Implications of Relativistically Consistent Wave Function Collapse

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In the current formalism of quantum mechanics, collapse of the wave function is envisioned as occurring "instantaneously". Since this is in conflict with the fact that "simultaneity" is not a relativistic invariant, quantum mechanics and relativity are in conflict with each another. This conflict is benign as long as faster-than-light (FTL) phenomena are disallowed. This paper explores this conflict and considers the implications if collapse can be specified to occur in a way that is consistent with relativity. In particular, relativistically consistent wave function collapse forces us to reconsider our preconceptions of causality. We are led to consider two cases; timelike and spacelike. For two events that are causally connected by a timelike interval, the earlier-in-time event is the cause in all reference frames, but the spatial ordering is not preserved. For two events that are causally connected by a spacelike interval, the temporal ordering is not preserved but the spatial ordering is, just the reverse. This is philosophically disturbing since for spacelike causes half the reference frames see the cause as proceeding backwards in time. However, in and of itself this is not logically inconsistent. Backwards-in-Time Causality (BTC) seems at first glance to permit temporal paradox, since two spacelike causal connections can be used to create a closed causal loop in spacetime. While temporal paradox *is* logically inconsistent, BTC can still be allowed if there is also a censor mechanism that prevents temporal paradox. In relativity, FTL and BTC are two sides of the same coin, so the major implication of relativistically consistent wave function collapse is that quantum systems should be able to support both FTL and BTC phenomena despite Eberhard's "proof."

I. Introduction

THIS paper is the fourth of eight integrated papers[1,2,3,4,5,6,7,8] to explore the potential of quantum nonlocality to support superluminal signaling; i.e., communicating at faster-than-light (FTL) speeds[9]. Spacelike causality raises a number of issues that must be addressed if nature is to permit any kind of FTL phenomenon. These include consistency with Special Relativity, a broadened formulation of causality, and either resolution or avoidance of temporal paradox[10]. These issues are addressed with increasing sophistication through the series of eight papers.

This paper considers the implications if collapse of the wave function really occurs along symmetric spacetime intervals. There are implications for the nature of causality, and there are implications that flow from closed loops in spacetime. A cursory inspection of these issues would suggest that relativistically consistent collapse is not possible. Upon a deeper look, however, we find that sense can be made of spacelike causality and in particular, that closed loops in spacetime offer a potential resolution to the measurement problem.

II. Background

The previous paper derived the symmetric spacetime interval, thereby placing on a firm foundation the hypothesis that wave function collapse occurs along symmetric spacetime intervals.

III. Conceptual Development

If the hypothesis that collapse of the wave function occurs along symmetric spacetime intervals is correct, then there are two implications that must be dealt with: a change in our view of causality, and the issue of closed causal

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loops in spacetime. Spacelike causes need not occur before their effects and closed causal loops can lead to temporal paradox.

A. Causality

Causality between timelike events in classical physics is a straightforward concept; it is the possibility of spacelike causality that violates our preconceptions[11]. In contrast, the issue of causality in quantum systems is significantly more problematical. Therefore, we will investigate the issues with causality from both a classical and a quantum perspective.

1. Classical Causality

The current view of causality is that two events that are causally connected must be separated by a timelike spacetime interval, and that the earlier-in-time event is the cause. This has the advantages of fitting common sense and of being relativistically consistent, since the temporal ordering of timelike events is a relativistic invariant. However, in order to permit spacelike causality, we must let go of this preconception, since for spacelike causes the earlier-in-time event is not necessarily the cause. The symmetric interval allows all relativistic observers to determine which event is the cause, and they will all agree on the selection. They can agree on whether the causal event is the one to the right or if it is the one to the left, but they will not in general agree on which one was first.

There is an attractive symmetry here. For timelike causal events, the temporal ordering is a relativistic invariant, but the spatial ordering of the events is not. For spacelike causal events, the spatial ordering is a relativistic invariant, but the temporal ordering of the events is not.

The philosophical objection to backwards-in-time causality is that it is illogical for an effect to precede its cause. This preconception is applicable only to the region of timelike causality. For spacelike causes, it cannot be said that either the cause precedes the effect, or the effect precedes the cause since the temporal ordering is not preserved. Which came first is not an objective fact of reality. Isolated spacelike causes, if there is a reliable relativistically consistent way to determine which event is the cause, are not illogical. The symmetric interval meets these criteria.

However, we can imagine a situation where an effect precedes its cause, and is an objective fact; two timelike separated events where the later one is the cause. Call this case *inverted causality*. An effect preceding its cause along a timelike interval has become an objective fact. It is now possible to construct a causal closed timelike loop using a timelike cause and an inverted cause. This has the potential to be paradoxical, and there does not see to be any way in which classical physics can survive a temporal paradox. Therefore, from logical arguments we might reasonably conclude that inverted causality is not permitted in physics.

Figure 1 shows a spacetime causality diagram. Classical causality (also called Einsteinian Causality) is permitted only between timelike separated events and the earlier in time event is always the cause (the forward light cone). Quantum mechanics may support spacelike causality (outside the light cone). Inverted causality, timelike separated events where the later in time is the cause, is strictly prohibited since it leads to time machines and temporal paradox (backward light cone). The problem of course is that two spacelike causal connections slanted in different directions have the potential to create an inverted causality situation, and so it has been assumed that spacelike causality must be prohibited.

However, closed loops in spacetime can be either paradoxical or indeterminate. All that would be required to allow them is for there to exist a censor mechanism that prohibits paradoxical loops. We believe that a variant on the Many Worlds interpretation of quantum mechanics (to be covered in the next paper in this series) offers such a censor mechanism.

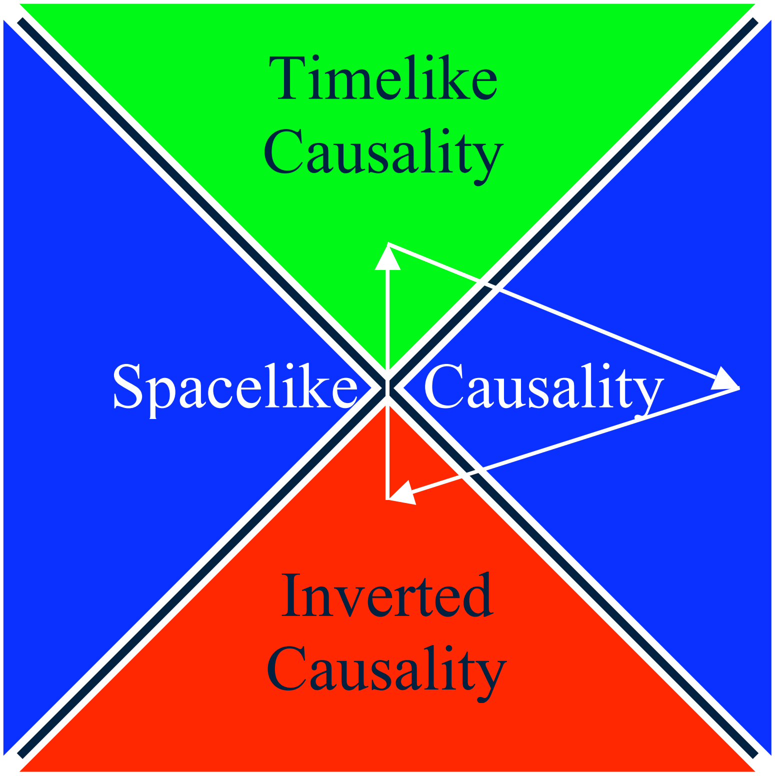

Figure 1: The spacetime causality diagram.

2. *Quantum Causality*

The issue of causality in quantum systems is, to say the least, muddled. Measurements are statistical (i.e., acausal) yet the mathematics of the wave equation is deterministic. Hidden variable theories have been disproved[12], so matter is nonlocal. Therefore, correlations exist across spacelike regions that cannot be explained by either Einsteinian causality or common causes in the past light cone[13]. There is no agreement on whether collapse of the wave function even happens, but if it does, there is no explanation for why, when or how[14]. The measurement process is central to the formalism of quantum mechanics but without a specification for collapse, the causes of measurements remain mysterious. Further complications arise from conjugate variables, where the simultaneous determinations of conjugate properties of a quantum system are not possible. What exists seems heavily dependent upon the very act of observation – just to look is to cause. What is going on?

In the current formulation of quantum mechanics, collapse of the wave function is envisioned to occur "simultaneously" in all reference frames. While in obvious conflict with at least the spirit of relativity, this conflict is benign unless spacelike causality is permitted. However, on closer inspection, it is more accurate to say that collapse of the wave function is spacelike. Observers are free to claim it collapses any way they like as long as there is no timelike component to the collapse. This also means that if one could specify a specific spacelike collapse that all observers could agree on (such as collapse along symmetric intervals), it would be at least as consistent as the current approach (instantaneous collapse) and would leave the door open to FTL phenomena, including in particular, backwards-in-time causality (BTC). BTC is a problem only if there is no censor mechanism to prevent temporal paradox.

The symmetric spacetime interval introduced and derived in the previous papers shows one way to do this. It is possible to specify which of two causally connected spacelike-separated events is the cause and which the effect. All observers will agree on this determination even though in general half of them see the causality as propagating backwards in time.

We therefore have two competing hypotheses on wave function collapse. Is collapse instantaneous in all reference frames (current formulation), or does collapse occur in a relativistically consistent way along symmetric spacetime intervals (our hypothesis)? While both are consistent with current knowledge, symmetric intervals permit the construction of spacelike closed causal loops in spacetime, and such loops offer a potential explanation for quantum causality in all its many forms.

For convenience, the quantum causality issues that closed loops in spacetime may explain are listed below.

1. Acausality
2. Nonlocality
3. Spacelike correlations
4. Collapse
5. Deterministic evolution
6. Conjugate variables

B. Spacelike Closed Causal Loops in Spacetime

Closed causal loops in spacetime are an example of self-reference. In order to get a handle on self-reference the first paper considered logical systems that can indicate and evaluate self-referential forms. These are normally identified as nonlinear or imaginary logics, but are not well known.

1. Conjugate Logic

Figure 2 shows two simple feedback circuits, a BUF gate and a NOT gate. A BUF gate simply replicates its input, while a NOT gate inverts it. The first circuit is easy to evaluate, it is either a 1 or a 0. Since we want to treat this system as a metaphor for logical self-reference, we shall use the symbols T and F. Now the NOT gate seems to be a paradox; if the input is true the output is false, while if the input is false the output is true. However, we can resolve this paradox by simply adding imaginary truthvalues to this system, true imaginary (I) and false imaginary (J). In both cases, the ultimate resolution is acausal, since there is no input to force a deterministic value. The two categories of truthvalues form two different measurement bases. With this extension, the self-referential NOT gate is two valued just like the self-referential BUF gate.

A:≈A (T or F) BUF gate (a)

A:~A (I or J) NOT gate (b)

Figure 2: Self-referential digital circuits and imaginary truthvalues. Let T and F be the eigen-truthvalues in the real basis and let I and J be the eigen-truthvalues in the imaginary basis. Both self-referential forms are therefore paradoxical in one basis, but indeterminate in the other. They collapse randomly to a truthvalue in the basis in which they are indeterminate.

This gives us a formal system with two bases; a real basis with eigenvectors T and F, and an imaginary basis with eigenvectors I and J. A logical value can be real, or it can be imaginary, but it cannot be both. The result is that the logical value of a loop looks like a conjugate quality. For instance, T = I OR J and F = I AND J, which makes the real truthvalues, true and false, look like superpositions of the imaginary truthvalues. Notice how the inclusion of imaginary truthvalues has allowed either loop to avoid being paradoxical. Each is paradoxical in one basis but indeterminate in the other. This suggests that closed causal loops in spacetime, if based on quantum entanglements, may provide their own censor mechanism to prevent temporal paradox.

In this model, an idealized self-referential circuit, whether it is in the real basis or the imaginary basis, often permits two or more values, and the circuit must settle out (collapse) to one of them. This settling out is an acausal event, since the choice of the collapse is beyond the control of the digital engineer. Closed causal loops offer a kind of causality violation – there is no input to force a result, so multiple results are possible.

If this sounds an awful lot like a quantum measurement event, we agree. The measurement problem is an underappreciated problem in the foundations of quantum mechanics, but some authors are beginning to raise the battle cry that it is time to solve it[15]. The seventh paper will consider how cyclic entanglements may select the basis in which self-collapse of an isolated quantum system can occur without an external classical measurement apparatus.

Digital circuits are generally categorized into two major taxonomies, combinatorial circuits and sequential circuits. Combinatorial circuits have no loops, and so the effect of the inputs on the outputs is strictly deterministic. Sequential circuits do have loops and their values are either indeterminate or depend on the history of the circuit while in operation. In other words, digital circuits behave deterministically except for instances of self-reference. Similarly, quantum systems evolve deterministically except for collapse of the wave function.

2. Closed Loops of Symmetric Intervals

Since the symmetric interval connects entangled quantum objects over a spacelike interval, nonlocality is automatic. This extended connection also accounts for the correlations seen over spacelike separations.

Consider two entangled particles (particles 1 & 2) going their separate ways, which we presume are connected by a growing symmetric interval. However, since neither has yet been measured, either one could turn out to be the encounter particle (the one's whose measurement causes the collapse of the joint wave function). Until this is determined, the cause and effect relationship can go either way. Now let one of them entangle with another particle (particle 3), which is in turn already entangled with particle 4. There are now two particles on opposite ends of a chain of entanglements. If we were to measure either end particle, a causal chain of events would be instigated from one end of the chain to the other. Obviously, the propagation can go either way, and along each leg, it could be propagating either forward or backward in time depending on the observer's frame of reference. Twiddling with either end makes it the cause and the other the effect, so here is a case of mutual causality. Figure 3(a) shows two pairs of entangled particles (1,2) and (3,4), which became post-entangled when particles 2 and 3 interacted. Causality can precede either left or right depending on when particles 1 and 4 are measured.

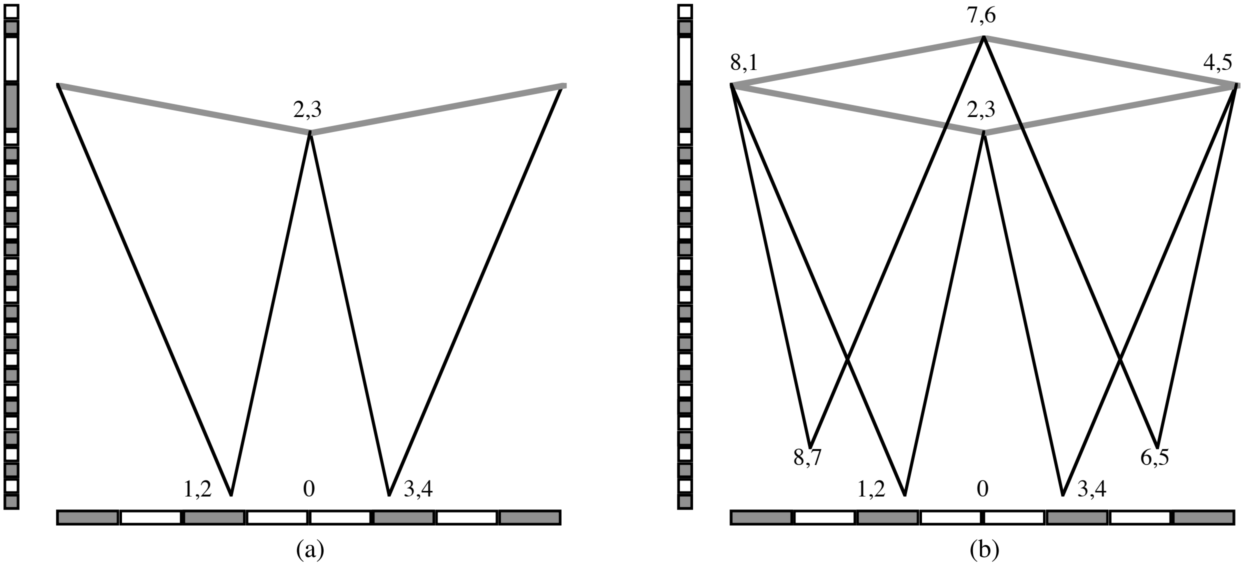

Figure 3: Self-referential quantum entanglement around symmetric intervals.

The addition of two more pairs of entangled particles permits the construction of a spacelike closed loop in spacetime, shown in Figure 3(b). Before the cycle was completed, causality could have proceeded either way, but now the entire entanglement collapses "at once," causality propagating from the "last" entanglement to all the earlier ones. Collapse occurs in a basis specified by the particulars of the cyclic entanglement. In particular, conjugate variables guarantee that the cycle will not be paradoxical; in at least one basis, it will be merely indeterminate. Selection of the eigenvectors in that basis is acausal, but no observer or macro measurement device is required for the collapse.

Our closed loop in spacetime has performed a self-measurement – an observer free measurement. In general, there will be two choices for this collapse; what the two choices are depends upon the particulars of the cyclic entanglement. There is no causal mechanism for the choice: which way the loop collapses is acausal. If the entanglement of particles 6 and 7 was the entanglement that completed the cycle, propagation is everywhere backwards in time from the point of view of the lab frame. However, for relativistic observers moving fast enough, some will see causality propagating forwards to the 8,1 entanglement, others will see it propagating forwards to the

4,5 entanglement. All observers will see collapse of the 2,3 point occur prior to the 7,6 point. Self-referential entanglements, i.e., closed loops in spacetime, offer a compelling measurement mechanism.

Most isolated quantum systems are very sparsely populated, the number of states greatly outnumbering the number of quantum objects, so self-referential entanglements are exceedingly rare in these situations. To get a measurement, the isolated quantum system must interact with a macro system where there is parity between the density of states and the number of quantum objects. In this view, the cyclic entanglements within the macro system determine the basis, and the external quantum system to be measured, having become entangled with the cycle, collapses with the cycle in the same basis.

IV. Analysis

We will present a hypothesis and a test.

A. Hypothesis

We are led to hypothesize that self-referentially entangled quantum systems collapse. The closed loops in spacetime that can be formed by symmetric spacetime intervals create the self-referential entanglements. This can be stated as a formal hypothesis.

> Hypothesis: *Closed loops in spacetime consisting of symmetric spacetime intervals form self-referential entanglements that lead to collapse of the wave function. The complex superpositions of the entanglements around the closed loop specify a basis for this collapse so that paradox is impossible.*

What is appealing about this hypothesis is how neatly it ties up the loose ends of quantum mechanics. We get a formal measurement mechanism that leads to relativistically consistent collapse, demonstrates acausality, nonlocality, conjugate variables, and shows that SLC and paradox-free BTC are possible. We wish to emphasize that this is not merely an interpretation of quantum mechanics but is an appeal to testable ideas. Since a collapsed system has lost its coherence, it can therefore no longer support interference effects. The hypothesis of self-referential collapse can be tested by demonstrating the loss of interference effects in an isolated quantum system. While the statistics of simple measurements on systems that may have collapsed but may also still be in a superposition are the same, an interference measurement can distinguish between an ensemble of collapsed systems versus an ensemble of uncollapsed systems.

It has been noted in the literature that any nonlinearity in quantum mechanics should lead to collapse of the wave function. Self-referential entanglements introduce nonlinearity in a natural way that is superior to current approaches, which make an ad hoc attempt to add nonlinear terms to Schrödinger's equation.

B. Eberhard's Proof

It should be pointed out that Eberhard has written a comprehensive paper disproving that quantum entanglement can be used for any kind of FTL communication[16]. His basic argument is that quantum statistics make it impossible for an observer to send a detectable signal by simply changing the basis in which he measures one particle of an entangled particle pair. In this, he is correct, and he makes a serious attempt to produce a comprehensive argument. However, all of his cases involve joint acts of measurements on an isolated quantum system. His arguments do not consider experimental setups where the sender has options to create more sophisticated entanglements in different ways without performing a measurement leaving it to the receiver to make a single measurement that then reveals what kind of entanglement existed prior to collapse.

We should also point out that the meaning of the word entanglement is subject to a conceptual degeneracy not often delineated in the current literature. We use it in its most general form, as a synonym for non-separable states. In its more restricted form, it refers to EPR style entanglements, (what we call degenerate cyclic entanglements) where the correlations are driven by the choice of measurement bases and the difference between them, rather than by a choice between different types of entanglements.

We believe that this subtlety still leaves a loophole through which FTL might be achieved, and having shown that temporal paradox can be avoided (next paper) this potential loophole should be explored.

C. Test

A hypothesis that cannot be falsified is a poor hypothesis. We believe that the hypothesis that self-referential entanglements lead to collapse is testable, but at this time, we have not investigated potential experiments beyond the concept stage.

We have considered one thought experiment that probably could not be implemented directly, but at least captures the key concepts of self-referential collapse. Consider a variation on the double slit experiment consisting of four quantum wells, in a two by two configuration. Each is so constructed that it may contain at most a single particle. We now imagine a particle gun that can shoot particles toward the four wells with two different energies and with four different superpositions. At the low energy, a particle will be trapped in a superposition of two wells. Each well needs to be isolated from the environment sufficiently that it won't be collapsed by decoherence on the time scale of the experiment. If we number the wells counter-clockwise from one to four we can envision them as being in the four quadrants of the Euclidean plane. The four superpositions are adjacent cells, (4,1), (1,2), (2,3), and (3,4). We'll let wells 3 and 4 be the "double slits". When the wells are empty a particle sent at the high energy setting in the (3,4) superposition, will form an interference pattern on the screen behind the wells.

Now, shoot three particles at the low energy setting toward the wells with superpositions (4,1), (1,2) and (2,3), so that they are trapped in those four wells in an entangled superposition. Then shoot a particle at the high energy setting in the (3,4) superposition. The high energy needs to be just high enough that the particle penetrates the wells and continues on to the screen, but low enough that it has time to entangle with the other three particles already in the well. If self-collapse happens, the fourth particle will have transitioned only one well, randomly, resulting in an overlapping diffraction pattern instead of an interference pattern. To distinguish between a diffraction pattern and an interference pattern requires a sequence of particles in the (3,4) superposition, so a means to empty the wells of their collapsed occupants is also an experimental necessity. While this is just a thought experiment (and unlikely to be doable as described), it does capture the essential concepts. Variations that are more practical should be doable and offer a test of the concept that self-referential entanglements are the measurement mechanism.

An alternative thought experiment is considered in the last paper.

V. Conclusion

While the nonlocality of nature is now a well-known aspect of quantum physics, there has been reluctance to accept at face value the implied spacelike causality since it would seem to lead inexorably to temporal paradox. However, unlike inverted causality and the timelike closed spacetime loops they lead to, the spacelike closed spacetime loops supported by the symmetric interval are able to avoid temporal paradox. They do this by performing a self-measurement where conjugate variables supply enough degrees of freedom that there is always a basis in which the loop is merely indeterminate and not paradoxical. This also explains the acausal nature of collapse – a closed loop has no external causal influence and in general has two possible resolutions. These closed loops in spacetime support a logically consistent causality paradigm, make collapse of the wave function consistent with relativity, provide an observer free measurement mechanism, avoid temporal paradox by using conjugate variables to settle on a basis that makes the loop indeterminate, and show that both SLC and BTC cannot be ruled out.

Acknowledgments

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