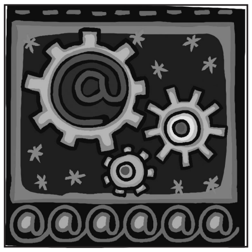
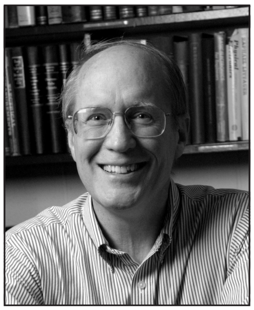


The Importance of Causality in Quantum Mechanics

William R. Wharton



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Christian theology preferentially favors some philosophical interpretations of quantum mechanics. By using a case study of stationary states of atoms, this paper examines the various interpretations. The preferred interpretation is that all localized events in space-time are parts of chains of contiguous events traversing space-time at a rate limited by the speed of light. This is the process of becoming, i.e., the creation of reality. It is usually not deterministic, leaving room for many first causes that are the initiation of new causal chains.

I have developed the "causality model" of quantum mechanics (QM) … [and] will argue that stationary states occupy space-time regions which lack events.

Causality is important to our Christian world view because of its implicit role in the biblical account of both God and human activity in nature and the consequences of such activities. Each of God's actions is never an isolated event, but is part of a causal chain of events, often with long-lasting consequences toward teleological outcomes. The Bible emphasizes that humans are agents, whose actions also create causal chains with outcomes, for which they are responsible. The Bible, through narrative, strongly suggests that no event can be placed in isolation, but rather everything that happens is part of one or more causal chains, affecting and/or being affected by other events.[1] In science, special relativity requires that successive events in a causal chain be contiguous (locality) in space-time. The ideas of causal chains from both theology and science can be fruitfully integrated into a more complete world view. This world view will require that any change in reality be part of such causal chains.

In this paper, an event is defined as a reality localized in space-time. The argument is presented that when the influence of other events is lacking there is no localized reality. Regions of space-time may lack events. Every event is part of one or more causal chains, affecting and/or being affected by contiguous events. Using this principle, I have developed the "causality model" of quantum mechanics (QM). This paper will concentrate on one of the most common and widely studied systems, stationary states. I will argue that stationary states occupy space-time regions which lack events. This opens up the possibility that a first cause in the future can create a causal chain which traverses the present space-time, providing events. Such an occurrence is known as backward causation.

The main purpose of this paper is not to argue for backward causation, but to affirm our Christian world view with the causality model of QM, of which backward causation is only a part. Scientists, for the most part, also hold sacred that processes in nature consist of causal chains. Unfortunately, the small collection of scientists actively working to understand QM are all too easily giving up on the notions of causality. This abandonment of what was once sacred to science manifests itself in many different ways, of which four are identified below.

Firstly, QM is a stochastic theory in which the theory is primarily limited to giving probabilities of outcomes of processes in the laboratory, instead of deterministic predictions. Furthermore, this indeterminism appears to be an ontological property of nature rather than resulting solely from an epistemic limitation due to incomplete human knowledge. A sufficiently large number of identically prepared, indistinguishable quantum systems give all possible outcomes under identical measurements. Some scientists interpret this to mean everything unseen that is allowed to happen has a reality consistent

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with what is known and measured. Specifically, reality includes everything that is allowed by the laws of nature. This reality is constrained but not determined by earlier events and similarly does not uniquely determine later events. Not only is its existence unseen, but there is no specific cause-effect delineating it. These ideas of reality without causation influence how we interpret the reality that we can examine and measure. This will become clearer later when we examine the properties of stationary states.

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Secondly, special relativity, which is a well-founded, beautiful theory of nature, suggests that time does not flow. Two so-called space-like events are spatially separated and close enough in time that no signal, limited by the speed of light, has time to go from one to the other. Such events appear in different time sequences to different observers, meaning that there is no frame-independent flow of time. There is no universal reference of past, present, and future. This, coupled with the a-priori concept of "relativity" (no preferred reference frame) has led to the notion of a "block universe," in which the future already exists. From this perspective, the whole book on the history of the universe is written and final. We may be on page 100 and do not know what is in the future on page 150. Nevertheless the contents of page 150 already exist. The future is just as real as the past. This notion of a block universe undermines the concept of causal chains and would certainly contradict the common notion of humans as responsible agents. Sure, in this world view, humans are dynamic characters in the story of life, but the story is already written and cannot be changed by any choices we make in the present. This fatalistic view of the future is demotivating for humans to function as agents exercising controlling or creative opportunity.

Thirdly, the dominant paradigm under which physicists view QM is the Copenhagen interpretation. This interpretation may be primarily a convenient, reliable, and practical way to conceptualize QM rather than a strongly held belief, but nevertheless it influences how physicists view reality. A central component of the Copenhagen interpretation is that a property of a quantum system is not a reality until after it is observed. For example, the electron does not have a position or momentum until the position or momentum, respectively, is measured. Since these two measurements are incompatible, the electron cannot simultaneously have a well-defined position and momentum. In QM, incompatible refers to two types of measurements that uncontrollably change each other's outcomes when done in succession. These ideas, by themselves, do not undermine causal chains. However, in conjunction with this is the inclination of scientists to believe in an objective reality, independent of the observer. The desire is to have a reality separate from the observer. In this philosophy of objective reality, the experimenter decides which measurement is measured, but does not cause the reality. Or at the very least, free choice is too subjective to be considered part of the reality studied by physics. According to the causality model, this denies recognition of an important causal chain that is crucial to a self-consistent understanding of QM.

Fourthly, QM is a nonlocal theory, in which two space-like measurements affect the probability distributions of each other's outcomes. According to special relativity, these events cannot be causally related. Two widely separated particles, once in contact with each other, can be entangled, meaning a measurement on one appears to alter the properties of the other. In attempts to understand this, many people limit QM to empirical adequacy, giving up on a deeper understanding with a causal model. Those using nonlocal models to interpret QM must distort the whole notion of causality. For example, Bohm's pilot wave model treats the QM wavefunction as a holistic field that nonlocally guides particles along their trajectories. Michael Dickson thinks this idea can be understood in a universe with an absolute and deterministic beginning.[2] The guidance condition does not "cause" entangled behavior, he argues, but merely represents behavior that flows deterministically from the initial conditions of the universe. The causality model, requiring causal chains of contiguous events, rejects Bohm's pilot wave model on physical grounds.

Newton's first law states that an object free of external forces will move at a constant velocity through space. Its straight-line path through space-time represents a causal chain composed of a potentially infinite number of contiguous events in Newtonian mechanics. The event initially determining its velocity would be the first cause in the chain. On the other hand, in QM we are usually unable to see all of the events in a causal chain. We can observe only separated events. It is only a matter of interpretation whether or not a causal chain connects the separated events, even if it can be shown the events are correlated with each other. Stephen Hawking writes in *The Universe in a Nutshell*:

> We are used to the idea that events are caused by earlier events that in turn are caused by still earlier events. There is a chain of causality stretching back

Words that we view as temporal words, should rather be understood as causal words. Becoming *is the process of a causal chain. The words,* before, until, *and* after, *often are pointing from or to some event in a causal chain …*

> into the past. But suppose this chain has a beginning. Suppose there was a first event. What caused it? This was not a question that many scientists wanted to address. They tried to avoid it … In my opinion, this is not a position any true scientist should take. If the laws of science are suspended at the beginning of the universe, might not they fail at other times also? A law is not a law if it only holds sometimes. We must try to understand the beginning of the universe on the basis of science. It may be a task beyond our powers, but we should at least make the attempt.[3]

On the next page, he talks about casinos and rolling dice that he compares to a universe experiencing multiple histories, each with its own probability. He follows this with a pictorial of Feynman's path integral, see figure 1, in which a particle takes every possible path between the two points that are the detected events. Hawking is trying to replace causal chains between two observed events with a web of all possible reality. However, this argument is problematic. While the mathematical technique of the Feynman path integral is very successful in predicting the probability of some future unrealized event, using it to make inferences about the inaccessible past of a realized event is unjustified. There is absolutely no experimental evidence that a particle takes more than a single path between two points. Any interaction identifying a path would nullify all paths inconsistent with the observation, meaning that separate distinct paths can never be verified.

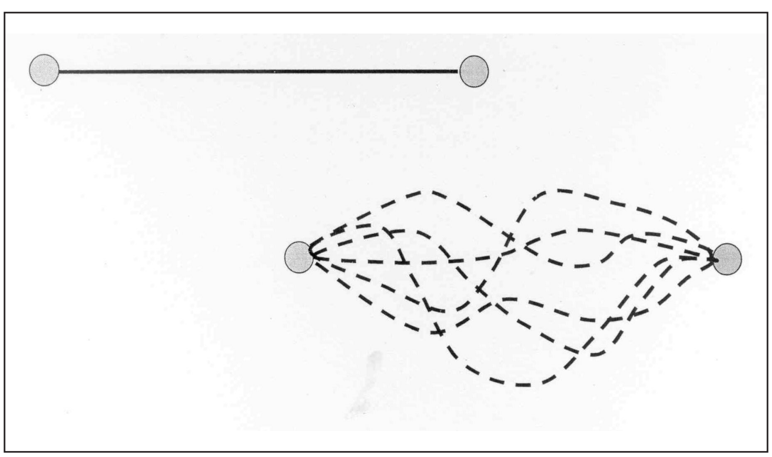

Figure 1. The path of a classical particle (solid line) represents a causal chain. A few of Feynman's paths of multiple histories (dashed lines) replace a causal chain. The endpoints are boundaries determined by external observations.

Special relativity is almost certainly correct that time does not have any flow, and instead should be thought of as a coordinate, similar to the three spatial coordinates.[4] The flow that we associate with the concepts of past, present, and future is a causal flow that does not depend on the reference frame, i.e., each causal chain flows in the same direction in all reference frames. However, different observers have different definitions of the present, because they are experiencing different causal chains. An observer, or agent, has present knowledge of her past that is the collection of all events earlier in her causal chains. The agent is acting in his present to have a causal effect on his future that is further down the causal chain(s). Since different observers are experiencing different causal chains, there is no such thing as a unique global past, present, and future. Words that we view as temporal words, should rather be understood as causal words. *Becoming* is the process of a causal chain. The words, *before*, *until*, and *after*, often are pointing from or to some event in a causal chain, and are not strictly temporal words.

The block universe model, which denies the ontological process of becoming, is not very pertinent to the study of stationary states, which is the main emphasis of this paper. However, the block universe approach is a central part of attempts to understand other paradoxes of QM, such as Hardy's paradox, and is criticized in my more detailed paper on the causality model.[5]

Nonlocality in QM can be understood, consistent with special relativity, as causal chains moving both forward and backward in time. Backward causal chains are inaccessible to the outside world, thereby preventing superluminal (faster than speed of light) signals. One may find a fuller treatment of locality in my more detailed paper.[6] Both the block universe and the treatment of nonlocality seriously confront our Christian world view, but both are much more technical, as they pertain to QM, than are the issues discussed in this paper. A block universe goes beyond the Christian view of predestination and requires that the future already is a reality.

Stationary States

The ground state of hydrogen consists of a proton and an electron with zero orbital angular momentum. This means that the proton and electron can only move in a radial direction toward or away from each other. This state is known to be stationary, meaning that all observable properties are static or unchanging with time. QM, the most successful theory in physics, of course, also predicts that this state is stationary. Figure 2 shows the energy, potential well, and radial distribution of the electron in the ground state of hydrogen. The hydrogen atom's ground state has spherical symmetry. The Fourier transform of the ground state spatial wave function of the electron is:

$$f(\mathbf{k}) = 2(2a_0^3)^{1/2} \frac{1}{\pi(1+a_0^2k^2)^2} \quad (1)$$

where **k** is the wave vector and a_0 is the Bohr radius. The probability distribution for measuring the component of **k** along an arbitrary z-axis is

$$P(k_z) = \iint f^*(\mathbf{k})\, f(\mathbf{k})\, dk_x dk_y =$$

$$\frac{8a_0^3}{\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{dk_x dk_y}{[1+a_0^2(k_x^2+k_y^2+k_z^2)]^4} = \frac{8a_0}{3\pi}\frac{1}{(1+a_0^2k_z^2)^3}. \quad (2)$$

It is common to identify $\hbar k$ as the momentum of an electron in the hydrogen ground state and $\hbar k_z$ as its component along the z-axis. This identity is the de Broglie wavelength, $\lambda = h/p$, and $k = 2\pi/\lambda$.

To verify a similar distribution for helium, calculated the same way as equation (2), in 1937, x-rays were scattered off electrons in a large number of helium atoms in their ground state.[7] If we define **p** as the momentum of the electron of mass m immediately prior to the x-ray scattering, standard kinematics gives the equation:

$$2\mathbf{p}\cdot\Delta\mathbf{P} = \Delta P^2 + 2m\Delta E \quad \text{with } \Delta E << mc^2 \quad (3)$$

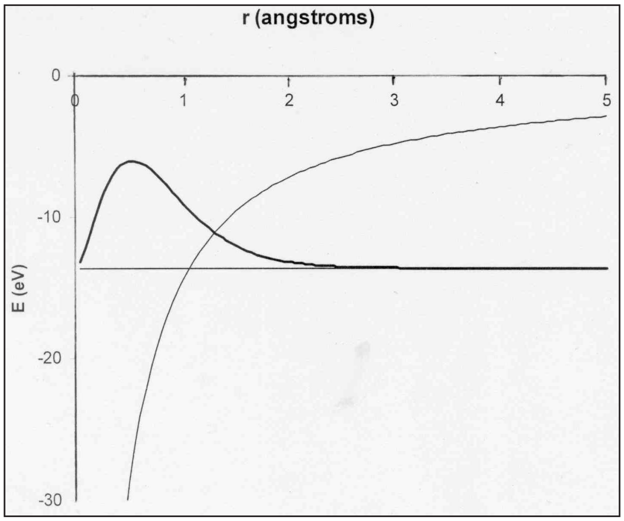

Figure 2. The radial probability distribution of the electron in the hydrogen ground state, plotted above its binding energy of –13.6 eV. The coulomb potential energy curve is also shown.

where $\Delta\mathbf{P}$ and ΔE are the changes in the x-ray's momentum and energy, respectively. Letting $\Delta\mathbf{P}$ define the direction of the arbitrary z-axis, the experimental distribution of p_z values obtained using the x-ray data and experimental equation (3), gave an identical result as the theoretical prediction of the helium atom within experimental errors, as shown in figure 3.

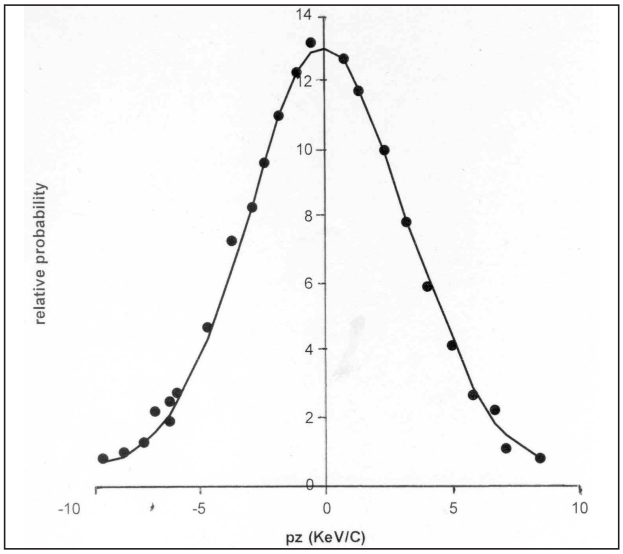

Figure 3. The points are relative probabilities for measuring various values of p_z, obtained from the experimental intensities of Compton scattering from helium,[8] using equation (3). The continuous line is the momentum probability distribution calculated from the helium-atom electronic wave function in the same manner as equation (2).

Let us discuss the meaning of the measured p_z. It is not the momentum of the electron immediately after the x-ray scattering, when its value is $p_z - \Delta\mathbf{P}$. Before the x-ray scattering, the helium atom is in a stationary state. We know this both from theory and experiment. The definition of nonzero momentum of the electron necessitates the movement of mass (energy) from one spatial location to another. This is completely absent in a stationary state. Of course, several simultaneous movements can cancel each other out, making the atom appear stationary. Classically, not even two electrons moving in opposite directions can cancel out movement of mass, because they cannot always be in the same position. They would have to be in all allowed positions at all times, moving in opposite directions. A single electron, as in hydrogen, would have to have both multiple positions and momenta at all times to be stationary. There are three major classes of interpretation of this x-ray experiment: the Copenhagen interpretation, the Everett multi-universes approach, and the de Broglie–Bohm theory.

The **Copenhagen interpretation** says that the electron does not have a precisely defined momentum before the measurement. The measurement process brings to reality its momentum. In this interpretation, the reality can only exist for an instant because after the x-ray scattering, the

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electron has a different momentum. Many people interpreting QM today object to the concept of measurement creating reality. Thus they reject the Copenhagen interpretation.

There is another problem with this interpretation. Having a momentum exist only for a point-like instant in time is nonsensical. Momentum, by definition, involves the spatial relocation of mass/energy over a finite time. If momentum only exists for a point-like instant at measurement, there is no movement of mass/energy and therefore no momentum.

The **Everett multi-universes** approach also allows measurement to modify reality.[9] However, it is not so much the creation of reality but rather the splitting off of reality into an infinite number of universes. If the electron simultaneously has all possible momenta, according to the theoretical distribution prior to measurement, then this would be consistent with a stationary state. Upon measurement, a specific value of p_z becomes an exclusive reality in our universe and all other values of p_z become realities in other universes. This interpretation assumes that all of the allowed values of momentum already exist so that measurements merely redistribute them among the various universes. The main motivation and appeal of the Everett interpretation is that the reduction of the distribution from many values to a single value upon measurement is an emergent property of the model.

The **de Broglie–Bohm theory** fails badly in describing these stationary states.[10] In this model, the electron is at rest and at a single spatial location. This would imply that the hydrogen atom has a zero p_z and a nonzero electron dipole moment, both in contradiction to experiment. In this model, in contrast to the other models, the wave function is intended to describe the average properties of an ensemble of many such atoms rather than a single atom. The main attraction of this model is to make QM deterministic.

There are many other interpretations of QM, but none to my knowledge give a viable interpretation of this x-ray experiment. Most interpretations do not explain all of QM, but only selected experiments, and many interpretations do not address the meaning of stationary states. Amazingly, arguments (see next section) based simply on causal chains give a very natural, unforced explanation of this x-ray experiment without any other excess baggage. The excess baggage in the Copenhagen interpretation is the tacked-on, unexplained reduction of the wave function. The baggage of the Everett interpretation is, of course, the multiple, extremely large number of universes.

The causality model has some strange consequences that are properties of QM. Everything follows naturally from the principle that all events must be part of causal chains and that all causal chains must have a first cause. Of course, some may consider causal chains as baggage just as we consider multiple universes as baggage. Hawking considers first causes to be baggage. To understand the importance of causal chains, it is important to contrast stationary states with nonstationary states.

Nonstationary States

Both experiment and QM theory indicate that the properties of any stationary state do not depend on how it was made or on its past history. This is very clear when one considers that all hydrogen ground states are identical, i.e., indistinguishable, regardless of their circumstances. All of its properties are completely determined by the laws of nature and conserved properties, such as energy, angular momentum, charge, lepton number, etc. Conservation laws are different from causal chains. Conserved quantities are permanent and never change, but are simply redistributed. Only by adding or removing a conserved quantity will the stationary state change. Causal chains deal with the process of change and becoming and may or may not involve the redistribution of conserved quantities.

In contrast to stationary states, nonstationary states depend on their past history. Some event or perturbation must trigger the formation of a nonstationary state. QM theory makes this perfectly clear. A nonstationary state is not an eigenstate of the system's Hamiltonian, meaning that something outside the system must have affected it. The best-studied nonstationary states are in Rydberg atoms, which are atoms with an electron weakly bound in a very large orbit. Sometimes this orbit is 1,000 times larger than other bound orbits. The motion of an electron in its nonstationary Rydberg orbit can be observed in various ways. For example, a short optical pulse excites an electron into a superposition of Rydberg states, forming a small radial wave packet.[11] It is the superposition of these states which make it nonstationary. The electron (i.e., wave packet) moves classically in and out from the ionic core in a highly elongated elliptical orbit. Only if the electron is near the ionic core will photoionization by visible light occur. A collection of such Rydberg atoms are formed identically by the same optical pulse and their behavior is monitored by photoionization. Intensity peaks in this ionization are observed at times after the optical pulse that are integral multiples of the classical round-trip time of the electron moving in its orbit. This confirms that the electron's movement approximates this classical orbit.

Application of the Causality Model to Stationary States

Whereas there is clear experimental evidence of movement and change in a nonstationary state, there is no evidence whatsoever of change in a stationary state, even after extensive study. A typical physicist will find no need to explain the reason for the difference, because the difference is already fully explained in the QM equations. The equations are in complete agreement with experiment for both stationary and nonstationary states. The physicist's mentality is that the ultimate understanding is to write down, from first principles, the mathematical equations that describe the processes in nature. No deeper understanding need be attained.

In contrast, this paper is an attempt at a deeper metaphysical understanding, based on the foundational assumption that causes effect change. If a stationary state is totally immune to anything happening around it, then it is possible that it is not changing or becoming. If it is not becoming, then it may be lacking full reality. An event is defined as reality at a localized space-time region, and such events cannot exist in isolation from what is around them. Every event must be part of a causal chain of contiguous events, either the first cause of the chain or an event being caused by, and then causing, other events.

A particle, such as an electron, moving along a path through space-time is experiencing a causal chain. If a causal chain is absent, then the particle does not have a position or momentum at any specific time. However, a particle may acquire a causal chain through interaction with some other object, such as an x-ray. Werner Heisenberg, the co-founder of QM, described this very well in chapter 2 of his book, *Physics and Philosophy*:

> The concept of the probability wave was something entirely new in theoretical physics since Newton. Probability in mathematics or in statistical mechanics means a statement about our degree of knowledge of the actual situation …
>
> The probability wave of Bohr, Kramers, Slater, however, meant more than that; it meant a tendency for something. It was a quantitative version of the old concept of "potentia" in Aristotelian philosophy. It introduced something standing in the middle between the idea of an event and the actual event, a strange kind of physical reality just in the middle between possibility and reality.[12]

This is a valid description of the causality model. The electron in a stationary state does not have a position or momentum. Its changeable attributes are not yet a localized reality. Just as the electron exists but does not have a value for its momentum or position because there is no causal chain, so also energy exists but is not realized as either potential or kinetic energy. In this sense, there is no final reality, but only a propensity for such reality. This raises the philosophical question, how can something exist without having a value, or how can energy exist without having a form? Using ideas borrowed from Aristotle, we call some of the substance of the universe eternal, or "essential."[13] However, some of the elements present in things are "accidental," resulting from cause and effect that represent change.

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Using these ideas, I say that the hydrogen atom is not normally subjected to any causal chains and therefore is not undergoing change. However, as long as the atom is left alone, all of its properties, determined by conservation laws, are essential. None of these properties can be changed without the addition or removal of a conserved quantity. The electron's momentum or position is not a conserved quantity because of its interaction with the proton. A reasonable belief, based on the notion of causality, is that the electron's future momentum currently lacks reality. Time symmetry suggests a similar property for the past. The laws of physics, as they pertain to the hydrogen atom, are completely time-symmetric; momentum, and anything else subjected to unrealized causal chains, lacks reality in the past as well as the future. Time does not flow, and causal chains, if they are lacking, must be absent in both time directions for stationary states. There should be no distinction between past and future.

This approach is the complete opposite of the Everett interpretation, in which the electron has numerous positions and momenta simultaneously, rather than none at all. For some reason, most people prefer to assign multiple realities rather than no reality, and I think this is fundamentally flawed. At any instant, if electrons exist in multiple locations with multiple values of momentum, then there has to be more than one electron. This would violate lepton number conservation. Everett is able to retain lepton number conservation by claiming there is a separate universe for each electron. However, the probability distribution in figure 3 makes no sense in the Everett interpretation, which states that each possible outcome of the p_z measurement is realized in some post-measurement universe. If each value of p_z is realized, they should have equal weights that would favor a fairly flat distribution unlike the curve in figure 3. The Everett model does not have a procedure to interpret the measured distributions.

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To some extent, however, it is necessary to adopt this multi-valued approach. Electric charge is a conserved quantity, and it is constantly interacting with its surrounding environment. Such interaction requires the charge of the electron to spatially exist in the hydrogen atom, and, ignoring distortions caused by external interactions, it exists as a symmetric cloud with the probability distribution shown in figure 2. Here the probability must be more than a "potentia." In fact, it must be a reality. The probability distribution in figure 2 gives the actual distribution of the one unit of electric charge spread around the proton. The Everett model, with equal weights for every location, cannot explain this distribution.

The cloud of charge does not define the location of the electron. The electron is neither localized, nor in multiple places in space-time. Let us briefly examine the measurement of the electron's spatial position. The probability of finding the electron a distance, r, from the proton in hydrogen is shown in figure 2. Although there is zero uncertainty in the energy of the hydrogen ground state, energy conservation can be violated briefly. This allows for a nonzero exponential fall-off of the probability at large distances from the proton, meaning that a small probability exists for finding the electron in the "classically forbidden region," e.g., for values greater than about 1 Angstrom in figure 2. Here the coulomb potential energy is greater than the total energy. However, the electron, in an isolated hydrogen atom, could never exist as an event at these large distances, although some of its charge can be there. The exponential fall-off in the probability distribution at large distances could conceivably be examined using an electron tunneling microscope probe. The probe provides enough negative potential energy to allow the realization of the propensity for the electron to exist at such a great distance. This is commonly referred to as tunneling, where the electron is pictured initially inside the coulomb barrier, tunnels through, and appears on the other side when detected.

In our interpretation, there is no causal chain going backward in time from this detection event. There is no motion through the barrier, which is impossible because of the lack of kinetic energy under the barrier. The electron simply has a propensity to exist where it is detected, and this has been brought to reality by the probe. This measurement will be the first cause in a new causal chain. The probe will see the probability of finding the electron increase exponentially as it is brought closer to the proton, thereby reproducing the probability curve in figure 2. This process involves two transfers. One is the transfer of energy from the probe to the hydrogen atom causing it to be ionized. The second is the transfer of negative charge from the atom to the probe. Causal chains inside the atom cannot describe these transfers, since nothing is moving continuously through space. The temporal redistribution of electric charge could conceivably be studied through the electromagnetic interaction of the atom with its surroundings. There are QM limits to the temporal resolution. I suspect that the redistribution of charge occurs in an instant.

Comparison of the Causality Model with the Copenhagen Interpretation

The causality model is closely aligned with Bohr's Copenhagen interpretation. However, it also accommodates some of the criticism which Einstein and others have concerning Bohr's interpretation. The primary difference between the causality model[14] and Bohr's is that the former allows causal chains going backward in time, i.e., backward causation. Backward causation allows the measured value of p_z to exist for a finite time in the x-ray experiment. Using the terminology of Willem M. de Muynck,[15] Bohr's interpretation is based on the following interconnected ideas: contextualistic realism, strong correspondence principle, complementarity, Copenhagen indeterminism, and probabilistic description of individual objects. The following is a brief description of these ideas contrasted with ideas favored by Einstein and compared to the causality model.

Contextualistic realism claims that reality of a property of an object comes solely from its interaction with a measuring instrument. In contrast, Einstein felt that there should be a theory that can describe objective reality independent of measurement. The causality model explains contextualistic reality as the effect of causal chains going both forward and backward in time and initiated by the measurement that is the first cause in each chain. Realism must be contextualized in terms of both the initial preparation of the quantum state and the later measurement, since both actions initiate causal chains into the quantum system. Einstein probably would not have any problem with contextualizing realism in terms of the preparation, and in our time-symmetric model, measurement is treated the same as preparation. Abraham Pais related a conversation with Einstein, questioning contextualistic realism:

> We often discussed his notions on objective reality. I recall that during one walk Einstein suddenly stopped, turned to me and asked whether I really believed that the moon exists only when I look at it.[16]

The lack of reality in space-time (i.e., events) only occurs in the microworld, in which the object is waiting for a future event that can bring the reality through backward causation. Einstein's word "exists" is ambiguous since it can refer either to space-time properties or to existence generally. I propose that the electron exists in the hydrogen ground state, but it does not have a position or momentum. Its existence, which does not require a causal chain, is separate from its space-time properties. Unlike the electron in the hydrogen atom, the position and momentum of the moon have been determined by past events. These properties have reality even if no one observes them.

The strong correspondence principle claims that quantum phenomena correspond to classical terms and can be unambiguously communicated only by classical terms. This idea is closely aligned to contextualistic reality in that reality can only be described in conjunction with the classical measuring device. However, Bohr's philosophy has some ambiguity here between ontology and epistemology. Whereas Bohr claimed the reality comes from the measurement, the classical description of the measurement is fundamentally flawed since classical concepts are partially inadequate to explain quantum phenomena. He did not hold out much hope for a more adequate explanation. In the causality model including backward causation, classical concepts such as momentum or position of a particle become a reality as a result of measurement and/or preparation. In addition, the classical concept of waves in QM is mostly associated with potentiality, which is a different kind of reality subject to change from a future measurement. Hence, the correspondence principle is valid in that classical concepts of particles and waves are accurate when applicable and interpreted correctly, and is not inherently flawed.

I propose that the electron exists in the hydrogen ground state, but it does not have a position or momentum.

Complementarity claims that incompatible observables cannot simultaneously have precise values because of the incompatibility of the measuring arrangement for each observable. This also includes particle-wave complementarity. For example, the measuring arrangement for observing a unique classical path of a particle is incompatible with that for observing an interference of two or more paths. In the causality model, a particle that has a unique classical position and/or momentum is constrained by the existence of causal chain(s). A particle acting as a wave, with wavelets simultaneously traversing multiple paths, is less constrained by existing causal chains. The wave nature of a particle is a potentiality open to the effects of causes that have not yet acted on the particle. Simultaneous observations of these different phenomena are incompatible because the situations are different. The difference, determined by the experimental apparatus, is based on the existence or non-existence of causal chains.

In conjunction with complementarity is *Copenhagen indeterminism*, which claims that the value of a measured observable cannot be an attribute prior to measurement. In contrast, Einstein treated indeterminism as epistemic. He felt that reality has to be precise. The causality model has Bohr's concepts in a modified form. In the observer's reference frame, the measured observable is not a reality until after the measurement. However, because of backward causation, the past is in a state of becoming; it is not time which flows, but rather the causal chains that include flow backward in time. After the measurement (in a causal sense), the measured attribute becomes a reality for the object at earlier times. Complementarity is also modified. In the situation where the preparation chooses a precise value of one observable and the measurement chooses a precise value of another incompatible observable, *The causality model claims QM is not a universal theory, but only pertains to the microworld, defined as the space-time region where causality can go in both time directions. Humans, taken in totality, are probably in the macroworld where causality effectively only goes forward in time.*

the object acquires precise values of both observables for the time between preparation and measurement.

A description of Stephen Hawking's interpretation of a free particle that has two precisely measured space-time locations is on pages 269–70 (see also figure 1). Whereas Hawking would claim the particle does not have a well-defined momentum in between the two measurements, the causality model claims the particle's path is a unique straight world line connecting the two space-time points. This particle acquires precise properties of two incompatible observables by backward causation, and the time between the two measurements lies in the inaccessible past. The world line defines precisely both the magnitude and direction of the particle's momentum. Here, momentum and position are incompatible observables, but both have precise values for all times in between the two measurements.

The Copenhagen interpretation interprets quantum mechanics as giving a *probabilistic description of individual objects* rather than a statistical description of an ensemble of identically prepared objects. Specifically the probability distribution is an ontological reality for individual microscopic objects and not simply a lack of knowledge. Einstein would favor an epistemic statistical description. For him, the particular microscopic object has precise properties, even if they are not classical properties, and must be thought of quantum mechanically as one in a possible ensemble of identically prepared objects. The causality model adopts the Copenhagen interpretation on this point. The probabilistic description is ontological for a single particle until a measurement is made on it. The measurement modifies the probability via backward causation by giving the particle a more precise value at times before the measurement. The probabilistic reality is a different kind of reality than the reality of a measurement. The probabilistic reality is not composed of events in space-time. Rather its existence comes from the initial boundary conditions and the conservation laws. The conservation laws require certain properties of nature to exist and to be real even before events associated with these properties come into existence through causal chains. The conservation laws constrain the causal chains, but do not create the causal chains.

The Copenhagen interpretation has some undesirable features. For example, it postulates that the observer obeys different physical laws than the non-observer, which has been criticized as a form of vitalism, that life is different from matter. The causality model retains differences between the observer and the quantum system, but defines more clearly what these differences are in a way that is not vitalistic. In particular, the causality model claims QM is not a universal theory, but only pertains to the microworld, defined as the space-time region where causality can go in both time directions. Humans, taken in totality, are probably in the macroworld where causality effectively only goes forward in time. The closest idea to vitalism is that humans, as agents, are free to engineer selected causal chains on objects of their choosing. The Copenhagen interpretation claims that the act of observing a system changes it in a random fashion, instantaneously over an extended region (nonlocal). Instantaneous is a problematic word according to special relativity, since there is no unique definition of simultaneity for spatially separated events. The causality model solves this nonlocality problem using backward causation. Specifically the changes that take place in a measurement satisfy the locality condition of special relativity, in which causal chains cannot propagate faster than the speed of light.[17]

Conclusions and Reflections from a Christian World View

The focus of the paper has been a scientific/philosophical analysis of stationary states, showing that a causality model is the most logical interpretation of the conceptual difficulties presented in QM analysis of these states. It is important to emphasize that this approach is grounded in our Christian world view. The block universe, that claims the future already exists, is an objectionable philosophy to our Christian world view. It is the rejection of a block universe, which forms the basis of my underlying presupposition of causality. A block universe denies the process of becoming and the responsibility of human beings. It is particularly troublesome to see the block universe model used to solve paradoxes in QM, and I critique this in detail.[18] The block universe idea comes from special relativity, which essentially demands that time does not flow. Since I have gained a deep understanding and appreciation of special relativity, I reject any thoughts of altering it. Rather I feel compelled to find a way to make it compatible with my Christian world view. The only way I see to do this is to interpret our perception of (and the biblical perception of) time flow as a causal flow. For this to work, I have to say that the reality of events must be part of causal chains that are series of events through time (and usually space) through which cause-effect propagates. This is the process of becoming (creation of reality) and gives us a perception of time flow.

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Both Everett's many worlds interpretation and Hawking's use of Feynman's multiple histories separate reality from cause-effect. In their models, reality does not need a cause, nor does it need to affect other reality in any uniquely identifiable way. Not only do their models fail to explain the perceived flow of time, but also they fail to conceptually explain the absence of time flow in stationary states. I naturally chose stationary states, without time flow, as the case study of this paper because the perception of time flow, which is in fact causal flow, is so central to my Christian world view. QM is filled with many characteristics leading to various informative case studies. I chose stationary states as the one which seemed most revealing.

One aspect which complicates the causality model is the recognition that microscopic causal chains are very fragile and easily terminated. For example, in figure 1, the two endpoints are measurements. If these two measurements are far enough apart in space-time, and activity from other sources is occurring between them, there likely is not any causal chain connecting the measurements. In fact, there would be considerable doubt that the two measurements are observing the same particle. It is impossible to keep track of a single particle's identity when other identical particles are nearby. This is why wave functions must include all terms in which pairs of identical particles are interchanged.

The termination of causal chains and the disappearance of space-time reality are very compatible with a Christian world view. It leaves open the opportunity for both humans and God to create new reality and it avoids the clockwork universe of Newtonian mechanics. I separate the quantum world from the macroscopic world where causal chains are much less fragile and progress reliably forward in time. This is consistent with the Bible, which teaches that long-lasting causal chains exist. This is what gives us our strong sense of time flow. So-called quantum measurements occur at the boundary of the microworld and macroworld, creating first causes and new causal chains in both worlds. This is a source of creativity. The Everett model wrongly explains creativity and novelty as the creation of new worlds.

My model also includes backward causation in which cause-effect progresses backward in time, but limits it to the microworld. This strange notion does not come from my Christian world view. My motivation to include backward causation originally came from the nonlocality of QM, and my insistence that the interpretation of this nonlocality be completely consistent with special relativity. I do not think any other interpretation does this. A confirming result of backward causation is that it fits in so beautifully and naturally with the other parts of the causality model that do come from my Christian world view. Neither my Christian world view nor my understanding of science reveals precisely the boundary between the microworld where QM dominates and the macroworld described by classical physics. In summary, the Christian world view provides some broad constraints on the interpretation of science, but does not dictate specifics of the causality model. ✵

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Notes

[1]There are 1,750 occurrences of "cause" in the NIV version of the Bible. Often it is the word "because." The vast majority of these refer to either God's actions or human actions.

[2]William Michael Dickson, *Quantum Chance and Non-Locality: Probability and Non-Locality in the Interpretation of Quantum Mechanics* (Cambridge: Cambridge University, 1998).

[3]Stephen Hawking, *The Universe in a Nutshell* (New York: Bantam Books, 2001), 79–83.

[4]Special relativity has beauty, elegance, and simplicity in unifying various properties of nature, including space and time. It has extensive experimental verification.

[5]William Wharton, "Understanding Time and Causality is the Key to Understanding Quantum Mechanics," http://xxx.lanl.gov/abs/quant-ph/0310131.

[6]Ibid.

[7]J. W. M. Dumond and H. A. Kirkpatrick, "A Direct Spectrum of the Structure and Shift of the Compton Line with Helium Gas as the Scatterer," *Physical Review* 52 (1937): 419–36.

[8]Ibid.

[9]H. Everett, "Relative State Formulation of Quantum Mechanics," *Review of Modern Physics* 29 (1957): 454–62. Also http://plato.stanford.edu/entries/qm-manyworlds/

[10]K.Berndl, et al., "A Survey on Bohmian Mechanics," http://arxiv.org/abs/quant-ph/9504010.

[11]T. F. Gallagher, "Quantum-Beat, Level Crossing, and Anticrossing Spectroscopy," in *Atomic, Molecular, and Optical Physics: Atoms and Molecules* 29B, ed. F. B. Dunning (London: Academic Press, 1996), 331–2. For a more recent work, see S. N. Pisharody and R. R. Jones, "Probing Two-Electron Dynamics of an Atom," *Science* 303 (Feb. 6, 2004): 813–5.

[12]Werner Heisenberg, *Physics and Philosophy: The Revolution in Modern Science* (New York: Harper, 1958), chap. 2.

[13]Aristotle, *Physics,* Book II.

[14]Wharton, "Understanding Time and Causality."

[15]Willem M. de Muynck, "Towards a Neo-Copenhagen Interpretation of Quantum Mechanics," *Foundations of Quantum Mechanics, an Empiricist Approach,* Fundamental Theories of Physics 127 (Kluwer Academic Publishers, 2002). See also the Los Alamos preprint archives, http://arXiv.org/abs/quant-ph/0307235 (July 31, 2003).

[16]Abraham Pais, *Subtle Is the Lord: The Science and the Life of Albert Einstein* (New York: Oxford University Press, 1982).

[17]Wharton, "Understanding Time and Causality."

[18]Ibid.

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