a definite x-spin. It is in a superposition of x-spin up and x-spin down corresponding to its eigenstate of z-spin up. And clearly, if we have a theory which entails that we hold false beliefs about the world, then it would be impossible for us to be justified in believing such a theory based on the evidence provided to us by our beliefs about the world. However, this is only a problem if we take the beliefs we hold to be global. We have no empirical justification for believing our beliefs to be global, and if we take our beliefs to be local to the state within which they exist, then they are completely accurate. Similarly, the no-collapse theory of quantum mechanics predicts the very beliefs that we find ourselves to hold, the theory just adds that the world is not as straightforward
as it may seem, an appearance which is also predicted by the theory.

Barrett points out that if this description really is the case, then after a measurement of x-spin on a particle with z-spin up, the particle is in fact still in a linear superposition of x-spin eigenstates, and thus is still in an eigenstate of z-spin. This would seem to suggest (and Barrett falsely concludes) that the no-collapse theory predicts that a subsequent measure of z-spin should preserve the same result as the particles initial condition. In other words, it might seem as though a measurement made by O of z-spin after measuring x-spin should give with probability one, the same z-spin state that the system started out with. However, this is an oversight of the mathematics of the theory. As before, let our electron start in a state of z-spin up. And as before, let our observer O, perform a measurement of x-spin, and thus enter a linear superposition of finding the electron to have x-spin up and x-spin down. Now we want our observer to perform an observation of z-spin again, but our observer cannot be simply described as our observer. He is now in a linear superposition of having found the particle to have x-spin up and of having x-spin down, thus the new observation of z-spin will actually be a linear superposition of observing z-spin having already found the particle to have x-spin up and observing z-spin having already found the particle to have x-spin down. Thus the proper evolution of the wavefunction for this system would be as follows

$$\psi_1 = |\text{ready}_O| \uparrow_z S = 1/\sqrt{2} |\text{ready}_O| (|\uparrow_x S + |\downarrow_x S|$$

$$\psi_2 = 1/\sqrt{2}(|\text{ready}_O \text{up}_x| \uparrow_x S + |\text{ready}_O \text{down}_x| \downarrow_x S)$$

$$= 1/2(|\text{ready}_O \text{up}_x| (|\uparrow_z S + |\downarrow_z S| + |\text{ready}_O \text{down}_x| (|\uparrow_z S + |\downarrow_z S|)$$

$$\psi_3 = 1/2(|\text{up}_x \text{up}_x| \uparrow_z S + |\text{down}_x \text{up}_x| \downarrow_z S + |\text{up}_x \text{down}_x| \uparrow_z S - |\text{down}_x \text{down}_x| \downarrow_z S)$$

This final wavefunction corresponds to a probability 1/2 of finding the particle with z-spin up and probability 1/2 of finding the particle with z-spin down, just as we have seen in experiment. If however the observer had not made an x-spin
measurement, then the two terms corresponding to a measurement of z-spin down would be the same except the second has a negative coefficient, and thus the amplitudes would cancel out, and the probability of finding the particle with z-spin down would be zero, just as we find empirically.

The next, and possibly most complicated issue with respect to the no-collapse theory is that of statistical results. Classical quantum mechanics predicts probabilistic results which we find to be consistent with the statistical distribution of empirical results. Given N particles all in the same state $\alpha|a\rangle + \beta|b\rangle$ we find experimentally that as N gets large, a measurement to determine if the particle is in state $|a\rangle$ or $|b\rangle$ we get the result $|a\rangle$, $|\alpha|^2$ of the time and we get $|b\rangle$, $|\beta|^2$ of the time. Just as classical quantum mechanics predicts we should. Barrett gives an excellent explanation of why we would expect the same behavior under a no-collapse theory in his book, which we will briefly examine here.

In a previous example, we saw why given an observer measuring x-spin of a z-spin up electron, the observer would be in an eigenstate of claiming he got a single result from his experiment. While he was in a linear superposition of two states, but states shared the property of him believing that he had a single result. If we consider a similar setup, with our observer and this time N particles, all in the same state $\alpha|a\rangle + \beta|b\rangle$, and let the observer measure for the particle being in state $|a\rangle$ or $|b\rangle$ successively for each of the N particles. Now the question we will ask our observer, or the operator we will apply to the final wavefunction, is “Did you get the expected distribution of $|a\rangle$, $|\alpha|^2$ of the time and $|b\rangle$, $|\beta|^2$ of the time?” As N gets large, the mathematics work out that the amplitude of answering the question “No” gets very small and the amplitude of answering the question “Yes” approaches One. Thus as N approaches infinity, the wavefunction approaches a state where with probability One, the observer will see the expected quantum distribution.

The last issue that Barrett brings up against the no-collapse theory is that given the theory, it is completely unrealistic to presume that any part of the world is ever actually in such a simple determinate state. For example, when
our physicist friend measures x-spin of an electron with z-spin up, he puts the entire world into a linear superposition of his finding the electron to have x-spin up and of his finding the electron to have x-spin down. The world will be in this superposition for the rest of time, and various other experiments will continue to complicate the superposition that describes the world. Furthermore, it is not only physics experiments that cause the complication of our superposition, but any interaction that depends on the property of something not in an eigenstate of that property. As such, our world right now would be a linear superposition of an infinitude of different states. Some of which likely describe a world drastically different than our own. Imagine a mad scientist with a large explosive device capable of destroying life on earth who rests his decision of whether or not to detonate the device on a quantum coin toss; the outcome of an x-spin measurement of an electron in a z-spin eigenstate. Then the world would be in a linear superposition of earth having no more life, and earth having life as each state independently evolves. But this is not a problem, so long as we do not take ourselves to be able to ever describe the global wavefunction, but rather only a local determinate state, which we can examine to see how it would evolve as a component of the global superposition describing the world.

Some have taken the basics of a no-collapse theory, and tried to make it easier to understand by describing it in terms of a many minds or many worlds theory. This is a fallacy. While it may not be immediately intuitive to think of ourselves as being in a linear superposition of different states, and it may be difficult to grasp what this really means metaphysically, thinking about the theory in terms of one of these methods creates more questions than it answers.

Let us examine a form of no-collapse theory where the world splits into self consistent worlds for each state of the linear superposition. This raises problems of what basis do we use to determine world splitting, what event triggers a world split, as well has making it impossible for any interaction to exist between worlds, which would not be quite the case. The basics of a world splitting theory involve a system which is expressed as a linear combination of different
states corresponding to a combination of independent worlds. Thus when our observer measures the x-spin of a z-spin up electron, the result is two different worlds, one where the observer measured x-spin up, and one where the observer measured x-spin down. But it is never clear when the world splits. Before the measurement, the system was already in a linear combination of x-spin states if we look at the wavefunction under the x-spin basis, but it was also in a single determinate z-spin up state, if we look at the wavefunction under the z-spin basis. The proponent of a many worlds theory needs to provide an explanation of why this electron’s existence does not constitute two different worlds. The question of world splitting is just as bad as the original quantum measurement problem raised by classical quantum mechanics. The other problem with such a description is that it does not allow for one of the strangest behaviors that classical quantum mechanics explains, interference. If a wavefunction evolves in such a way that there is a $+\alpha$ amplitude for a particular term, and the wavefunction also carries a $-\alpha$ amplitude for another instance of the same term, then that term will cancel out, and the state it corresponded to will never be observed. In a world splitting theory, the different parallel worlds are taken to be completely independent, so such interference phenomena could not exist.

The various many-minds theories are even worse. They exist in an attempt to accept the world as a linear superposition of different states, and still call it only one world, except refuse to describe our mental states as a linear superposition and describe them as multiple simultaneous and independent mental states. The only advantage being we would have the luxury of justifying our apparent determinate beliefs as corresponding to a single one of many minds inhabiting our person. Any proper many-minds theory would also have to give us a story as to why our minds are so special, and do not behave the same way that all other physical objects behave with respect to the laws of quantum mechanics. Such a story is at best difficult to justify. The various many-minds theories exist only to avoid the concept of our mental states being in a state of linear superposition with respect to our beliefs.
Our no-collapse theory, as explained, provides us with a complete theory of everything that happens under quantum mechanics. We are no longer left with unanswerable question about when waveform collapses occurs, and we no longer have questions as to how a waveform will collapse. It becomes a meaningless to ask “Which result will I get?” as the answer is that you will be put into a linear superposition of both results. This is the right way to approach quantum mechanics. It may remain to be understood what type of interaction will cause quantum entanglement, but that is not a problem that the theory claims is unanswerable. It will be a matter of time, and scientific progress, just as scientific realism expects.

References
