A Proposed Test of the Local Causality of Spacetime

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(Dated: 10 July, 2005 (revised July 2008))

A theory governing the metric and matter fields in spacetime is \textit{locally causal}\ if the probability distribution for the fields in any region is determined solely by physical data in the region’s past, i.e. it is independent of events at space-like separated points. General relativity is manifestly locally causal, since the fields in a region are completely determined by physical data in its past. It is natural to ask whether other possible theories in which the fundamental description of space-time is classical and geometric — for instance, hypothetical theories which stochastically couple a classical spacetime geometry to a quantum field theory of matter — might also be locally causal.

A quantum theory of gravity, on the other hand, should allow the creation of spacetimes which violate local causality at the macroscopic level. This paper describes an experiment to test the local causality of spacetime, and hence to test whether or not gravity behaves as quantum theories of gravity suggest, in this respect. The experiment will either produce direct evidence that the gravitational field is not locally causal, and thus weak confirmation of quantum gravity, or else identify a definite limit to the domain of validity of quantum theory.

I. INTRODUCTION

Abner Shimony’s many profound contributions to theoretical physics have greatly deepened our understanding of the nature of physical reality. This paper is devoted to subjects on which Abner’s work is particularly celebrated, namely the theoretical definition and understanding of locality and local causality and the ways in which these properties can be experimentally tested in Nature.

General relativity and quantum theory are both impressively confirmed within their domains of validity, but are, of course, mutually inconsistent. Despite decades of research, there are still deep conceptual problems in formulating and interpreting quantum gravity theories: we don’t have a fully consistent quantum theory of gravity, nor do we know precisely how we would make sense of one if we did.

One initially natural-seeming possibility is combine general relativity and quantum theory in a semi-classical theory that couples the metric to the expectation of the stress-energy tensor via the Einstein equations \cite{1, 2, 3}. However, the problems with this suggestion are well-known. In particular, if the unitary quantum evolution of the matter fields is universal, then it would imply that the complete state of the matter fields in the current cosmological era ought to be a superposition of many (in fact, presumably an infinite continuum of) macroscopically distinct cosmologies. A semi-classical theory of gravity coupled to these matter fields would imply, inter alia, that the gravitational fields in our solar system and galaxy correspond to the weighted average over all possible matter distributions, rather than the actual distribution we observe. This would be grossly inconsistent with the observed data. It is also contradicted by terrestrial experiment \cite{5}.

One might try to rescue the hypothesis by supposing, instead, that unitary quantum evolution is not universal and that the metric couples to the expectation of the stress tensor of non-unitarily evolving matter fields. Obviously, this requires some explicit alternative to unitary quantum theory, such as a dynamical collapse model \cite{4}. It is not presently known whether such a theory can be combined with a metric theory of gravity in a generally covariant way. An interesting related possibility is that a classical metric might be coupled to quantum matter via stochastic equations \cite{6, 7}; however, no consistent and generally covariant theory of this type has yet been developed either.

I take here a possibly controversial stance. It seems to me that, because we haven’t made any really certain progress in understanding how general relativity and quantum theory are unified, we should take more seriously the possibility that the answer might take a rather different form from anything we’ve yet considered. On this view, even apparently rather basic and solid intuitions are worth questioning: if an intuition can be tested experimentally, and we can unearth a sliver of motivation for speculating that it might possibly fail, we should test it.

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II. GRAVITY, LOCAL CAUSALITY AND REALITY

A. Sketch of experiment

Before getting into technicalities, let me summarise the proposed experiment.

We start with a standard Bell experiment, carried out on an entangled pair of elementary particles, in which the measurement choices and measurement outcomes on both wings are spacelike separated.

The choices and outcomes are then amplified to produce distinct local gravitational fields, on both wings. This amplification can be carried out by any practical means, for example by recording the choice and outcome on each wing in an electronic signal, and feeding this signal into a circuit connected to a device that moves a macroscopic quantity of matter to one of four possible macroscopically distinct configurations. Note that this amplification need not necessarily maintain quantum coherence.

These gravitational fields produced are then directly measured, by observing their influence on small masses in the relevant region, for example by Cavendish experiments. This is done quickly enough that the region in which the amplified gravitational field on wing $A$ is measured, is spacelike separated from the region $B_1$ in which the Bell measurement choice on wing $B$ was made, and similarly $A_1$ is spacelike separated from $B_2$. The results of these measurements are recorded and compared, to check whether they display the correlations which quantum theory predicts for the relevant Bell experiment.

B. Standard expectations and why they should be tested

Almost all theoretical physicists would, I think, fairly confidently predict that any experiment of this type will indeed produce exactly the same non-local correlations as those observed in standard Bell experiments. What I want to argue is that there are some coherent – although of course speculative – theoretical ideas which would imply a different outcome, and that these provide scientific motivation enough to justify doing the experiment. To justify this, one needn’t argue that the standard expectation is likely to be wrong (indeed, I think it’s very likely right). One need only argue that there are some alternative lines of thought which have some non-negligible probability of being closer to the truth.\footnote{Obviously, there’s no precise way to quantify how likely a surprising outcome must be to make an experiment worth doing. But to give a rough illustration, a probability of $10^{-5}$ of a surprising answer here would seem to me more than sufficient justification for carrying out an experiment that requires relatively modest resources.}

1. One possible motivation

One view of quantum theory, advocated by Bell and taken seriously by many, is that the theory is incomplete without some mathematical account of “beables” or “elements of reality” or “real events” — the quantities which, ultimately, define the sample space for quantum probabilities, i.e. which are the things which quantum probabilities are probabilities of. Most attempts to resolve this problem postulate that the beables are at least approximately localised in space-time.

Now, a standard Bell experiment ensures that the particles in the two wings enter detectors at space-like separated points, in a sense which we can justify intuitively within the quantum path integral formalism (and more precisely in some interpretations of quantum theory). But this does not ensure that any beables or real events associated with the measurements are necessarily space-like separated. For instance, if the beables or real events are associated with the collapse of the wavefunction, and if this collapse takes place only when a measurement result is amplified to macroscopic degrees of freedom, then the relevant question is whether these amplification processes on the two wings take place in space-like separated regions.

Consider now:

Assumption I Bell experiments appear to produce non-local correlations, consistent with the predictions of quantum theory, when the relevant beables are time-like separated (i.e. when there is time for information about the first relevant real event to propagate to the second), but not when they are space-like separated.

Assumption II in all Bell experiments to date, the relevant beables have indeed been time-like separated.

If both assumptions were correct, the apparent demonstration of non-locality in Bell experiments to date would be an artefact. The assumptions may, however, at first sight seem purely conspiratorial and completely lacking in...
theoretical motivation. Surprisingly, though, it is possible to sketch an alternative version of quantum theory which appears to be internally consistent, is not evidently refuted by the data, and implies both I and II [16].

Now, let us extend this speculation further. It is sometimes suggested that the solution to the quantum measurement problem is tied up with the link between quantum theory and gravity. Consider

**Assumption III** to ensure that a real event (selecting one outcome and one of the possible fields) takes place requires a measurement event whose different possible outcomes create measurably distinct gravitational fields.

If (I-III) were all true, the gravitational Bell experiment described above would indeed produce a different outcome from standard Bell experiments. To be sure, taking this possibility seriously requires one to take seriously three non-standard hypotheses. From the perspective of a firm believer in the universality of unitary quantum evolution and in quantum gravity, each of these hypotheses might be seen as quite implausible. It is worth stressing, though, that none of these hypotheses is an ad hoc invention, produced specifically for the purposes of the present discussion. Each of them has an independent motivation:

(I) results from a nonstandard but interesting way of trying to reconcile beable quantum theory and special relativity.

(II) becomes quite plausible if one takes seriously the idea of wave function collapse as a real physical process defined by explicit equations. Models, such as those defined by Ghirardi-Rimini-Weber-Pearle [4], which have this feature and which are consistent with other experiments tend to imply that collapse only takes place quickly (on a scale of \(\mu s\)) as the measurement result becomes amplified to a macroscopic number of particles (of order \(10^6\)). In other words, according to these models, collapse need not take place at all quickly in the photo-detectors or electronic circuits used in standard Bell experiments. Hence, it need not necessarily be the case that there are spacelike separated collapses in the two wings of such experiments: as far as I am aware, in all Bell experiments to date, reasonable choices of the GRWP collapse parameters would imply that no significant collapse occurs until later, after the data have been brought together and stored.

(III) is a widely considered, if non-standard, intuition about the possible form of a theory unifying quantum theory and gravity. It is also related to another motivation for the proposed experiment, to which we now turn.

2. **A second possible motivation**

Perhaps quantum theory and general relativity are unified, not via a quantum theory of gravity, but by some theory which somehow combines a classical description of a space-time manifold with a metric together with a quantum description of matter fields. Any such theory would presumably have to have a probabilistic law for the metric, since it seems essentially impossible to reconcile a deterministic metric evolution law with quantum indeterminism. That is, a fundamental law of nature selects a 4-geometry drawn from a probability distribution defined by some set of principles, which also define the evolution of matter. Also, to be consistent with observation to date, these principles must tend to produce spacetimes approximately described by the Einstein equations on large scales.

Granted, we don’t even know whether there is a consistent generally covariant theory of this form. Before dismissing the entire line of thought as thus presently unworthy of attention, though, one should remember that we don’t know if there’s a consistent quantum theory of gravity either. The idea of a stochastic hybrid theory, with a classical manifold coupled to quantum matter, has some attraction, despite its difficulties, as it suggests a possible way around some of the conceptual problems that arise when trying to make sense of a quantum theory of spacetime.

Suppose then that we agree to take this idea as serious enough to be worth contemplating exploring a little. Given the central role of causality in general relativity, it seems reasonably natural to consider the class of metric theories whose axioms require the metric encode some version of Einstein causality. Such theories would preclude the gravitational field exhibiting the type of non-local correlations that quantum theory predicts for matter fields — and so would have surprising and counter-intuitive features. Once again, it needs to be stressed that we neither want nor need to argue that this is the likeliest possibility, only that it has some theoretical motivation and has testable consequences. In the next section we define a local causality principle adapted to non-deterministic metric theories, and examine its consequences.

III. **LOCAL CAUSALITY FOR METRIC THEORIES: TECHNICALITIES**

One key feature on which various theories and proto-theories of gravity differ is the causal structure of the classical or quasi-classical space-time which emerges. Bell’s definition of local causality [8] applies to physical operations taking place in a fixed Minkowski space-time. As Bell famously showed, quantum theory is not locally causal. The possibility of adapting the definition to apply to theories with a variable space-time geometry (or a variable structure of some
sort from which space-time geometry is intended to emerge) has been considered by Rideout and Sorkin \[10\] and Henson \[11\], among others. The following definition is a modified version of one suggested by Dowker \[12\].

Define a \textit{past region} in a metric spacetime to be a region which contains its own causal past, and the \textit{domain of dependence} of a region $R$ in a spacetime $S$ to be the set of points $p$ such that every endless past causal curve through $p$ intersects $R$.

Suppose that we have identified a specified past region of spacetime $\Lambda$, with specified metric and matter fields, and let $\kappa$ be any fixed region with specified metric and matter fields.

Let $\Lambda'$ be another past region, again with specified metric and matter fields. (In the cases we are most interested in, $\Lambda \cap \Lambda'$ will be non-empty, and thus necessarily also a past region.)

Define

$$\text{Prob}(\kappa | \Lambda \perp \Lambda')$$

to be the probability that the domain of dependence of $\Lambda$ will be isometric to $\kappa$, given that $\Lambda \cup \Lambda'$ form part of space-time, and given that the domains of dependence of $\Lambda$ and $\Lambda'$ are space-like separated regions.

Let $\kappa'$ be another fixed region of spacetime with specified metric and matter fields.

Define

$$\text{Prob}(\kappa | \Lambda \perp \Lambda'; \kappa')$$

to be the probability that the domain of dependence of $\Lambda$ will be isometric to $\kappa$, given that $\Lambda \cup \Lambda'$ form part of space-time, that the domain of dependence of $\Lambda'$ is isometric to $\kappa'$, and that the domains of dependence of $\Lambda$ and $\Lambda'$ are space-like separated.

We say a metric theory of space-time is \textit{locally causal} if for all such $\Lambda, \Lambda', \kappa$ and $\kappa'$ the relevant conditional probabilities are defined by the theory and satisfy

$$\text{Prob}(\kappa | \Lambda \perp \Lambda') = \text{Prob}(\kappa | \Lambda \perp \Lambda'; \kappa').$$

**IV. TESTING LOCAL CAUSALITY OF METRIC THEORIES**

By definition, general relativity is locally causal, since the metric and matter fields in the domain of dependence $\kappa$ of $\Lambda$ are completely determined by those in $\Lambda$ via the Einstein equations and the equations of motion. If we neglect (or believe we can somehow circumvent) the fact that quantum theory is not locally causal (in Bell’s original sense), it would also seem a natural hypothesis that any fundamental stochastic theory of space-time, or any fundamental stochastic theory coupling a classical metric to quantum matter, should be locally causal. One reason for considering this possibility is that, while it admittedly seems hard to see how to frame closed form generally covariant equations for any theory of this type, it seems particularly hard to see how to frame such equations for a non-locally causal theory. If we allow the evolution of the metric, and hence the causal structure, at any given point to depend on events at space-like separated points, it seems difficult to maintain any notion of causality, or to find any other ordering principle which ensures that equations have a consistent solution.

However, we should \textit{not} expect a quasiclassical space-time emerging from a quantum theory of gravity to be locally causal, for the following reason. Consider a standard Bell experiment carried out on two photons in a polarization singlet state. For definiteness, let us say that the two possible choices of measurement on either wing are made by local quantum random number generators, and are chosen to produce a maximal violation of the CHSH inequality \[14\].

We suppose that the two wings of the experiment, $A$ and $B$, are fairly widely separated. Now suppose that the measurement choices and outcomes obtained by the detectors in each wing mechanically determine one of four macroscopically distinct configurations. To be definite, let us suppose that the Bell experiment is coupled to local Cavendish experiments on each wing, in such a way that each of the two settings and two possible measurement outcomes on any given wing causes one of four different configurations of lead spheres – configurations which we know would, if the experiment were performed in isolation, produce one of four macroscopically and testable distinct local gravitational fields. Suppose also that the Cavendish experiments are arranged so that the local gravitational fields are quickly tested, using small masses on a torsional balance in the usual way. The separation of the two wings is such that the gravitational field test on either wing can be completed in a region space-like separated from the region in which the photon on the other wing is detected.

A quantum theory of gravity should predict that the superposition of quantum states in the singlet couples to the detectors in either wing to produce entangled superpositions of detector states, and thence entangled superpositions that include the states of the Cavendish experiments, and finally entangled superpositions of states that include the
states of the local gravitational field. Extrapolating any of the standard interpretations of quantum theory to this situation, we should expect to see precisely the same joint probabilities for the possible values of the gravitational fields in each wing’s experiments as we should for the corresponding outcomes in the original Bell experiment. As Bell [13] and Clauser et al. [14] showed, provided we make the standard and natural (although not logically necessary) assumption that the measurement choices in each wing are effectively independent from the variables determining the outcome in the other wing, these joint probabilities violate local causality in Bell’s original sense.

We now make the further natural assumption that when, as in our proposed experiment, the measurement choices are made by the outputs of the local quantum random number generators, the choices made on each wing are independent of the metric and matter fields in the past of the measurement region on the other wing. Then, if is the region immediately surrounding the measurement choice and outcome in one wing of the experiment, the corresponding region for the other wing, the past of and the past of we have

\[ \text{Prob}(\kappa|\Lambda \perp \Lambda') \neq \text{Prob}(\kappa|\Lambda \perp \Lambda'; \kappa'). \]

Does such an experiment even need to be performed, given the impressive experimental confirmation of quantum theory in Bell experiments to date? In my view, it does.

Taking the Bell experiments to date at face value – that is, neglecting any remaining possible loopholes in their interpretation – they confirm predictions of quantum theory as a theory of matter fields when gravity is negligible. Specifically, they confirm predictions of quantum theory for experiments involving matter states when those states do not produce significant superpositions of macroscopically distinct gravitational fields.

The question at issue here is precisely how far quantum theory’s domain of validity extends. When it comes to predicting whether or not the metric is locally causal, there is a genuine tension between intuitions extrapolated from quantum theory and those which one might extrapolate from general relativity. Examining and testing this question seems a very natural development of the line of questioning begun by Einstein, Podolsky and Rosen [15] and continued by Bell [14].

Standard Bell experiments test the conflicting predictions implied by quantum theory and by EPR’s intuitions about the properties of elements of physical reality. EPR’s intuitions can be motivated by a combination of classical mechanics (which suggests that the notion of an element of physical reality is a sensible one) and special relativity (which suggests the hypothesis that an element of physical reality has the locality properties ascribed to it by EPR). In the experiment considered here, we again have a tension between intuitions drawn from two successful theories – in this case quantum theory and general relativity.

V. POSSIBLE COUNTERARGUMENTS

But isn’t this a crazy line of thought? How could the correlations obtained from Bell experiments possibly be altered by coupling classical devices to the detector outputs? Is the Bell experiment supposed to know that the classical devices are waiting for the data, and change its result because of that? Or, even more weirdly, is the gravitational field in each wing supposed to know that the classical lumps of matter are being moved around as the result of a Bell experiment, and change its behaviour — violating the predictions of Newtonian gravity as well as general relativity within a local region — because of that?

I find it hard to accept the full rhetorical force of such objections, natural though they are. Nature has a capacity to surprise, and surprising experimental results sometimes have theoretical explanations which occurred to nobody beforehand. The “common sense” view just expressed implicitly assumes, among other things, first, that the outcomes of detector measurements in Bell experiments constitute local, macroscopic events that in some physically meaningful sense are definite and irreversible once they occur, and second, that the local gravitational fields respond instantly to these events in the same way as they would if they resulted from isolated experiments on unentangled states. These plausible propositions may very well be given precise meaning and completely justified by some deeper understanding of quantum theory and gravity than we currently have. Even if they don’t turn out to have a precise and literal justification — for instance, because the fundamental theory contains no definition of definite local events — it seems very plausible that we nonetheless reach the right conclusion about Bell experiments and gravity by reasoning as though they were true. However, none of this is completely beyond reasonable doubt in the light of our current knowledge.

As we’ve already noted, there’s some independent motivation for exploring variants of quantum theory in which definite local events are defined but in which photo-detector measurement outcomes aren’t, so to speak, macroscopic enough to constitute such events.

There’s also some motivation for exploring theories of quantum theory and gravity in which a probabilistic law defines a locally causal classical gravitational field. Standard reductionist reasoning would break down in such a
theory — as it does, though in a different way, in quantum theory — and the behaviour of the gravitational field in one wing of a Bell experiment would indeed depend on the configurations of both wings of the experiment.

What, then, are the conceivable experimental outcomes, and what would they imply? One is that the violations of local causality predicted by quantum theory, and to be expected if some quantum theory of gravity holds true, are indeed observed. This would demonstrate that space-time is indeed not locally causal, as predicted by quantum theories of gravity, but not necessarily by other hypotheses about the unification of quantum theory and gravity. It would thus provide at least some slight experimental evidence in favour of the quantization of the gravitational field. It might be argued, pace Page and Geilker [5], that this would be the first such experimental evidence, since, as noted above, Page and Geilker’s experiment tested a version of semi-classical gravity already excluded by astronomical and cosmological observation.

A second logical possibility is that the violations of local causality predicted by quantum theory fail to be observed at all in this particular extension of the Bell experiment: i.e., that the measurement results obtained from the detectors fail to violate the CHSH inequality. This would imply that quantum theory fails to describe correctly the results of the Bell experiment embedded within this particular experimental configuration, and so would imply a definite limit to the domain of validity of quantum theory.

A third logical possibility is that the Bell experiment correlations follow the predictions of quantum theory, but that the Cavendish experiments show gravitational fields which do not correspond to the test mass configurations in the expected way (or at least do not do so until a signal has had time to travel from one wing to the other). This would suggest the coexistence of a quantum theory of matter with some classical theory of gravity which respects local causality, but which has the surprising property that classical gravitational fields do not always couple to macroscopic matter in the way suggested by general relativity.

In summary: although our present understanding of physics leads us to expect the first outcome, the point at issue seems sufficiently fundamental, and our present understanding of gravity sufficiently limited, that it would be very interesting and worthwhile to carry out experiments capable of discriminating between some (and of course, ideally, all) of the possible outcomes outlined above.

Acknowledgments

I am particularly indebted to Fay Dowker for very helpful comments on an earlier draft, for inspiring the definition of local causality used in the present version of the paper, and for many thoughtful criticisms. I am also very grateful to Nicolas Gisin, Valerio Scarani, Christoph Simon and Gregor Weihs for valuable discussions on various criteria for gravitationally induced collapse and experimental tests. Warm thanks too to Harvey Brown, Jeremy Butterfield, Robert Helling, Graeme Mitchison, Roger Penrose and Rainer Plaga for some very helpful comments. Last but by no means least, I would very much like to thank Abner for his characteristically kind and warm encouragement to pursue this idea.

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