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Quantum computation, entanglement and state reduction

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Some general foundational issues of quantum mechanics are considered and are related to aspects of quantum computation. The importance of quantum entanglement and quantum information is discussed and their curious acausal properties are addressed. The question of quantum state reduction is also considered, and a specific suggestion for a gravitational state-reduction scheme is put forward. A general proposal for an experiment to test this scheme is also suggested.

Keywords: quantum state reduction; quantum gravity experiment; quantum entanglement; quantum information; quantum computation; Schrödinger–Newton equation

1. Quantum entanglement

It has been stressed in several of the accompanying articles that the essential feature of quantum mechanics that is taken advantage of by quantum computation is *quantum entanglement*, the phenomenon referred to by Schrödinger as ‘the essence of quantum physics’. It is not my purpose here to try to summarize the various manifestations of quantum entanglement that have been commented upon or made use of in these contributions. Some of the phrases that have come up in this connection may, however, give some flavour of the relevant issues: ‘quantum teleportation’, ‘dense coding’, ‘quantum telephone exchange’ and many others. These are remarkable phenomena; and they are essentially dependent upon the entanglement properties of quantum physics. Such phenomena simply cannot occur in a classical world.

In quantum computation, one wishes to maintain and make essential use of the full potentialities of quantum entanglement. One way to understand the potential power of quantum entanglement is to appreciate, first, that the vast majority of the quantum states of a system are entangled, for a system with several distinct parts, and, second, that it is this very vastness of the Hilbert space of quantum states that one wishes to take advantage of in quantum computation. Recall that entangled states arise when arbitrary complex linear combinations of the unentangled ‘classical’ states are taken, whereas, in the classical situation, only these unentangled states may themselves be used. Moreover, the quantum Hilbert space is larger than the classical space by basically an *exponential factor*. This is what allows the ‘massive parallelism’ that is potentially available in quantum computation.

However, the very vastness of this Hilbert space carries with it technical problems of its own. It is not easy to keep track of what the state actually *is*. Environmental entanglement, or ‘decoherence’, may destroy useful quantum information, and (in effect) reduce the situation to a probability mixture of classical information. Various procedures have been described in the accompanying articles for dealing with

these problems, going under the headings of ‘entanglement distillation’, ‘syndrome extraction’, ‘quantum error correction’ and so on. New notions have arisen so that these issues can be studied theoretically, such as ‘the entropy of entanglement’ and ‘quantum information’. Quantum information, in particular, is an aspect of quantum entanglement which I find particularly intriguing, and I wish to make a few remarks specifically addressing this notion in the next section.

2. Quantum information

There is a feature of quantum information which has not been particularly emphasized in the other articles, but which I regard as especially noteworthy. This is that quantum information is not constrained by the usual spatio-temporal ‘causality’ requirements of relativity. There need be no contradiction here because quantum information cannot be used directly to transmit a classical signal, although it can be used in conjunction with classical signalling to achieve effects beyond the capabilities of any entirely classical system. Remarkably, there is even nothing against quantum information ‘travelling backwards in time’; indeed, such curious behaviour seems to be *required*, as we shall see.

This kind of point of view has been argued by Aharonov & Vaidman (1990), Costa de Beauregard (1989), Werbos (1989) and, particularly, Jozsa (1998). It provides us with a very direct way of understanding how quantum teleportation operates. Alice wishes to send to Bob the ‘information’ contained in a certain quantum state, say the precise *direction of the spin* of a spin- $\frac{1}{2}$ particle, yet she is allowed only to send Bob a few bits—namely two, in this case, from the $2^2 = 4$ independent Bell measurements—of discrete classical information. She is able to achieve this only because she and Bob also each possesses one member of an Einstein–Podolsky–Rosen (EPR) pair of entangled particles—each of spin- $\frac{1}{2}$, in this case, where the spin variable is all that is being considered. How is it that the *continuous* ‘information’ of the spin direction of the state that she wishes to transmit (basically a point on the Riemann sphere: the ratio of two complex amplitudes) can be transmitted to Bob when she actually sends him only two bits of discrete information? The only other link between Alice and Bob is the quantum link that the entangled pair provides. In spacetime terms, this link extends back into the past from Alice to the event at which the entangled pair was produced, and then it extends forward into the future to the event where Bob performs his measurement (a measurement which acts on his member of the entangled pair, the particular measurement that he performs being determined by the classical signal that he receives from Alice). Only *discrete* classical information passes from Alice to Bob, so the complex number ratio which determines the specific state which is being ‘teleported’ must be transmitted via the *quantum* link. This link has a channel which ‘proceeds into the past’ from Alice to the source of the EPR pair, in addition to the remaining channel which we regard as ‘proceeding into the future’ in the normal way from the EPR source to Bob. There is no other physical connection (see figure 1).

A side remark may be appropriate here. In the original discussion (Bennett *et al.* 1993) of the quantum teleportation of a state belonging to a two-dimensional Hilbert space (e.g. of the spin of a spin- $\frac{1}{2}$ particle), the quantum information link between Alice and Bob consists of a past-directed and a future-directed channel each of which corresponds to a *two-dimensional* Hilbert space (the two channels together giving

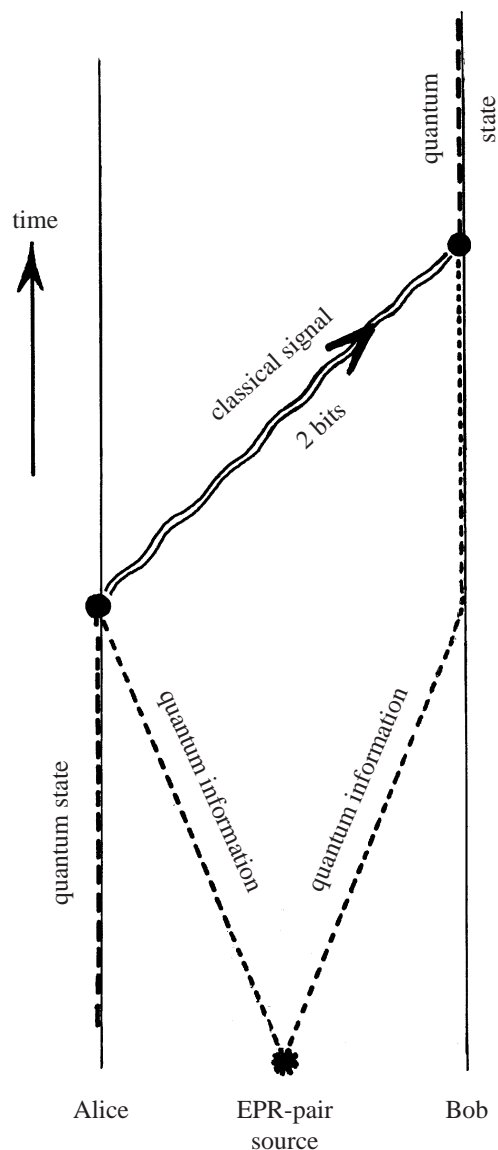


Figure 1. Spacetime diagram of quantum teleportation.

a four-dimensional Hilbert space: the tensor product of the Hilbert spaces of each individual channel with that of the other). However, in the actual experiments that have been performed so far (with photons, not spin- $\frac{1}{2}$ particles), it has proved to be difficult to measure all the four Bell states that would be needed for a complete quantum teleportation without loss (Bouwmeester *et al.* 1997). One way that one might ease this particular problem would be to use a larger-dimensional Hilbert space for the quantum information channel, so that one could make use of the redundancy that would be available. I am not aware that this possibility has been exploited as yet.

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3. Orientation reversal in EPR pairs

Let us return to the general question of the backward propagation of quantum information. Although there might seem to be something dangerously close to paradox in this notion of an ‘information’ which can travel in both directions in time, this notion actually proves to be surprisingly helpful in enabling us often to see at a glance what the implications of a quantum entanglement must be, in situations where these implications may be far from otherwise obvious. An additional feature of the ‘reverse-time’ channel of a quantum information link is that the quantum amplitudes appear in a form that is the *complex conjugate* of what they would have been in forward-time propagation. This has some direct geometrical implications which are not otherwise immediately obvious.

To illustrate what I mean by this, let us consider an example. Suppose that an EPR pair is created, consisting of two spin- $\frac{1}{2}$ particles. We might imagine that the pair was produced by the decay of a spin-0 particle, or alternatively by the decay of a spin-1 particle, or by any other means. We can allow, in the production of the EPR pair, that one or other of the particles (or both) has its spin direction rotated by, for example, a magnetic field. Let us ask the question: is it possible to arrange that one of the resulting EPR particles has a spin direction which is always correlated with exactly the *same* direction for the spin for the other particle? Recall that in the case when the two particles are produced from a spin-0 state, the spin direction of each of the particles is correlated with exactly the *opposite* direction of the other. In fact the answer to our question has to be ‘no’. This fact can be understood by a direct computation, but let us see how we can see it immediately, and without calculation, by use of the concept of quantum information.

The key property of quantum information that we appeal to here is that in any process which produces an EPR entangled pair, the ‘past-propagating’ quantum information in one channel is ‘reflected back into the future’ to become the ‘future-propagating’ quantum information in the other channel. In fact, it makes no difference which channel is regarded as past propagating and which as future propagating; the essential fact is that there is a *time reversal* in the relation of one channel to the other which occurs at the creation of the EPR pair. Since a time reversal involves taking the complex conjugate of the amplitudes, there must be an *orientation reversal* between the Riemann sphere of one of the spin- $\frac{1}{2}$ particles and that of its partner. For a spin- $\frac{1}{2}$ particle, the Riemann sphere of states translates directly geometrically into the possible alternative directions of the state of spin of the particle. Thus the correlation between the sphere of possible spin directions for one of the particles and the sphere of possible spin directions for the other particle has to be an *orientation-reversing* rotation. The most familiar example occurs when the two spins together constitute a spin-0 eigenstate, so that the spin directions of the two particles are exactly anticorrelated; the antipodal map is indeed an orientation-reversing relationship. The situation is essentially similar if the two particles arise from a spin-1 initial state, but here the relation between the two Riemann spheres is a more general orientation-reversing rotation.

This situation has relevance to the production of photon pairs in parametric down-conversion. We can deduce that it is *not possible* to arrange things so that the two correlated photons each have always the *same* state of polarization. This would correspond to the two entangled photons having Riemann spheres which correlate

without any reflection which, as stated above, cannot occur. (The precise relation between the geometry of the Riemann sphere and that of the polarization states is given in Penrose (1989, fig. 6.28). It is essentially given by the ‘Stokes parameters’.) In particular, with measurement of plane polarization, if the directions of the planes of polarization of the two photons correlating with each other are the same, then it must be the case that right-handed circular polarization for one of the two photons correlates with left-handed circular polarization for the other.

Considerations of this nature can also be applied to EPR triplets, as Greenberger *et al.* (1989) have discussed. One way of doing this is to regard the triplet as a pair, one member of which is itself a pair. The details of this are left to a later discussion.

4. Quantum state reduction

One of the most puzzling features of quantum entanglement is that, according to the standard quantum-mechanical procedures of unitary evolution, entanglements will have a tendency simply to spread throughout the universe, so that it becomes exceedingly unlikely that any given quantum state can be treated as unentangled. As remarked above, in §1, the unentangled ‘classical-like’ states constitute a very tiny minority of quantum states, so widespread entanglement will be the normal result of unitary evolution. Only in very special or deliberately contrived situations will unentangled states be the result. One must ask the question, therefore, why is it possible, in any practical situation, to have quantum states that can be effectively treated as though they are unentangled with the outside world? Almost any quantum particle, for example, ought to have its state inextricably entangled with vast numbers of other particles spread throughout the universe; yet in many quantum experiments one can treat particles as though they indeed have individual quantum states.

The answer to this problem is essentially bound up with the *measurement problem* of quantum mechanics. The well-known procedures of quantum mechanics, as they are used in practice, do not merely allow that states evolve according to unitary evolution alone. From time to time, whenever it is considered that a ‘measurement’ has taken place, unitary evolution is abandoned, and the state vector of the quantum system is taken instead to ‘jump’ into an eigenstate of some Hermitian operator, determined by the apparatus that is doing the measurement. It is this latter process that, in effect, ‘cuts’ the entanglements that the system under consideration previously had with the outside world.

Of course, all this leads us into the murky issue of what one considers is ‘actually’ going on in a measurement of a quantum system. On the face of it, the state-vector reduction that is considered to take place in a measurement is simply in blatant contradiction to the process of unitary evolution. There are four broad categories of philosophical standpoint for coming to terms with this seeming contradiction.

(1) According to the ‘Copenhagen’ viewpoint of Niels Bohr, the state vector is not considered to represent a quantum-level ‘reality’, but merely the ‘state of mind’ of the experimenter. On this view, the ‘jumping’ that occurs in the procedure of *state-vector reduction* is considered to be merely the result of a discontinuous change in the state of knowledge of the experimenter and not a physical change to which can be attributed a physical reality.

(2) In the ‘environmental decoherence’ viewpoint, it is considered that in the process of measurement the system becomes inextricably entangled with its environment,

and that because the degrees of freedom in the environment are to be regarded as random and unobservable it becomes necessary to ‘sum over’ those degrees of freedom and use a density-matrix description rather than a state vector. When this density matrix becomes (effectively) diagonal in the physically appropriate basis, it is considered that ‘for all practical purposes’ (FAPP) the system is in a state represented by one of the diagonal elements, with probability given by the value of that diagonal element.

(3) There is the ‘many-worlds’ viewpoint, according to which the state vector, evolving by strict unitary evolution, is taken to represent reality; consequently, in a measurement, all outcomes coexist, but they are each entangled with different states of the observer’s consciousness. Accordingly, the corresponding different consciousness states also coexist, each one experiencing a different ‘world’ and encountering a different outcome of the measurement.

(4) Finally, it may be considered that the conventional formulation of quantum mechanics is provisional, and some *new* theory is needed in order to make real sense of the process of measurement. Various different proposals have been put forward. According to some of these (such as the de Broglie–Bohm theory (cf. de Broglie 1956; Bohm 1952; Bohm & Hiley 1994)), the new formalism is not considered to have any observable consequences different from standard quantum mechanics, but according to others, there would, in principle at least, be experiments to distinguish the new theory from standard quantum mechanics.

This is not the place for a discussion of the pros and cons of these various alternative viewpoints. I shall merely remark, here, that my personal belief is that there are severe difficulties with each of (1)–(3), despite the prevailing popularity of these ‘conventional’ viewpoints, and that some development in line with (4) is necessary (see Penrose (1989, 1993, 1994, 1996) for some accounts of my evolving position on these matters over the past ten years). To be more specific, I belong to the general school of thought that maintains that the phenomenon of quantum state reduction is a *gravitational* phenomenon, and that essential changes are needed in the framework of quantum mechanics in order that its principles can be adequately married with the principles of Einstein’s general relativity. There are still various different proposals, in accordance with these sentiments (cf. Károlyházy 1966; Karolyházy *et al.* 1986; Kibble 1981; Diósi 1987, 1989; Ghirardi *et al.* 1990; Percival 1995). My present position differs in important respects from all of these, and I shall give a brief account of it in the next section.

The essential point about all these proposals (and not necessarily only the gravitational ones (cf. also Pearle (1985, 1989), Pearle & Squires (1995) and Ghirardi *et al.* (1986))) is that state-vector reduction is considered to take place objectively and spontaneously, in contradiction with the strict unitary evolution of the quantum state. Accordingly, when a measurement is made on a system, its entanglements with the outside world are indeed objectively cut, so that the aforementioned problem of the persistence of complicated entanglements of a system with the rest of the universe is thereby removed.

5. A specific gravitational quantum state-reduction scheme

Of course, there are many other difficulties that any such new scheme would have to address. Not the least of these would be to avoid contradiction with the complete

agreement that the standard quantum formalism has with all experiments to date. The proposal that I am making here follows closely that put forward in Penrose (1996), according to which a certain already existing conflict between the fundamental principles of general relativity and of quantum mechanics is appealed to. I shall address the question of the *stationarity* of a quantum system which consists of a linear superposition $|\psi\rangle = |\alpha\rangle + |\beta\rangle$ of two well-defined states $|\alpha\rangle$ and $|\beta\rangle$, each of which would be stationary on its own, and where we assume that each of the two individual states has the same energy E :

$$i\frac{\partial|\alpha\rangle}{\partial t} = E|\alpha\rangle, \quad i\frac{\partial|\beta\rangle}{\partial t} = E|\beta\rangle.$$

If gravitation is ignored, then the quantum superposition $|\psi\rangle = a|\alpha\rangle + b|\beta\rangle$ would also be stationary, with the same energy E :

$$i\frac{\partial|\psi\rangle}{\partial t} = E|\psi\rangle,$$

and this is the normal supposition. However, when the gravitational fields of the mass distributions of the states are taken into account, then a new feature arises. For we must ask what the Schrödinger operator $\partial/\partial t$ actually *means* in such a situation. Let us consider that each of the stationary states $|\alpha\rangle$ and $|\beta\rangle$ takes into account whatever the correct quantum description of its gravitational field might be, in accordance with Einstein's theory. Then, to a good degree of approximation, there will be a classical spacetime associated with each of $|\alpha\rangle$ and $|\beta\rangle$, and the operator ' $\partial/\partial t$ ' would correspond to the action of the Killing vector representing the time displacement of stationarity, in each case.

Now, the problem that arises here is that these two Killing vectors are *different* from each other. They could hardly be the same, as they refer to time symmetries of two different spacetimes. It could only be appropriate to identify the two Killing vectors with one another if it were appropriate to identify the two different spacetimes with each other point-by-point. But such an identification would be at variance with the principle of general covariance, a principle which is fundamental to Einstein's theory. Nevertheless, according to standard quantum theory, unitary evolution requires that there be a Schrödinger operator that applies to the superposition just as it applies to each state individually; and its action on that superposition is precisely the superposition of its action on each state individually. There is thus a certain tension between the fundamental principles of these two great theories, and one needs to take a position on how this tension is to be resolved. My own position is (provisionally) to take the view that an *approximate* pointwise identification may be made between the two spacetimes, and that this corresponds to a slight error in the identification of the Schrödinger operator for one spacetime with that for the other. This error corresponds, in effect, to a slight *uncertainty in the energy* of the superposition. One can make a reasonable assessment as to what this energy uncertainty E_G might be, at least in the case when the amplitudes a and b are about equal in magnitude. This estimate (in the Newtonian approximation) turns out to be the gravitational self-energy of the difference between the mass distributions of the two superposed states (Penrose 1996). This energy uncertainty E_G is taken to be a fundamental aspect of such a superposition and, in accordance with Heisenberg's uncertainty principle, the reciprocal \hbar/E_G is taken to be a measure of the *lifetime* of

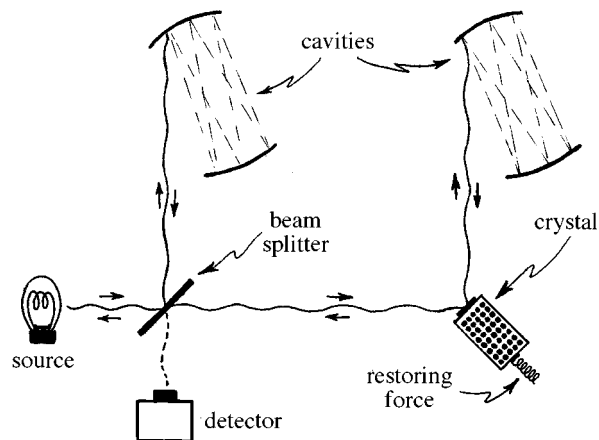


Figure 2. A proposed experiment for testing state-vector reduction as a gravitational phenomenon (highly schematic).

the superposition (as with an unstable particle). The two decay modes of the superposition $|\psi\rangle = a|\alpha\rangle + b|\beta\rangle$ would be the individual states $|\alpha\rangle$ and $|\beta\rangle$, with relative probabilities $|a|^2 : |b|^2$.

This scheme has a number of points in common with that of Diósi (1987, 1989), particularly in that no additional fundamental constants are introduced other than the standard ones \hbar , G and c (where, in fact, c does not enter, in this Newtonian approximation). However, Diósi's scheme encountered a certain severe difficulty, as pointed out by Ghirardi *et al.* (1990), who suggested a remedy that, unfortunately, required the reintroduction of an additional constant whose value is without fundamental motivation.

This difficulty is closely related to the fact that there has been no specification of which particular quantum states are to be regarded as the (stable) 'basic' ones and which are to be regarded as the 'superpositions of basic states', the states which are to decay into basic states. If, for a single point particle, we considered the basic states to be position states, then the superpositions would involve an *infinite* gravitational energy uncertainty E_G so that state reduction to one of the basic position states would occur *instantaneously* on this scheme, which is clearly an unreasonable requirement. It is for this kind of reason that an additional parameter defining a fundamental length scale was introduced by Ghirardi *et al.* (1990), so that the state reduction would be to an entity of the size of this fundamental length.

In the scheme that I am arguing for here, the problem is treated in a quite different way, and no additional parameters are required. The *basic stationary states* into which a general superposition would decay by state reduction are to be stationary solutions of the *Schrödinger–Newton equation* (SN-equation), in this Newtonian approximation, where velocities and gravitational potentials are small. What I mean by the SN equation is the Schrödinger equation for a wavefunction Ψ , where there is an additional term provided by a Newtonian potential Φ , and where Φ is the gravitational potential for the Newtonian matter distribution which is the expectation value of the mass distribution given by the Schrödinger wavefunction Ψ . The (stationary) solutions of the SN equation are obtained, therefore, by solving this nonlinear pair of coupled differential equations. (Some encouragement that this is a sensible proce-

ture may be gained from some recent work done in conjunction with I. Moroz and K. P. Tod, which provides convincing evidence that for a single point particle, there are indeed stationary solutions of the SN equation with the appropriate boundary conditions (Moroz *et al.* 1998.) A more complete discussion will be given elsewhere.

As a final comment, it should be made clear that, according to the state-reduction scheme of this section, *all* quantum measurements arise because of the instability of quantum superpositions involving significant mass displacements. In various circumstances, where a piece of physical apparatus is involved in making the measurement, the mass movement would occur in the measuring apparatus itself. An extreme situation might occur in an observer's retina or optic nerve, when it is the reception of an individual photon that is involved. Very frequently, the major mass displacement would take place in the (random) *environment* when this environment becomes entangled with the quantum system under consideration. Spontaneous state reduction in the environment would necessarily be accompanied by the simultaneous reduction of any quantum system with which it is entangled. In this way, contact is made with the standard 'decoherence' viewpoint of quantum state reduction, the essential distinction being that in the present scheme the state reduction is taken as *actual* rather than merely FAPP.

6. A proposed experiment

It is of some considerable interest that the proposal set out in the previous section may well be subject to feasible experimental test. I wish to describe the general outline of an experimental set-up that might be used. I am grateful to a number of colleagues for suggestions in relation to this. Most particularly, Johannes Dapprich suggested the idea that a small (Mössbauer-like) crystal might be the appropriate object to put into a linear superposition of two slightly differing locations. Considerable encouragement about feasibility issues, and specific suggestions about the appropriate scales for the experiment, were put to me by Anton Zeilinger and several members of his experimental group at the Institute of Experimental Physics at the University of Innsbruck.

The basic experimental arrangement is indicated in figure 2. I have illustrated the set-up with the incident particle being a photon. However, it should be made clear that this is for ease of description only. The experiment might well be better performed using some other kind of incident particle, such as a neutron or neutral atom of some suitable kind. For convenience in what follows, I shall refer to this incident particle simply as a 'photon'.

A beam splitter is placed in the path of this incident photon, and one leg of the resulting superposition of the photon's state is kept in some kind of cavity which is capable of preserving the photon's state for, say, about one-tenth of a second without loss of phase coherence. In the other leg of the photon's state, the photon impinges upon a small crystal—containing, say, about 10^{15} nuclei—and the photon is reflected from the crystal, imparting a significant fraction of its momentum to the crystal. The reflected photon state is itself kept in a similar (or even the same) cavity as the other part of the photon's state. The crystal is to be such that the entire momentum of the photon's impact upon it is shared by all the crystal's nuclei acting as a rigid body (as with a Mössbauer crystal), without there being a significant probability of exciting internal vibrational modes. The crystal is subject to some kind of restoring

force (indicated in figure 2 by a spring) of such strength that it returns to its original location in, say, one-tenth of a second. At that moment, the part of the photon's state which impinged upon the crystal is released from the cavity so that it reverses its path, cancelling the velocity of the returning crystal as it does so. The other part of the photon's state is then also released, with very precise timing, the two parts coming together at the original beam splitter. Provided that there has been no loss of phase coherence in the entire process, the two parts of the photon's state combine together coherently and exit the same way that they came in, so that a detector positioned in the alternative exit beam from the beam-splitter would detect nothing.

Now, according to the proposal of § 5, the superposition of two crystal locations, which persists for about one-tenth of a second in the preceding descriptions, would be unstable, with a decay time of about that order. This is assuming that the wavefunction of the crystal is such that the expectation value of the mass distribution of the locations of the nuclei is rather tightly concentrated about their average nuclear positions. Thus, according to that proposal, there would be a large probability that the superposed crystal locations (a 'Schrödinger's cat') will spontaneously reduce *in actuality* to one location or the other. The photon's state is initially entangled with that of the crystal, so that spontaneous reduction of the crystal's state entails a simultaneous reduction of the photon's state. In this circumstance, the photon has now 'gone one way or the other' and is no longer a superposition of the two, so that phase coherence is lost between the two beams and there is now a significant (calculable) probability that the detector will detect the photon.

Of course, in any actual experiment of this nature, there are liable to be many other forms of decoherence which would destroy the interference between the two returning beams. The idea here is that after all these other forms of decoherence are reduced to a sufficiently small degree, then by varying the parameters involved (size and specific nature of the crystal, the distance it is displaced in relation to lattice spacing, etc.), it would be possible to identify the particular signature of decoherence time inherent in the proposal of § 5. There are many modifications of this proposal that can be considered. It seems to me that there is a considerable prospect of putting to the test not only the scheme being proposed here but also various other state-reduction schemes that have been put forward in the literature.

7. Relevance of state reduction to quantum computation

The above considerations certainly have some distinct relevance to quantum computation. It is important for the possibility of quantum computation on a vast scale that large-scale quantum superpositions can be maintained for a significant time. Would the considerations of § 5 lead us to expect that there is an absolute limit on the size of computations that can be carried out quantum computationally? It does appear that this is so, but rough considerations concerning the amount of superposed mass displacement that is necessary in quantum computation indicate that any such absolute limit would be well beyond the range of other practical limitations. The whole issue is well worthy of further study, however.

More interesting is the question of whether the phenomenon of quantum state reduction might have a *positive* role to play in some form of quantum computation. In fact, state-vector reduction is already made use of in 'conventional' quantum computation. The most obvious place where this comes in is at the *end* of a quantum

computation, where an appropriate measurement must be made in order to ascertain the result of the computation. Moreover, and this is not often stated explicitly, since there is in principle no general way to be sure how long a computation is going to last (because of the computational insolubility of the halting problem for Turing machines) it is necessary to have a means of checking, from time to time, whether or not a quantum computation has indeed ‘halted’. This checking requires a measurement (and therefore a state reduction) to be performed on the system. Finally, there are procedures for ‘purifying’ the states used in quantum computation (the ‘entanglement distillation’, ‘syndrome extraction’, ‘quantum error correction’, referred to in § 1) which themselves make use of quantum state reduction.

These procedures make use of quantum state reduction in its standard form, and it does not make a great deal of difference to which of the general viewpoints (1)–(4) of § 4 one adheres. The result of a state reduction is taken to be *random* (with probabilities obtained by use of the standard ‘squared amplitude modulus’ rule of quantum theory). However, it might well be the case, according to the proposal of § 5, that the result of a reduction is not simply random but is (perhaps partially) fixed by some other mathematical scheme. According to the suggestions put forward in Penrose (1987, 1989, 1994), this mathematical scheme ought to be something non-computational and it plays an essential role in actual conscious thought processes taking place in the brain. A specific proposal along these lines has been put forward by Hameroff & Penrose (1996*a, b*). It is a significant aspect of this specific proposal that it depends critically upon an objective state-reduction scheme of the nature of that proposed in § 5. Thus, the Hameroff–Penrose proposal would be refuted by a negative result in the experiment set forth here in § 6.

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Discussion

P. MARCER (*BCS Cybernetic Machine Group, Keynsham, UK*). During teleportation, it appears as if time reversal is the simplest apparent explanation of what physically is actually taking place. This is the same conclusion as Professor Schempp

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has reached in relation to what is happening during tomographic (fMRI) imaging. Here, the theory of quantum holography, validated in relation to other aspects of the image extraction process, infers that for enhanced image extraction to happen, not only is time reversal taking place but that space itself is being 'squeezed' (see Schempp 1997). Phase conjugation is also consonant with this idea. fMRI would therefore probably allow it to be tested.

R. PENROSE. I understand that Y. H. Shih and his associates have made use of this effect.

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