Relativistically Consistent Collapse of the Wave Function along Symmetric Spacetime Intervals

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A thought experiment is presented that provides a hint as to how quantum wave functions can collapse in a relativistically consistent way. The thought experiment consists of a central source of photon pulses midway between two detectors, which is examined relativistically from both the lab frame and a frame moving with respect to the source and detectors. The total number of pulses between the two detectors is the only invariant and this leads to the idea that collapse might occur along special spacetime intervals, which we call symmetric spacetime intervals. In the current formalism of quantum mechanics, collapse is envisioned to occur "instantaneously", in clear violation of relativity. It is shown that what the current formalism actually specifies is that collapse is merely spacelike. However, if quantum collapse occurs along symmetric spacetime intervals, then collapse of the wave function can be made consistent with relativity and all observers can agree upon which of two spacelike-separated causally connected events is the cause and which the effect.

Nomenclature

x = normalized distance in light seconds (ls)
t = normalized time in seconds (s)
γ = Lorentz factor
s = spacetime interval
u = normalized velocity (ls/s)
c = speed of light (1.0 ls/s)
y = a quantum object
z = a quantum object
d = separation between pulses (ls)
L = separation between detectors (ls)
ν = frequency (s^{-1})
n = number of pulses
β = slope of the symmetric interval (s/ls)

I. Introduction

THIS paper is the second 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 introduces a thought experiment that suggests how quantum wave functions might collapse in a relativistically consistent way. This thought experiment leads to the concept of a special spacelike spacetime interval, which we call the symmetric spacetime interval. The hypothesis is formulated that collapse of entangled quantum systems occurs along symmetric intervals. Given the experimental particulars, all relativistic observers can determine and agree upon cause and effect; which not only makes collapse relativistically consistent but also overturns "Einstein causality" and opens the door to backwards-in-time causality (BTC).

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II. Background

Our central hypothesis is that quantum temporal paradox is the measurement mechanism. In this hypothesis, closed loops in spacetime consisting of self-referential quantum entanglements, create the nonlinearities necessary for wave function collapse. The sections below introduce the fundamentals of special relativity[11] and of quantum mechanics[12] relevant to our thesis.

A. Special Relativity

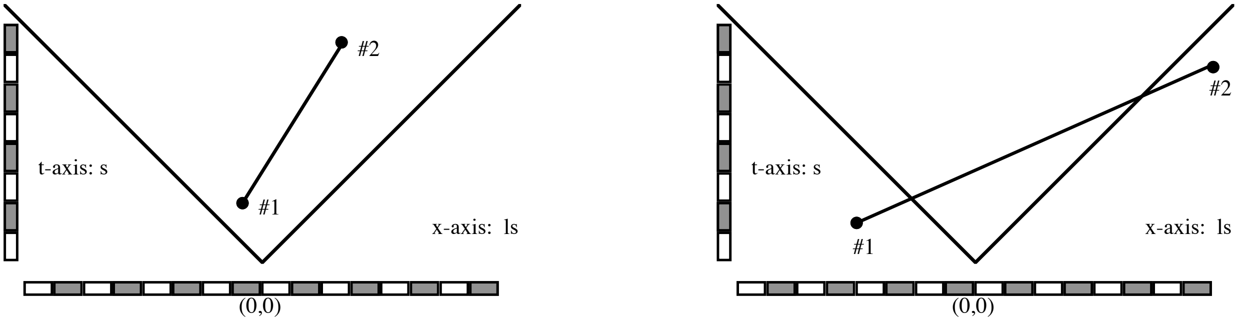
We will be using normalized coordinates where time is measured in seconds (s) and distance is measured in light-seconds (ls). Therefore, the Lorentz equations are;

$$\begin{aligned} x' &= \gamma\left(x - ut\right) \\ t' &= \gamma\left(t - ux\right) \\ \gamma &= \frac{1}{\sqrt{1-u^2}} \end{aligned} \tag{1}$$

where u is the velocity (ls/s) of the relativistic observer in the unprimed frame. In a two-dimension spacetime diagram, time proceeds upward and space is left to right. The ultimate physical velocity is the speed of light (1 ls/s), and so the world lines of photons are at a 45° angle. A pair of world lines for photons moving in opposite directions forms the so-called light cone. Tangible matter moves at less than the speed of light, so these world lines are steep, they lie inside the light cone, and their velocities are all less than 1.0. Of central importance in relativity is the spacetime event, a physical occurrence with a specified location in space and time. Two events define a spacetime interval, s;

$$s = \sqrt{\left(x_2 - x_1\right)^2 - \left(t_2 - t_1\right)^2} \tag{2}$$

which is an invariant quantity in relativity. If s is imaginary, the spacetime interval is timelike and the two events can be causally connected (Einstein causality); i.e., the earlier in time event can be the cause of the later event, and this temporal ordering is preserved across reference frames. If the interval is zero, it is lightlike and lies along the light cone. If s is real, the spacetime interval is spacelike and the temporal ordering of the two events is not preserved across reference frames; however, the left-right ordering is preserved. Figure 1 shows two spacetime diagrams; one with a timelike interval and the other with a spacelike interval.



(a) Timelike Interval; Event 1 is a Possible Cause of Event 2.

(b) Spacelike Interval; According to Einstein Causality, Neither Event can be the Cause of the Other.

Figure 1: Two Spacetime Diagrams.

The intervals and world lines will look different to an observer moving at relativistic velocities; they will lean toward each other on opposite sides of the light cones in what is called a Poincaré rotation. It is the Poincaré rotation that leads to the familiar relativistic effects of length contraction and time dilation.

B. Quantum Mechanics

In quantum physics, individual objects and systems of objects can be (and in general are) in a superposition of states. Once measured, the system "collapses" to just one state. A quantum system or object in a single pure state has a classical value. The superposition of systems consisting of more than one object, where y & z are the particles, |1> & |2> are the states, and a, b, c, & d are the complex weightings, may be separable;

$$\Psi_s = \begin{Bmatrix} ac|1\rangle_y|1\rangle_z + ad|1\rangle_y|2\rangle_z + \\ bc|2\rangle_y|1\rangle_z + bd|2\rangle_y|2\rangle_z \end{Bmatrix} \tag{3}$$

or nonseparable;

$$\Psi_e = |1\rangle_y|2\rangle_z - |2\rangle_y|1\rangle_z \tag{4}$$

in the latter case, objects y and z are said to be entangled. Because of conjugate bases, measurements on entangled objects can exhibit correlations that cannot be explained by the common past of the two objects in question (Bell's inequality).[13] Furthermore, experiments have been done where the individual measurements occur "first" in both reference frames and the correlations are preserved; therefore, Einstein causality cannot explain their correlations either.[14] These are the only two known causes of correlations in classical physics – quantum physics apparently supports a little-understood third form of causality. It is known that simple entanglements cannot support spacelike causality, but it is only a presumption that more sophisticated entanglements cannot do so either.[15]

In the current formulation of quantum mechanics, the measurement of either y or z collapses the state of the system "instantaneously", so for entangled particles, the state of the unmeasured particle must become determined at the "same time" as that of the measured particle. However, "instantaneous" is not an invariant quantity in relativity and two observers will typically disagree on which measurement occurred first, yet measurement was clearly the cause of the change in state. In relativity, spacetime is an integrated whole; however, timelike causality is permitted, while spacelike causality is not – a violation of symmetry that is aesthetically unsatisfying. If spacelike causality were permitted, then "earlier in time" cannot be the discriminator of which event is the cause, since it is not an invariant; however, a different discriminator (a different type of causality) could potentially be consistent with relativity. If a discriminator exists, it means that some observers will see causes propagating backwards in time, and it seems that backwards-in-time causality must lead to temporal paradox, which leads to deep logical problems of consistency.

We are thus left with the following conundrum; permitting spacelike causality between entangled parts of a quantum system can make collapse consistent with relativity, but must of necessity, permit backwards-in-time causality which leads to logical paradox. Denying spacelike causality weakens the symmetry between space and time, and keeps quantum mechanics from being consistent with relativity. This inconsistency has been regarded as benign, because faster-than-light (FTL) phenomena have been regarded as impossible. If FTL is possible, the inconsistency must be resolved. Conversely, if the inconsistency can be resolved, then perhaps FTL phenomena are possible. Any resolution requires a solution to the problems of relativistic consistency, causality, and temporal paradox.

III. Conceptual Development

Our solution then, is to reformulate quantum mechanics so that wave function collapse is relativistically consistent.

A. The 12 Light Second Thought Experiment

We start by examining the spacetime interval, the relativistic invariant between observers.

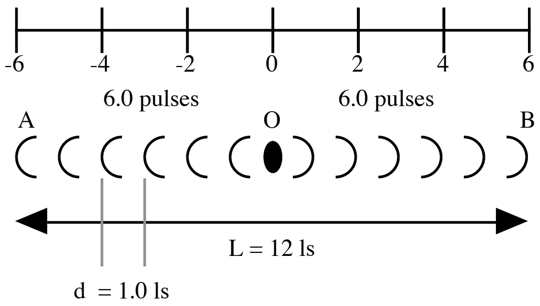


Figure 2: The 12 Light Second Thought Experiment as Seen from the Lab Frame.

Figure 2 shows a simple thought experiment, as viewed from the rest frame, where a central source O emits pairs of photons (or even just pairs of pulses of light) towards two distant detectors, A and B. Let A and B be 12 ls apart, with O exactly halfway between them, emitting a steady sequence of pulses precisely once per second ν_p. Therefore, there are a total of 6 pulses between A and O, and another 6 between O and B, for a total of 12 pulses between A and B at all times. The separation between pulses is just;

$$d = \frac{c}{\nu_p} = \frac{1}{1} = 1.0 \text{ lsec} \tag{5}$$

Figure 3 shows the same thought experiment, but now as viewed from a relativistic frame of reference "U" moving at -0.6c.

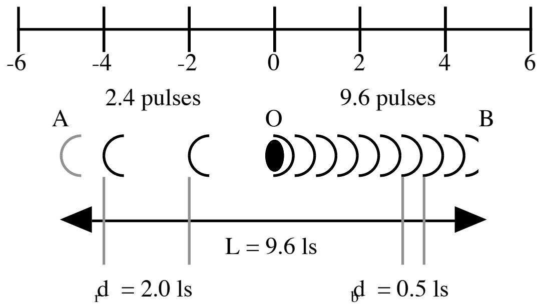


Figure 3: The 12 Light Second Thought Experiment as Seen from a Relativistic Frame Moving at –0.6c.

U observes this scene rather differently than O does. For instance, U sees different distances because of length contraction;

$$\begin{gathered} \gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{1}{\sqrt{1-.6^2}} = 1.25 \\ L' = \frac{L}{\gamma} = \frac{12}{1.25} = 9.6 \text{ lsec} \end{gathered} \tag{6}$$

and the pulse rate is different because of time dilation;

$$t_p' = \gamma t_p = 1.25 \bullet 1 = 1.25 \sec \tag{7}$$

Furthermore, the photons are Doppler shifted, blue towards B;

$$\left(\frac{\nu^{'}}{\nu}\right)_b = \gamma(1-\beta) = 1.25\bullet(1+.6) = 2.0 \tag{8}$$

and red towards A;

$$\left(\frac{\nu^{'}}{\nu}\right)_r = \gamma(1+\beta) = 1.25\bullet(1-.6) = 0.5 \tag{9}$$

U sees the separations between pulses as different too;

$$\begin{aligned} d_b &= d\left(\frac{\nu}{\nu^{'}}\right)_b = \frac{1}{2.0} = 0.5 \text{ lsec} \\ d_r &= d\left(\frac{\nu}{\nu^{'}}\right)_r = \frac{1}{0.5} = 2.0 \text{ lsec} \end{aligned} \tag{10}$$

just the inverse of their Doppler shifts. U doesn't even agree with O on the number of photons between A and O, nor between O and B. The numbers of blue and red shifted photons are;

$$\begin{aligned} n_b &= \frac{L/2}{d_b} = \frac{4.8}{0.5} = 9.6 \\ n_r &= \frac{L/2}{d_r} = \frac{4.8}{2.0} = 2.4 \end{aligned} \tag{11}$$

but remarkably, he does agree on the total between A and B;

$$n_{AO} + n_{OB} = n_r + n_b = 12 \tag{12}$$

B. Proof that the Number of Photons along a Symmetric Interval is Constant

The proof of the constancy of the number of photons along a symmetric spacetime interval is derived here.

Consider two detectors, A and B, separated by a distance L with a dual photon source halfway between at O. O emits pairs of photons toward the detectors at regular intervals. The number of photons between the source and each detector is just the distance from source to detector divided by the separation distance between the blue and red-shifted photons;

$$n_{AB} = \frac{d_b}{\lambda_b} + \frac{d_r}{\lambda_r} \tag{13}$$

In the lab frame this is just;

$$n_{AB} = \frac{L/2}{\lambda_o} + \frac{L/2}{\lambda_o} = \frac{L}{\lambda_o} \tag{14}$$

In the relativistic frame, accounting for the Doppler shifts and length contraction;

$$n^{'}_{AB} = \frac{L/2\gamma}{\lambda_o/\gamma(1+\beta)} + \frac{L/2\gamma}{\lambda_o/\gamma(1-\beta)} \tag{15}$$

Simplifying;

$$
\begin{aligned}
n'_{AB} &= \frac{L}{2\lambda_o}\left[(1+\beta)+(1-\beta)\right] \\
n'_{AB} &= \frac{L}{\lambda_o} = n_{AB}
\end{aligned}
\tag{16}
$$

which is exactly the same as for the rest frame. Therefore, the number of photons between A and B is a relativistic invariant.

The above analysis reveals what U observes in his present. Figure 4 shows the situation he sees as a spacetime diagram with snapshots taken on every pulse. Note the Poincaré rotation of the world lines of the detectors (0.6), the length contraction of the distance between them (9.6 ls), and the time dilation on the pulse frequency (1.25 s). Therefore, from U's point of view the pulses of light are emitted every 1.25 seconds. A snapshot of the location of every pulse (labeled from zero) as each new pulse is emitted is shown. The red and blue shifts are clearly evident as the distance between the pulses. The spacelike interval in gray is the Symmetric Spacetime Interval; it connects the detection events of the first pulse.

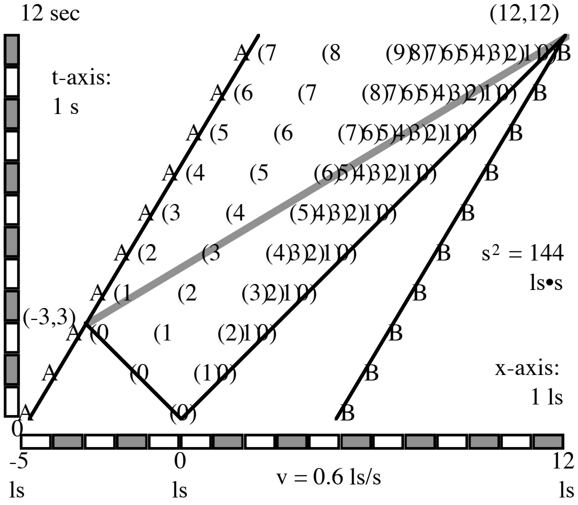


Figure 4: Spacetime Diagram of the 12 Light Second Though Experiment with Snapshots Taken on Every Pulse as Seen by the Relativistic Observer, U.

Zero coordinates are at the emission of the first pulse (0) at the location of the source. Successive emissions of light pulses follow the implied world line of the source, which stays halfway between A and B. When the first pulse is finally detected at B, U observes a total of 12 pulses between A and B. Note that the detection of pulse 0 at A occurs much earlier than its detection at B. From U's point of view, A has been racing towards pulse 0, closing the distance, while B has been racing away from it, opening up the distance. Given that he measures the speed of light to still be *c*, it is obvious that A will receive its pulse prior to B.

To determine the spacetime coordinates of these events, all we need are the Lorentz transformations between reference frames. The spacetime coordinates of the first detection of pulses in the rest frame are (-6,6) at A and (6,6) at B. Therefore, U observes the first detection at A at spacetime coordinates;

$$
\begin{aligned}
x_A &= \gamma(x-\beta t) = 1.25\big(-6-(-.6)\bullet 6\big) = -3.0 \text{ lsec} \\
t_A &= \gamma(t-\beta x) = 1.25\big(6-(-.6)\bullet(-6)\big) = 3.0 \text{ sec}
\end{aligned}
\tag{17}
$$

and the first detection at B at spacetime coordinates;

$$
\begin{aligned}
x_B &= \gamma(x-\beta t) = 1.25\big(6-(-.6)\bullet 6\big) = 12.0 \text{ lsec} \\
t_B &= \gamma(t-\beta x) = 1.25\big(6-(-.6)\bullet 6\big) = 12.0 \text{ sec}
\end{aligned}
\tag{18}
$$

The spacetime interval connecting these two events is of course the same in both reference frames;

$$\begin{aligned}
s^2 &= (\Delta x)^2 - (\Delta t)^2 \\
s_O{}^2 &= (6-(-6))^2 - (6-6)^2 = 144 \text{ lsec} \bullet \text{sec} \\
s_U{}^2 &= (12-(-3))^2 - (12-3)^2 = 144 \text{ lsec} \bullet \text{sec}
\end{aligned} \tag{19}$$

This spacetime interval is shown as the gray line. Since the value of *s* is a real number, it represents a spacelike connection between A and B. Since the source remains at the center of this interval, we will call it a symmetric spacetime interval.

To see how this helps, we shall redraw Figure 4 without the details (Figure 5). While Figure 4 shows the standard use of a spacetime diagram, it gives undue emphasis to the passage of time over the extent of space. This is implicit in the sequence of snapshots of pulse locations on every time step. Instead, in Figure 5 we take a single snapshot, not along a line of simultaneity, but rather along the symmetric spacetime interval itself. We choose to take it just as pulse 6 is emitted.

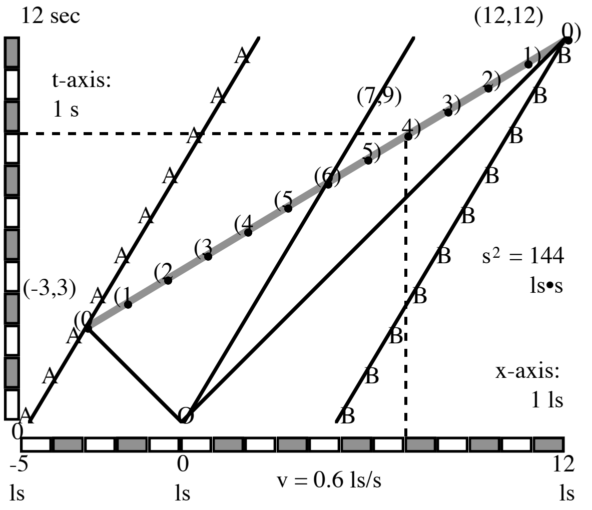


Figure 5: Spacetime Diagram of the 12 Light Second Though Experiment with a Single Snapshot Taken Along the Symmetric Spacetime Interval.

As can be readily seen, the pulses space themselves out evenly along the symmetric interval, 6 between A and O, and 6 between O and B. From this diagram, their conventional spacetime coordinates can be derived for any observer, and any observer can derive their locations along the symmetric spacetime interval from their own observations.

To demonstrate this, consider pulse 4 moving toward B just when the 6th pulse is being emitted. In the rest frame, its spacetime coordinates are (2,6). Therefore, in U's frame;

$$\begin{aligned}
x_{4B} &= \gamma(x - \beta t) = 1.25(2-(-.6)\bullet 6) = 7.0 \text{ lsec} \\
t_{4B} &= \gamma(t - \beta x) = 1.25(6-(-.6)\bullet 2) = 9.0 \text{ sec}
\end{aligned} \tag{20}$$

which puts the event right on the symmetric spacetime interval (shown with the dotted lines).

This leads then, to our Collapse Conjecture:

> *The wave function collapses instantaneously, not in time, but along the symmetric spacetime intervals that connect the entangled parts of the quantum system.*

Since all observers can derive the correct snapshot of events along the symmetric spacetime interval, they can all agree on which measurement collapses the wave function. It is the one closer to the source as measured along the symmetric spacetime interval. Let observer B move to B' just a little ways toward O. Even though U sees A receiving photons earlier in proper time, he computes that B got to them first along the symmetric interval. He (and all other relativistic observers), conclude that it is B's measurement that caused the wave function to collapse regardless of whether it occurs before or after the measurement at A. Therefore, all observers agree on their predictions of the experimental results, and relativity is preserved.

IV. Conclusion

A thought experiment was examined that provides a hint as to how one might specify wave function collapse in a way that is consistent with relativity. This thought experiment consists of a central source of regular photonic pulses half way between two detectors 12 light seconds apart. The only relativistic invariant in this thought experiment was the total number of pulses between the two detectors. Every other aspect, including the number of pulses between the source and each detector, is frame dependent. However, if each pulse is plotted in a spacetime diagram along symmetric spacetime intervals instead of along planes of simultaneity, then the number of pulses between source and detector along this interval is unchanged and all observers can agree on this. This observation leads to a Collapse Conjecture; that collapse of the wave function occurs along symmetric spacetime intervals. If correct, then quantum mechanics can be made consistent with relativity, and both FTL phenomena and backwards-in-time causality become conceivable.

Acknowledgments

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