Causal Quantum Theory and the Collapse Locality Loophole

Adrian Kent

Centre for Quantum Computation, Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Wilberforce Road, Cambridge, CB3 OWA, U.K.

(Dated: April 2002, revised March 2005)

Causal quantum theory is an umbrella term for ordinary quantum theory modified by two hypotheses: state vector reduction is a well-defined process, and strict local causality applies. The first of these holds in some versions of Copenhagen quantum theory and need not necessarily imply practically testable deviations from ordinary quantum theory. The second implies that measurement events which are spacelike separated have no non-local correlations. To test this prediction, which sharply differs from standard quantum theory, requires a precise definition of state vector reduction.

Formally speaking, any precise version of causal quantum theory defines a local hidden variable theory. However, causal quantum theory is most naturally seen as a variant of standard quantum theory. For that reason it seems a more serious rival to standard quantum theory than local hidden variable models relying on the locality or detector efficiency loopholes.

Some plausible versions of causal quantum theory are not refuted by any Bell experiments to date, nor is it evident that they are inconsistent with other experiments. They evade refutation via a neglected loophole in Bell experiments — the collapse locality loophole — which exists because of the possible time lag between a particle entering a measurement device and a collapse taking place. Fairly definitive tests of causal versus standard quantum theory could be made by observing entangled particles separated by \( \approx 0.1 \) light seconds.

I. INTRODUCTION

The subtle relationship between quantum theory and relativity raises questions fundamental to our understanding of nature. Entanglement was first identified as a potential source of tension between the two theories by Einstein, Podolsky and Rosen [1], while Bell’s work [2, 3] in the early 1960s made precise the sense in which classical intuitions based on the principles of special relativity conflict with quantum theory. Theoretical and experimental investigations have continued ever since.

After much careful analysis, a strong consensus emerged and has held firm over the last two decades. On this consensus view, insofar as special relativity inspires us to consider alternatives to standard quantum theory, those alternatives are characterised by Bell’s definition of local hidden variable theories. However, the experimental evidence very strongly favours quantum theory against local hidden variable theories. The hypothesis of local hidden variables can only be maintained by supposing that a local hidden variable theory somehow exploits one or more loopholes arising from our inability to construct perfect experimental tests.

Only two loopholes — the detector efficiency and locality loopholes — have generally been considered worth serious attention, and even they are not generally thought to be plausible mechanisms for reconciling local hidden variables with experiment. Indeed, one recent experiment [4] has succeeded in closing the detector efficiency loophole. And, although in principle the locality loophole can never be completely closed, it has been substantially closed by another recent experiment [5], which implies that local hidden variable theories which use the locality loophole would have to correlate the states of quantum random number generators with those of the entangled particles being measured.

Admittedly, no experiment to date has succeeded in simultaneously closing both loopholes, and there is a serious case for attempting still more stringent experiments (see e.g. [6, 7] for discussions). Nonetheless, the general consensus is that a local hidden variable mechanism which exploits either or both loopholes in a way which would not have shown up in experiments to date would require a theory so perversely conspiratorial as to be almost incredible.

However, one or two gaps in this analysis have lately been noted. Altering standard causation, either by directly postulating reverse causation [8] or by considering statistically based configuration space models [9], allows alternatives to local hidden variable theories that are consistent with relativity and not excluded by Bell’s theorem. Also, a previously neglected loophole in Bell experiments — the memory loophole — has lately been identified [10, 11]. However, no way of actually reproducing quantum predictions within non-standard causation models has been identified.

\(^*\)Electronic address: A.P.A.Kent@damtp.cam.ac.uk

\(^\dagger\)Affiliation when paper first drafted: Hewlett-Packard Laboratories, Filton Road, Stoke Gifford, Bristol, BS34 8QZ, U.K.
apart from ad hoc constructions that again appear perversely conspiratorial. As for the memory loophole, its potential effect, though real, is negligible when large numbers of entangled particle pairs are tested. Moreover, analysing the experimental data in a nonstandard but natural way can eliminate the effect entirely. Thus, though the memory loophole is an interesting subtlety, it does not per se constitute a serious challenge to the standard interpretation of Bell experiments. Its late discovery should, though, at least disturb the general confidence that absolutely everything was sorted out by Bell’s and Clauser et al.’s analyses and subsequent experiments (for example).

Non-standard causation models, too, have at least one virtue: they illustrate that considering new physical principles can suggest new ways of thinking about non-local correlations. One can too easily fall into the habit of caricaturing local hidden variable theories as involving small classical particles flying from source to measuring device, carrying tables of instructions telling them what to do when measured. For theories that exploit the locality loophole, the caricature version has little signalling devices sitting in the experimental apparatus, sending signals to something like a radio receiver attached to the particles, to inform them of prematurely made random choices. When the detector efficiency loophole is used, the caricature version equips the particles with probes which identify the detector, calculate its efficiency, and adjust the instructions tables accordingly. These pictures are indeed fantastically conspiratorial. But nothing in the mathematical analysis of non-local correlations implies that hidden variables theories have to work like this. Despite their admitted defects, proposals like reverse causation or statistical configuration models defined by local weightings do at least illustrate the possibility of a different sort of story.

II. CAUSAL QUANTUM THEORY AND THE COLLAPSE LOCALITY LOOPTHOLE

This paper considers another gap in the analysis of entanglement and non-local correlations — one which seems more serious than any of the loopholes previously considered. This is the possibility that state reduction is a well-defined physical process, localised in space-time, and that, once this definition is taken into account, strict local causality (in Bell’s sense) holds. Causal quantum theory is a useful umbrella term for the class of theories that arise in this way, modulo various possible definitions of state reduction.

The strict local causality hypothesis implies in particular that, if \( P_{\text{causal qt}}(A|A_P; \psi(-\infty)) \) is the probability of a state reduction \( A \) taking place at a point \( P \) in space-time, given all the state reduction events in the past light cone \( A_P \) of \( P \) and the initial state at \( t = -\infty \), and if \( B \) is any collection of state reduction events taking place at points spacelike separated from \( P \), then

\[
P_{\text{causal qt}}(A|A_P; \psi(-\infty)) = P_{\text{causal qt}}(A|A_P; \psi(-\infty); B). \tag{1}
\]

In other words, and contrary to standard quantum theory, state reduction involves no non-local correlations. On the other hand, local state reduction probabilities themselves, conditioned on past light cone events, should agree with those predicted by standard quantum theory, after perhaps allowing for some modification (which we will assume to be slight in the cases we consider here) arising from introducing a precise definition of state reduction:

\[
P_{\text{causal qt}}(A|A_P; \psi(-\infty)) \approx P_{\text{standard qt}}(A|A_P; \psi(-\infty)). \tag{2}
\]

Consider for example two widely separated particles prepared in a state close to (but, for reasons which will become apparent later, not precisely equal to) a singlet:

\[
|\psi\rangle \approx \frac{1}{\sqrt{2}} (|0\rangle_A|1\rangle_B - |1\rangle_A|0\rangle_B). \tag{3}
\]

As we will discuss in more detail below, according to causal quantum theory, if the two particles are measured in the \(|0\rangle, |1\rangle\) basis, and if the state reductions corresponding to the measurements are completed at space-like separations, the joint outcome probabilities are

\[
P_{\text{causal qt}}(0_A, 0_B) \approx P_{\text{causal qt}}(0_A, 1_B) \approx P_{\text{causal qt}}(1_A, 0_B) \approx P_{\text{causal qt}}(1_A, 1_B) \approx 1/4, \tag{4}
\]

whereas

\[
P_{\text{standard qt}}(0_A, 1_B) \approx P_{\text{standard qt}}(1_A, 0_B) \approx 1/2, \quad P_{\text{standard qt}}(0_A, 0_B) \approx P_{\text{standard qt}}(1_A, 1_B) \approx 0. \tag{5}
\]

It seems that this gross discrepancy should show up immediately in experiments on entangled particles: there is no need even to vary the measurement choices at \( A \) and \( B \) in order to see the difference between the two theories. Given the impressive confirmation of quantum theory in Bell experiments to date, what is the point in considering causal quantum theory?
The loophole is in the italicized qualification: if the state reductions corresponding to the measurements are completed at space-like separations. We can’t be sure that state reductions occur at space-like separations, without knowing precisely when they take place — in other words, without a precise theory of state reduction. And if the state reduction at $A$ in fact takes place in the past light cone of that at $B$, or vice versa, then

$$P_{\text{causal qt}}(0_A, 1_B) \approx P_{\text{causal qt}}(1_A, 0_B) \approx 1/2, \quad P_{\text{causal qt}}(0_A, 0_B) \approx P_{\text{causal qt}}(1_A, 1_B) \approx 0.$$  

(6)

in agreement with standard quantum theory. More generally, causal quantum theory will agree with standard quantum theory in any Bell experiment, so long as the state reductions for particles $A$ and $B$ in any given pair are timelike separated.

It is worth emphasizing that the loophole causal quantum theory exploits is quite distinct from the locality loophole, mentioned above. The locality loophole relies on the fact that it is difficult to arrange a Bell experiment so that the measurements at $A$ and $B$ are chosen randomly and independently for each pair, in such a way that the random choices are themselves made at points which are space-like separated from one another and from the point at which the measured singlet is created. As in principle one could imagine that a common source far in the past correlates hidden variables determining the particles’ actions with those determining the outcomes produced by any randomiser, it seems impossible to close the locality loophole completely. However, one can aim to close it beyond any reasonable doubt, and much experimental ingenuity has been devoted to doing so, from the famous experiments of Aspect et al. [15] utilising the quasi-randomness of high frequency waves, to recent experiments using fast quantum random number generators [16] or passive quantum switches [16].

The loophole considered here also involves locality, but it involves the problem of ensuring that the state reduction events associated with measurements are spacelike separated, rather than ensuring that randomly made measurement choices are. Let us call it the collapse locality loophole.

III. IS CAUSAL QUANTUM THEORY SELF-CONSISTENT?

The basic features of causal quantum theory are best illustrated in the idealised model of quantum states and measurements, commonly used in quantum information theory, in which subsystems are treated as effectively pointlike and measurements are carried out at a definite point in space and time. To simplify the notation further, we can also assume that the subsystems are stationary relative to one another, and that the hamiltonian is zero. Since the predictions of causal quantum theory depend on past events, we need to specify a state history as well as a state. We also assume that the subsystems are localised. However, to simplify the following discussion, we will suppose that the only relevant state reductions here correspond to measurements of the internal degrees of freedom, and we will assume that the subsystems remain in essentially the same locations throughout: in particular, we will ignore the evolution and eventual spreading of their spatial wave functions. We thus now suppose that we have some definite theory of state reduction which tells us precisely when a measurement takes place on any subsystem, and characterises the nature of the measurement, and that the theory tells us that no other reductions are relevant for the system in question.

The theory’s prescriptions take the following form: a state reduction takes place at $(x_i, t_i)$, defined by a set of operators $\{A_j\}$ which obey

$$\sum_j (A_j)\dagger A_j = I,$$

(8)
and which act on the Hilbert space corresponding to the internal degrees of freedom of particle \( i \). We define \( A_{ij} \) to be the corresponding operator on the tensor product Hilbert space: that is,

\[
A_{ij} = I \otimes \ldots \otimes I \otimes A_j \otimes I \otimes \ldots \otimes I,
\]

where \( A_j \) is the \( i \)-th term in the product.

In standard quantum theory, whenever such a reduction takes place on a state \( |\Psi\rangle \), we get outcome \( j \) with probability

\[
\text{Tr}((A_{ij})^\dagger A_{ij} \rho_{\Psi}) ,
\]

where \( \rho_{\Psi} = |\Psi\rangle \langle \Psi| \). After this reduction, the state becomes

\[
\frac{A_{ij} |\Psi\rangle}{\text{Tr}((A_{ij})^\dagger A_{ij} \rho_{\Psi})^{1/2}}.
\]

In between collapses, since the Hamiltonian is zero, the state remains constant.

In the corresponding version of causal quantum theory, in order to calculate outcome probabilities for a measurement taking place at \( P_i = (x_i, t_i) \), we first need to calculate a causally defined version of the standard quantum state — let us call it the local state — of the system at \( P_i \). This is obtained by starting from \( |\Psi(0)\rangle \) and then applying (11) for each measurement within the past light cone of \( P_i \), sequentially in time order, but no others: by assumption, the reductions are localised, so that (assuming, of course, that we have a Lorentz invariant reduction theory) the result is independent of the choice of frame which defines the time ordering. Equation (10), applied to the local state, then defines the outcome probabilities for the measurement at \( P_i \). Note that we do not define these probabilities in terms of the evolved state vector \( |\Psi(t_i)\rangle \), as we would in standard quantum theory.

To calculate the joint probabilities for outcomes of measurements at mutually space-like separated points \( P_1, \ldots, P_n \), we need first to calculate the probability of each possible configuration of measurements, and each possible set of outcomes, in the union of the past light cones of the \( P_i \); let us refer to these collectively as past data. We can calculate the conditional probability of outcome \( O_{ij} \) at point \( P_i \) given the past data, \( P(O_{ij} | \text{past data}) \). The joint probability of outcomes \( O_{i_1}, \ldots, O_{i_n} \) is

\[
\prod_{j=1}^n P(O_{ij} | \text{past data}) .
\]

Using these rules (and in principle using some small meshing of space-time, and taking the limit as the mesh size tends to zero), we can (in principle) proceed iteratively to calculate the probabilities of all possible configurations of measurement events in space-time.

But does this procedure always produce well-defined answers? Suppose for example that we begin with two sub-systems in a singlet state

\[
|\Psi(0)\rangle = \frac{1}{\sqrt{2}} (|0\rangle_1 |1\rangle_2 - |1\rangle_1 |0\rangle_2) .
\]

Suppose no reductions take place before time \( t \), and that at time \( t \), reductions take place at both \( x_1 \) and \( x_2 \) and that in both cases the reduction operators are \( \{P_0, P_1\} \), the projections onto \( |0\rangle \) and \( |1\rangle \). One possibility, which according to our rules has probability \( 1/4 \), is that the measurement outcome in both cases will be that corresponding to the operator \( P_0 \). If no further reductions take place before time \( T = t + |x_1 - x_2| \), then at that point our rules suggest the local states at the points \( (x_i, T) \) both become

\[
\frac{P_0 \otimes P_0 |\Psi(0)\rangle}{|P_0 \otimes P_0 |\Psi(0)\rangle} ,
\]

which is undefined. After this point, we thus have no rule for predicting future measurement outcomes. A similar problem arises if both outcomes correspond to \( P_1 \), of course.

There are two attitudes one can take to this. One is to conclude that causal quantum theory is not a properly defined theory, and deserves no further attention. The other is to note that, in practice and even in principle, the theory can be saved quite easily.

A practical counter-argument to the above follows from the fact that the singlet state is never precisely realised in nature. A more realistic version of the above discussion would thus begin with

\[
|\Psi(0)\rangle = \sum_{ij} a_{ij} |i\rangle_1 |j\rangle_2 ,
\]
where \( a_{01} \approx 1/\sqrt{2} \approx a_{10} \) and \( a_{00} \approx 0 \approx a_{11} \), but neither of the last two terms are precisely zero. A still more realistic version would take the initial state to be a mixture, dominated by states of approximately this form. Either way, the local states after measurement are, by virtue of the correction terms, well-defined.

More generally, whatever measurement operators arise in a theory of reduction, one would not ever expect to find in nature — or to be able to create artificially — a state that is precisely a zero eigenstate of a tensor product of non-zero operators.

An arguably more principled way of avoiding the difficulty is to require that the theory of state reduction should involve only measurement operators which have no zero eigenvalues. (So, in particular, it cannot include projections.) The Ghirardi-Rimini-Weber spontaneous localisation model [19] is an example of such a theory. (Note, though, that in current non-relativistic versions of the GRW model, the measurement operators are not perfectly localised, so that the probability of a collapse event centred at a point \( P \) is only approximately determined by events in the past light cone of \( P \): it depends also to some extent on events some way outside the past light cone.) In such theories, although the cumulative effect of measurements can asymptotically tend to the action of a projection, no collection of measurement events ever completely annihilates the component of the state in any given subspace. In particular, whatever the initial state, the calculations in the causal version of such theories will never produce a zero value for the unnormalised local state, and the local states are always defined.

Put succinctly, the worry about causal quantum theory was that it might imply combinations of measurement outcomes that are impossible in standard quantum theory — and that when that happens, causal quantum theory breaks down. The way around this is to notice that in practice the measurement outcomes which occur in causal quantum theory will almost surely never actually be impossible in standard quantum theory: if one prefers, by slightly restricting the theory of reduction one can ensure this is always true. However, unless the details of the reduction theory somehow prevent long-range entanglement, combinations of outcomes which are extremely unlikely according to standard theory can be expected to be fairly common in causal quantum theory.

IV. TESTING CAUSAL QUANTUM THEORY

As noted above, causal quantum theory and standard quantum theory predict different outcome probabilities for separated measurements on entangled states, so that Bell experiments seem the first obvious place to look for a refutation of causal quantum theory.

The greatest separation over which apparently non-local correlations have so far been demonstrated was in the beautifully designed experiments of Tittel et al. [16] and Zbinden et al. [20], who have demonstrated the violation of Bell inequalities, and the confirmation of quantum predictions, by entangled photons separated by \( \approx 10 \) km, or \( \approx 3 \times 10^{-5} \) light seconds. Tittel et al.’s experimental arrangement was somewhat asymmetric. Zbinden et al.’s experiment was designed to ensure that the photons arrive at separated detectors within a time interval of less than 5 ps (in laboratory frame): however, the relevant detectors here were surfaces coated in absorbing black paint rather than standard photo-detectors. This experiment was designed to test an intuition inspired by ideas of Suarez and Scarani [22]. Zbinden et al.’s experiment tests and refutes the hypothesis that correlations different from those of quantum theory arise when each absorbing paint detector carries out the measurement first, from the perspective of its own stationary reference frame.

As Zbinden et al. carefully note, some admittedly questionable, although plausible, assumptions are needed in order to justify interpreting their experiment as equivalent to a standard Bell experiment with photo-detectors. Let us in any case make the best case assumption that the results of Tittel et al. and Zbinden et al. imply that a standard Bell experiment could be carried out with effectively identical apparatus on both sides, such that entangled photons on both sides enter standard photo-detectors, or in an alternative version of the experiment hit patches of absorbing paint that function as detectors, at precisely the same times, and that the results would still confirm standard quantum theory. If we could be sure that any sensible theory of state reduction implies that reduction takes place within the photo-detectors, or alternatively within the absorbing paint, in a time shorter than \( 3 \times 10^{-5} \) seconds — or even merely that the times at which it takes place in the two detectors are separated by \( < 3 \times 10^{-5} \) seconds — then we could conclude from these results that causal quantum theory was definitely refuted.

But can we be so sure? All ideas about theories of state reduction are speculative, but among them, at least three have been taken seriously from time to time by a significant number of thoughtful people: Wigner’s suggestion [22] that state reduction could be somehow caused by conscious minds, Penrose’s suggestion [23] that state reduction takes place when required to prevent a superposition of macroscopically distinct gravitational fields, and Ghirardi-Rimini-Weber-Pearle type theories in which state reduction results from a spontaneous localisation process occurring stochastically at rates proportional to particle number or mass.

Insofar as these ideas can be made precise at all, none of them seems necessarily to imply state reductions in photodetectors that are necessarily separated by times short compared to \( 3 \times 10^{-5} \) sec. Indeed, if Wigner’s suggestion were
right, reduction wouldn’t occur at all until experimenters look at the data. The other two cases cannot properly be analysed without a detailed description of the apparatus. However, given that the reduction of a superposition in the GRWP and Penrose theories depends on the extent to which it involves macroscopically distinct separations of massive particles in position space, it would be surprising if very tight bounds on the reduction time in these experiments could be derived. Even in an experiment with perfect symmetry between the two wings, in which the photons enter the photo-detectors at the same time \( t \) in the experimental rest frame, it need not necessarily be the case that the collapse events also take place at the same time \( t + \delta \) — the time \( \delta \) before collapse could, as in GRWP theories, be stochastically determined, with independent stochastic processes associated to space-like separated points on the two wings. Using absorbing black paint in place of a photo-detector almost certainly would only make the numerics worse, since a photon hitting an absorbing surface does not at all quickly create a macroscopically distinct configuration of massive particles in position space.

Still, if one takes the idea of a state reduction theory seriously in the first place then, whatever one thinks of Wigner’s suggestion, there is a good reason to assume that reduction does take place (at the very latest) not long after the impression of a measurement result registers in a human observer’s brain — namely, our own experience. When we watch an apparatus carrying out measurements, it seems to us as though each measurement produces a definite result, and it seems to us that these results are accessible to us rather soon after the point at which the signal reaches our eye or ear.

Of course, this does not logically imply that a state reduction has taken place. It could conceivably be that we enter a superposition state, entangled with the apparatus and the measured system, at least for some time, but that the properties of our consciousness are such that it constructs for us the impression of quickly accessible definite results before reduction takes place. But once one entertains this hypothesis, there seems no reason to postulate state reduction at all. One might then as well go all the way, and follow Everettians in assuming that there is only unitary evolution, but that the properties of consciousness are such that we perceive things according to one component of the universal state vector, in which definite measurement results took place and were observed by us. (See e.g. Ref. \[24\] and references therein for recent discussions advocating this view.)

On this reasoning, any state reduction theory worth taking seriously should imply that reduction ordinarily would take place within \( \approx 0.1 \) sec — roughly the timescale over which we can discriminate events — of the signal from a measurement apparatus reaching us. Given this, a fairly definitive test of causal quantum theory could be carried out by allowing observers separated by \( \approx 0.1 \) light seconds to carry out synchronized measurements on entangled particles and directly observe the results, before later comparing them.

V. CONCLUSIONS

The standard case for studying loopholes in Bell experiments is that quantum non-locality has such fundamental significance that it is worth demonstrating as rigorously as possible. Even highly implausible alternative explanations are worth analysing and, if possible, refuting.

A more practical motivation has also recently been suggested \[23, 26\]. It may be crucial for future users of quantum cryptography and quantum communication systems to guard against fakery or sabotage by testing that states involving allegedly entangled separated subsystems genuinely are entangled states of the correct form. In principle, Bell experiments can do this. But, again in principle, a saboteur might make use of any Bell experiment loophole to produce apparent, but unreliable, evidence of entanglement.

While these are certainly sufficient motivations for considering the collapse locality loophole, I think there are stronger reasons. For there is a principled case for taking seriously both the hypotheses which define causal quantum theory.

Take first the idea that there is an explicit physical theory of state reduction. This is not, by any means, everyone’s preferred solution to the measurement problem — but it is a natural solution which has often been advocated. Indeed, almost everyone who has studied the Copenhagen interpretation must have wondered whether one could not replace the projection postulate, with its vague reference to measurement, with a precise physical law. Granted, devising explicit collapse models is a project fraught with difficulties. It seems hard to find satisfactorily relativistic versions of GRWP models (see e.g. Ref. \[27\] for a recent review). It is also hard to precisely formulate Penrose’s idea, let alone Wigner’s. These are very serious worries. But so far every proposed solution to the measurement problem is fraught with difficulties, and yet presumably there must be a solution.

As for the idea that strict local causality should hold: this is, obviously, inspired by special relativity. Of course, we have learned that quantum theory respects Minkowski causality more subtly. But strict local causality remains a natural hypothesis — albeit, unless nature has indeed deceived us by exploiting the collapse locality loophole, an incorrect one.

Against causal quantum theory, it might be argued there is something decidedly strange about a theory which — a
harsh critic could say — maintains consistency only by relying on the existence of small errors or by its own inability ever to give completely definite answers. Maybe: but then many features of standard quantum theory seem strange until, perhaps, familiarity breeds acceptance. Experimental evidence would be more convincing than arguments based on aesthetic preconceptions, particularly as the aesthetic arguments are not entirely one-sided.

A stronger argument, perhaps, is that, if causal quantum theory were right, one might expect detectable consequences other than in Bell-like experiments on entangled states. For instance, particles whose wave functions have extended support ought, so to speak, sometimes to appear to collapse and localise in two or more places at once. For the reasons already discussed, this need not lead to logical contradiction. For example, a causal quantum theory analysis could suggest that an apparent observation of a particular particle most likely derived from some other source, or that it was most likely due to detector error, even when these explanations would be very unlikely according to standard quantum theory. But one might think it ought to have observable consequences, in cosmology and elsewhere, which might be or have already been contradicted by experiment. Very possibly it does: the question deserves careful analysis.

Another fair argument is that it seems that, for causal quantum theory to be right, and yet not to have been detected in Bell experiments to date, the relevant parameters in the hypothetical explicit collapse model would have to be relatively fine-tuned. Bell experiments with separations of $>10^{-5}$ light seconds have been performed, with no detectable deviation from standard quantum theory: an experiment with separation of $\approx 10^{-1}$ light seconds should show dramatic deviations from quantum theory if causal quantum theory were correct. It would be a bit of a quirk of fate for the critical separation to lie in a range covered by fewer than four orders of magnitude. Of course, the type of measurement carried out in the experiments is crucial. The argument for the latter experiment sufficing relies on direct observation of the results by human observers, rather than the photo-detectors used in the former. According to Wigner’s suggestion, this makes all the difference, and so the fine-tuning argument does not apply against some Wignerian version of causal quantum theory. But, from a GRW or Penrosean collapse model perspective, it isn’t obvious that the human brain should be hugely better at inducing collapse than a photo-detector, and so the fine-tuning argument has some force in these cases.

At the moment, though, these counterarguments don’t seem totally compelling. Although the arguments against local hidden variable theories exploiting the detector efficiency and (standard) locality loopholes are stronger, experimentalists rightly continue to work towards more definitive tests. The Earth is large enough to allow almost, if not absolutely, conclusive experimental tests of causal versus standard quantum theory; if (at least) one part of the experiment were carried out on a short manned space flight, a completely definitive test could be made. It would be fascinating to see the experiments done, even if they do no more than remove a sliver of doubt. One hopes they will be, once technology allows suitably long range distribution of entanglement.

Acknowledgments

This work was supported by a Royal Society University Research Fellowships, projects EQUIP and PROSECCO (IST-2001-39227) of the IST-FET programme of the EC, and the Cambridge-MIT Institute. I thank Nicolas Gisin and Philip Pearle for helpful discussions, and the Perimeter Institute for support while revising this paper.

[1] A. Einstein, B. Podolsky and N. Rosen, Phys. Rev. 47, 777 (1935).
[2] J. S. Bell, Rev. Mod. Phys. 38, 447 (1966).
[3] J. S. Bell, Physics 1, 195 (1964).
[4] P. H. Eberhard, Phys. Rev. A 47, R747 (1993).
[5] M. A. Rowe et al., Nature 409, 791 (2001).
[6] G. Weihs et al., Phys. Rev. Lett. 81, 5039 (1998).
[7] A. Aspect, Nature 398, 189 (1999).
[8] L. Vaidman, quant-ph/0107057.
[9] H. Price, Time’s Arrow and Archimedes’ Point: New Directions for the Physics of Time, (Oxford University Press, Oxford, 1996).
[10] A. Kent, Locality and Causality Revisited, in Modality, Probability and Bell’s Theorems, eds. T. Placek and J. Butterfield (Kluwer Academic Publishers, Dordrecht, 2002); quant-ph/0202064.
[11] L. Accardi and M. Regoli, quant-ph/0007005, quant-ph/0007019, quant-ph/010086.
[12] J. Barrett, D. Collins, L. Hardy, A. Kent and S. Popescu, Phys. Rev. A 66, 042111 (2002).
[13] R. Gill, pp. 133-154 in Mathematical Statistics and Applications: Festschrift for Constance van Eeden, M. Moore, S. Froda and C. Léger, eds; IMS Lecture Notes Monograph Series, Vol. 42 (Institute of Mathematical Statistics, Beachwood, Ohio, 2003); quant-ph/0110137.
[14] J. Clauser, M. Horne, A. Shimony and R. Holt, Phys. Rev. Lett. 23, 880 (1969).
[15] A. Aspect et al., Phys. Rev. Lett. 47, 460 (1981); Phys. Rev. Lett. 49, 91 (1982); Phys. Rev. Lett. 49, 1804 (1982).
[16] W. Tittel et al., Phys. Rev. Lett. 81 3563 (1998); N. Gisin and H. Zbinden, Phys. Lett. A 264 103-107 (1999).

[17] J.S. Bell, *The theory of local beables*, Epistemological Letters, March 1976, reprinted in Dialectica 39 85-96 (1985).

[18] J.S. Bell, *Free variables and local causality*, Epistemological Letters, February 1977; reprinted in Dialectica 39 103-106 (1985).

[19] G. Ghirardi, A. Rimini and T. Weber, Phys. Rev. D34, 470 (1986); G. Ghirardi, P. Pearle and A. Rimini, Phys. Rev. A42 78 (1990); L. Diosi, Phys. Rev. A40 1165 (1989).

[20] H. Zbinden et al., Phys. Rev. A63 022111 (2001).

[21] A. Suarez and V. Scarani, Phys. Lett. A 232 9 (1997).

[22] E. Wigner, *Remarks on the mind-body question* in The Scientist Speculates, I. Good, ed. (Heinemann, London, 1961).

[23] R. Penrose, *The Emperor’s New Mind* (Oxford, 1999) and refs therein.

[24] D. Wallace, quant-ph/0107044 and quant-ph/0312157.

[25] D. Mayers and A. Yao, in Proceedings of the 39th Annual Symposium on the Foundations of Computer Science, 503 (IEEE, Computer Society Press, Los Alamitos, 1998); quant-ph/9809039

[26] N. Gisin, private communication.

[27] P. Pearle, quant-ph/0502069.