

Causation with Quantum Mechanics

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An interpretative understanding of quantum mechanics, making sense of many of its strange features, can be achieved using the paradigm of causal chains. This is the hypothesis that all localized reality in space-time is part of causal chains, and the process of becoming in nature is via causal chains of contiguous events. The fact that quantum systems may lack localized reality is intimately connected with their lack of causal chains. This paper concentrates on the science, but there are two metaphysical concepts coming into play. New causal chains come into existence with measurement, which implies first causes, and there is the inaccessible past, created by causal chains going backward in time.

I. Introduction

Almost every attempt to interpret quantum mechanics (QM) has discarded the notion of causal chains. The purpose of this paper is to argue that the rejection of this fundamental property of nature is a primary reason all these attempts to understand QM have failed. A causal chain is a series of events through which cause-effect propagates. An event is a localized reality in space-time. Prior to the development of QM causal chains was a centerpiece of all natural science world views. Special relativity (SR) reinforced causal chains with the restriction that the events in a causal chain must be contiguous in space-time and that the progression of cause-effect through space-time is limited by the speed of light. In fact SR makes causal chains even more dominant in the world view of nature. Prior to SR the standard view of time attributed to it a flow from past to future. In SR time does not have an inherent property of flow. The only reasonable alternative to understanding the meaning of past, present, and future is to understand these words in terms of causal chains. All observers experience causal chains. We are agents experiencing the present and making actions which will affect the future. The past includes events which have affected our present, and can not be changed by present or future events. In SR there is no universal present because different observers experience different causal chains. However every causal chain is Lorentz invariant in that the cause-effect propagates the same direction through the same events in all inertial frames.

QM is an inherently nonlocal theory in that space-like events appear to be causally correlated. Space-like events are events so spatially separated and close in time that cause-effect can not propagate directly from one to the other at less than the speed of light. Since causal chains can be considered a metaphysical concept and because QM and SR are mathematically compatible, a common solution to this nonlocality problem is to reject the notion of causal chains¹. There are other reasons to reject causal chains, all falling within the metaphysical realm of interpretation. The claim of this paper is that the rejection of causal chains leads to the insolvability of many of the strange paradoxes in QM.

This paper makes the starting hypothesis that every event (localized reality in space-time) is part of one or more causal chain(s), and that every causal chain is restricted

to contiguous events. This means that localized reality in space-time can not exist without causal chains. With this hypothesis I develop the so-called “Causality Model of QM”. This model gives a plausible interpretation of stationary states, which are predicted by QM, confirmed by experiment, and ubiquitous throughout nature. No other popular interpretation can give a plausible understanding of the essence of these states and contrast them with non-stationary states. To understand the properties of these states and to connect with experimental data involves an understanding of the QM measurement. The causality model demands a very specific interpretation of the QM measurement process. In the discussion of QM measurement I will briefly examine the non-locality in QM, giving a plausible explanation in terms of causal chains, consistent with SR.

II. Rules for the existence of stationary states

Stationary states in QM are bound systems, whose internal structure lacks time dependence. The two rules, which are both necessary and sufficient for a bound state existing in a stationary state are:

1. The system’s internal potential energy must not have time dependence.
2. The system must be in a pure eigenstate of the system’s Hamiltonian, with a specific energy.

Any bound system satisfying these two rules will have its internal structure in a stationary state. The second condition implies two other conditions:

- 2a. The internal energy is conserved, and there must be a lack of energy transfer with the surrounding environment.
- 2b. The spatial and momentum distribution of particles with the system is completely defined by the eigenstate of the Hamiltonian. This excludes any external event from either defining or limiting the relative positions and momenta of particles within the system.

These rules from QM explicitly prohibit any causal chains internal to the system from involving anything external to the system. The source of all reality within a stationary state comes solely from its conserved quantities, such as total energy, angular momentum, charge, lepton number, etc. Causal chains involving the process of becoming are completely lacking. Therefore, all non-conserved properties in stationary states, such as the position and momentum of a bound particle moving in a potential well, lack reality.

Because stationary states lack causal chains, the particle is waiting for a causal chain, with a first cause from outside, to give its non-conserved (accidental) properties a reality. All stationary state wave functions have a part which extends outside of the potential well, where the potential energy is greater than the total energy. The existence of the particle in this spatial region can only be made a reality if some outside probe, i.e. a scanning tunneling microscope, detects the position of the particle by imparting to it sufficient energy to actually exist where it is located. This is a first cause in a new causal chain; bringing reality to what previously was only a potentiality. To call this process tunneling through the barrier is a misnomer because the particle didn’t previously have a position inside the barrier. Similarly no bound particles in a stationary state can have momentum; otherwise they would be accelerating and giving off electromagnetic radiation, in contradiction to their stationary status. This rule that accelerating charge

must emit or absorb radiation is no less sacred than is energy conservation. We must find an interpretation which holds both of these rules to be true. Whereas the absence of causality leaves the position and momentum of the electron undefined, its electric charge is usually causally related to the outside world. Therefore the spatial charge distribution must be a reality, distributed as a cloud given by the square of the QM wavefunction.

III. The stationary ground states of atomic hydrogen and helium

The ground state of hydrogen consists of a proton and an electron with zero orbital angular momentum, a conserved quantity, therefore the proton and electron is constrained to move in a radial direction towards or away from each other. This state according to all experimental data and the predictions of QM is stationary, meaning that all observable properties are static, or unchanging with time. The hydrogen atom's ground state has spherical symmetry. The Fourier transform of the ground state spatial wavefunction of the electron gives the probability distribution of \mathbf{k} , the wave vector. It is common to identify $\hbar \mathbf{k}$ as the momentum of an electron in the hydrogen ground state. Helium has two electrons in a state similar to the electron state of hydrogen, and with a similar momentum distribution. To verify the momentum distribution of the electrons in helium in the year 1937, x-rays were scattered off electrons in a large number of helium atoms in their ground state². The experimental distribution of the momentum along a single z axis, p_z , obtained from the x-ray data gave an identical result as the theoretical prediction of the helium atom within experimental errors, as shown in figure 1. This experiment is historically significant because it was the very first time the shape of any quantum mechanical wavefunction was experimentally observed.

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 must include the impulse caused by the collision of the x-ray with the electron. Before the x-ray scattering the helium atom is in a stationary state. The definition of non-zero momentum of the electron necessitates the movement of mass (energy) from one spatial location to another. This is completely absent in a stationary state. The orthodox or Copenhagen interpretation says that the electron doesn't 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 electron has a different momentum. Many people interpreting QM today object to the concept of measurement creating reality, and 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 causality model agrees with the Copenhagen interpretation that measurement creates reality; however it doesn't allow measurement events like this to exist in isolation, apart from a contiguous causal chain. In the causality model a region of space-time, which lacks events, can be affected by causal chains, similar to the future. It is commonly accepted that an action can propagate as a causal chain into the future giving reality, where previously there was none. This is analogous to a measurement, which is an action propagating into the past of a stationary state giving reality, where previously there was none. This is the process of becoming. An alternative to causal

chains is to believe in a block universe in which the future and any property measured in the future is already a reality.

Generally all macroscopic regions, which are in the past and present, already have events. This restricts causal chains to movement forward in time. However if microscopic regions of space-time lack reality, there is nothing within QM preventing a causal chain, which is consistent with all conservation laws, progressing backward in time and giving reality to a space-time region lacking reality. This is known as backward causation and is an integral part of my causality model. Including backward causation with the Copenhagen Interpretation of the x-ray measurement of momentum of helium's electrons, makes it more palatable. With backward causation the measured momentum exists for longer than an instant in time.

It is commonly stated that the greatest difficulty in interpreting QM and making sense of it is the understanding of the measurement event. Here, I mean a non-trivial measurement in which the system being observed is not already in an eigenstate of the observable (does not previously have a single value for the observable). In the causality model of QM a measurement is a first cause, meaning it is the beginning of new causal chains, and it gives the observable its reality. The system being measured will have two new causal chains, one moving forward in time and one moving backward in time. The system making the measurement doesn't previously lack reality pertinent to the measurement. This not only allows it to make the measurement, but also limits any causal chain affecting it to a progression forward in time. The measuring device doesn't experience backward causation. This reality of the measuring device is what distinguishes a measuring device in QM from a system which can only become entangled by interactions with other systems, without choosing a specific value for the measured quantity. Entanglement, which involves probability distributions, is a propensity rather than a reality. Such entanglement is always open to the effects of future events, converting propensity to reality and therefore does not constitute a measurement.

An alternative interpretation is to associate the measurement process with human consciousness rather than with the reality of the measuring instrument. This is what leads to the absurd Schrödinger's cat. A real cat has the reality of being alive or dead, and its interaction with the QM system demands a measurement. Human consciousness assures a measurement, but is generally not the source of the measurement in the causality model. In the causality model the x-ray, because of the experimental arrangement, has a well defined momentum coming into the helium atom and leaving the atom, and is demanding partial specificity of the electron's momentum. This reality of the x-ray's momentum makes the measurement of the electron's momentum, i.e. it is requiring reality for the electron. Even though human design of the experiment assures that the x-ray has a real momentum, human consciousness can not logically take credit for the measurement. Since QM measurements are first causes and science doesn't deal with first causes, a deeper understanding of the measurement is a metaphysical problem, not a science problem.

IV. Other Stationary States: Atomic Nuclei

Very many features of nuclear structure and its properties can be explained by the independent particle model. Each nucleon inside a stable nucleus is in a stationary state, which is an eigenstate of a single particle Hamiltonian. The potential energy of this Hamiltonian approximates a rounded square well usually more than 50 MeV deep with a

diameter roughly the size of the nucleus in which the particle resides. This potential is a good approximation of the sum of the attractive part of the nucleon-nucleon force of a single nucleon with all the other nucleons inside the nucleus. The eigenstates of this Hamiltonian, which are single particle orbits, are in a one-to-one correspondence with the electron orbits in atoms. They have identical quantum numbers, 1s, 2s, 2p, etc. with identical angular shapes. The radial dependence is different because of the much smaller size of the nucleus and a somewhat different potential well. Often there are nuclear states studied in the laboratory which can be identified well by these single particle orbits³. The orbits are typically bunched together in energy with a large energy gap to the next bunch. These bunches are called shells. There are many nuclear states where a single particle is in a particular orbit in an otherwise empty shell and all lower shells filled. There are also many states in which the highest occupied shell has a single vacancy. These are the single particle or single hole states, respectively. Protons and neutrons are treated separately because of the Pauli Exclusion Principle. Even when there is measurable mixing of particle configurations in a single nuclear state through so-called entanglement between nucleons, the mixing is often small when the shells are all nearly filled or empty. In conclusion, it is common for the nucleons inside the nucleus to act as if they are nearly free to move around without collisions with the other nucleons.

What makes the success of the independent particle model puzzling is the fact that the density of all nuclei places the average spacing between the centers of nucleons to be about $1.2 \cdot 10^{-13}$ cm, which is only slightly larger than the size of each nucleon. This means the nucleons are packed together nearly as tightly as possible. There is an enormously strong short-range repulsive force in the nucleon-nucleon interaction which makes it energetically prohibitive for any two nucleons to overlap. The primary goal of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is to merge large nucleons together into quark-gluon matter. Even at the highest energy collisions available this process has only tentatively been confirmed. The fact that nucleons can not easily overlap suggests there is little free space for nucleons to roam around inside the nucleus, which is inconsistent with the independent particle model and its orbits. An answer used to explain this paradox is that collisions between nucleons are suppressed by the Pauli Exclusion Principle. The effect of any collision would cause a transition of the nucleons from one orbit to another. The Exclusion Principle requires that the new orbits be unfilled, and typically at significantly higher energy. Collisions are thereby inhibited by a lack of available energy. The argument is more a self-consistency statement rather than a solution to the paradox. It doesn't answer the question of why the concept of single particle orbits can be used in the first place.

The causality model of QM solves this paradox. Stationary states, which lack causal chains, have no localized reality. Both the positions and paths of motion of nucleons inside the nucleus lack reality. The single-particle orbits and also the potential well for each nucleon are derived from a superposition of standing waves. Each wave is simply a potentiality distribution of nucleon existence. Since waves of potentiality replace corpuscles with real locations, collisions are avoided. In contrast, anyone insisting that the positions and momenta of nucleons inside the nucleus are a reality would find the success of the independent particle model very puzzling. For those unfamiliar with nuclear physics there are also many instances where the collection of all

nucleons behaves in unison. For example, rotational states are common where the whole nucleus rotates, and the liquid drop model describes other features of the nucleus.

V. Backward Causation and Non-locality

Although QM doesn't include backward causation, backward causation is completely consistent with QM. One reason QM ignores backward causation is that this process only pertains to what is called the inaccessible past⁴. The inaccessible past, which is the past created by a future event, can not be studied scientifically. Any attempt to examine this past, before the future event which presumably creates it, disturbs the system in an uncontrollable way, so as to destroy the causal chain coming from the future event. This measurement disturbance prohibits illogical causal loops. Causal chains can not logically loop around back on themselves, and the strange properties of QM prevent this from happening. An example of a causal loop would be a person John going back in time and killing his ten year old grandfather.

The causal chain moving backward in time is able to explain⁵ the non-locality in QM, consistent with SR. The most commonly discussed nonlocality in QM is the EPR paradox¹. In this paradox two or more particles are entangled and were initially in close contact with each other. After they are separated the measured value of certain observables of each particle are correlated with each other. In the instances where the measurements are space-like events, SR prohibits a causal chain going directly through space-time from one to the other. This suggests that these measured values were a reality (or at least determined) prior to measurement, and that the stochastic measurement was not the deterministic cause of the observed reality. Such a hypothesis implies the existence of hidden variables, which determines the reality before it is measured. Within the constraints of the locality condition of SR, no local hidden variable model of QM can explain the correlation of the measured results. An underlying reason no hidden variable theory can explain the correlations is because of the free choice of the experimenters in separable choosing of the observable of each particle to become a reality. In summary, no causal chain of contiguous events, even including hidden variables, can explain this correlation, assuming all causal chains move forward in time. Hence, the EPR correlation is called a paradox. Backward causation solves this paradox⁵, consistent with SR. Briefly, the causal chain does not go directly from one measurement event to the other, but rather accompanies the particles. The causal chain connecting the two measurements moves backward in time with the particle which was measured to the space-time location where it is in contact with its entangled twin particle. The causal chain then continues forward in time with the twin particle to the other measurement event. Since the causal chain is progressing through space-time at the speed of the particles it is never violating the locality condition. Its progression never exceeds the speed of light.

The EPR correlations are probabilistic rather than deterministic. This implies probabilistic causation. A well-known unappealing feature of probabilistic causation is that it is mathematically symmetrical⁶. If event A affects the probabilistic occurrence of event B then mathematically event B similarly affects the occurrence of event A. This requires causation going in both time directions between events. In the causality model each measurement (A or B) is both a first cause (event) of a new causal chain and also affected by a causal chain coming from the other measurement. There are two causal

chains: one from event A to B and the other from event B to A. This symmetry happens when these causal chains are both probabilistic and pertain to different observables. Within these restrictions there is no illogical causal loop between events A and B. A specific example of this would be the measurement of spin correlations of the two particles along non-parallel axes. Measurement A may be the spin projection along a particular axis and then measurement B would be the projection along a non-parallel axis. The observed spin projections will be probabilistically correlated with each other, but neither measurement can determine the outcome of the other. It is important to note that observed spin projections along non-parallel axes are incompatible. Measurements of incompatible observables do not commute. Using the concept of causal chains, a measurement of an observable will terminate a causal chain, which defines another incompatible observable. This leads to the Heisenberg uncertainty relationship, which prevents two incompatible observables simultaneously having precise values. The incompatibility of the observables is what prevents illogical causal loops. Each measurement terminates the causal chain coming from the other measurement.

Whereas in QM two incompatible observables can not simultaneously have precise values, this is not true for the inaccessible past between the two measured events A and B in the EPR type experiment. The causal chains coming from A and B progress backward in time through some events and future in time through other events. Any set of these events has the two causal chains moving in opposite directions. Whereas each causal chain is terminated at the other measurement event, both causal chains simultaneously exist for all events inbetween A and B. Therefore, a particle will simultaneously have well defined spin projections along two non-parallel axes, but only in the inaccessible past.

Not only can the nonlocality of QM be explained consistent with SR, but most other strange features of the measurement can be understood in a consistent manner within the causality model. Most of the so-called scientific problem has been removed. There is still the problem of explaining the source of the first causes, but this is more a philosophical or theological problem, similar the problem of explaining the existence of the universe and its natural laws. These problems are properly classified as metaphysical questions, and so should be the classification of the measurement problem. This is a perfect example of how physics leads to metaphysical questions.

VI. The existence of causal chains in quantum mechanic

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*⁷:

“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 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..."

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, figure 2, 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.

Hawking's use of Feynman's multiple histories separate reality from cause-effect. In this model reality doesn't need a cause, nor does it need to affect other reality in any uniquely identifiable way. Not only does this model fail to explain the perceived flow of time, but also it fails to conceptually explain the absence of time flow in stationary states as compared with non-stationary states. One aspect which complicates the causality model is the recognition that microscopic causal chains are very fragile and easily terminated. For example, in figure 2 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 isn't 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.

One of the tenets of the Copenhagen interpretation of QM is the interpretation of its indeterminism. Bohr claimed 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 and continuous, without any first cause. When G. Lemaitre⁸ was discussing the Big Bang Theory of the Universe with Einstein, Einstein's reaction was: *Non, pas cela, cela suggere trop la creation* (No, not this; this too much suggests the creation). Although the causality model appeals to Einstein's preference for realism and is a solution to the EPR paradox totally consistent with SR⁵, Einstein would probably reject it because of its first causes. 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 backwards in time. After the measurement (in a causal sense) the measured attribute becomes a reality for the object at earlier times. Therefore the model takes some of Einstein's realism and combines it with Bohr's ontological indeterminism.

The causality model also modifies the Copenhagen tenet of *complementarity*. *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. The reason there is incompatibility of simultaneously observing these different phenomena is because the situations are different. The difference, determined by the experimental apparatus, is based upon the existence or non-existence of causal chains.

Whereas Hawking would claim the particle in figure 2 doesn't have a well-defined momentum inbetween the two measurements, the causality model claims the particle's path is a unique straight world line connecting the two space-time points. Only uncertainty in the positions at each measurement can spread out (make imprecise) the world line. Assuming there is no uncertainty in either the position or time of the measurements, this particle acquires precise properties of both position and momentum, incompatible observables. The world line defines precisely both the magnitude and direction of the particle's momentum. This determinism doesn't violate QM because it only exists in the inaccessible past.

For some reason Hawking and most people prefer to assign multiple realities rather than a single or no reality, and I think this is fundamentally flawed. Let us use figure 2 to discuss the motion of an electron. At any instant if an electron exists in multiple locations with multiple values of momentum then there has to be more than one electron. This would violate lepton number conservation. The causality model claims that distributions of observable quantities in a quantum state are potentiality distributions, and the observable quantity lacks a real value. This raises the philosophical question, how can something exist without having a value, or how can energy exist without having a form? Specifically, a particle in a stationary state doesn't have either a position or a momentum. This means it doesn't have either a potential energy or a kinetic energy, and yet its total energy is fixed and conserved. Using ideas borrowed from Aristotle⁹, we call some of the substance of the universe eternal, or "essential". However some of the elements present in things are "accidental", resulting from cause and effect that represent change. The total energy is conserved and therefore eternal, however the potential and kinetic energies are accidental, and not yet defined until causation acts upon the system.

VI. Comments

In conclusion, physicists have generally avoided ideas, which go beyond science, to explain quantum mechanics. Specifically the avoided ideas are the inaccessible past and causal chains with first causes. Causal chains have not previously been used to explain QM, because every causal chain must have a first cause. Neither the inaccessible past nor first causes can be studied using science (beyond simple identification). This, I believe, is the primary reason QM is so difficult to make sense of. One way to avoid first causes is to attribute QM measurement to human consciousness. Since the source of consciousness is not understood, the question of first causes is set aside with a vague hope that science will some day come up with a fuller explanation. Another popular

avoidance of first causes is the use of the Block Universe model, in which everything which will exist already exists. The future is already a reality. Such a view eliminates all causal chains and first causes. Another popular avoidance of first causes is to attribute all unpredictable outcomes to hidden variables. The hidden variables hypothesis has been discredited because the locality condition makes it inconsistent with QM. Another argument used to avoid first causes is to claim that everything, which is allowed to happen, will happen. An example of this is Hawking's use of Feynman's path integrals. This paper is a brief attempt to show that first causes and causal chains, moving in both time directions, can explain most strange features of QM.

Let me summarize the arguments in favor of causal chains. Causal chains have and continue to be a fundamental characteristic of all natural science, excluding QM. Causality explains the time flow forward in time as in human experience. No other model has identified the present in contrast to the past and future, and consistent with SR. Lack of causality gives an ontological explanation of stationary states in contrast to non-stationary states, which no other interpretation of QM has done. Backward causation explains non-locality in QM consistent with SR. No other interpretation of QM has accomplished this, and therefore the EPR paradox dominates interpretative issues about QM. QM has exactly the right properties to allow backward causation while preventing illogical causal loops. The primary reason that backward causation is rejected is because of the possibility of illogical causal loops. The properties of QM, which prevent causal loops, are fortuitous for the causality model and provide strong circumstantial evidence for the model. To emphasize this further I appeal to Chandrasekhar's book, *Truth and Beauty*¹⁰, in which a running thread is the quest for beauty in science. The very basic properties of QM seem nonsensical and yet they are absolutely essential for avoiding illogical causal loops. When a model can take strange and apparently arbitrary properties of nature and fit them together into a necessary component of nature's function ability, the truth becomes beauty. Finally science has been unable to make ontological sense of the QM measurement process. To save science the embarrassment, I propose taking this issue away from science and attributing it to metaphysical first causes.

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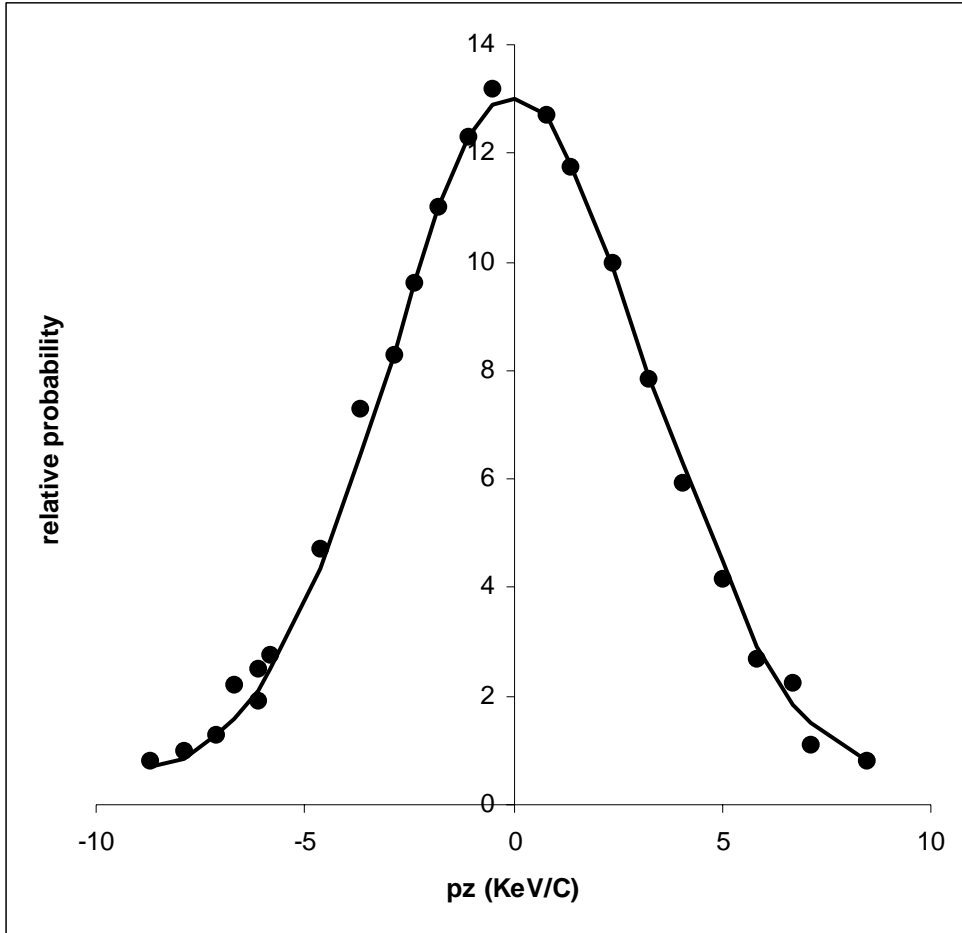


Figure 1. The points are relative probabilities for measuring various values of the z component of momentum, p_z , of an electron in the helium atom, obtained from the experimental intensities of Compton scattering from helium (ref. 2). The continuous line is the momentum probability distribution calculated from the helium-atom electronic wavefunction.

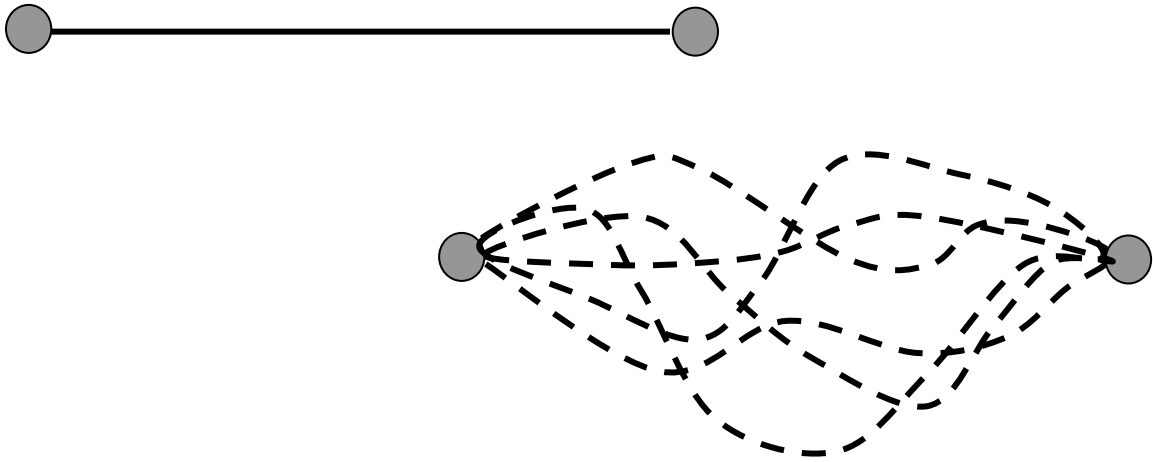


Figure 2. The path of a classical particle (solid line) represents a causal chain. A few of Feynman's paths of multiple histories (dashed lines) replace a causal chain. The end points are boundaries determined by external observations.