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On the Curiously Retro-causal Effects of Quantum State Reduction in Quantum Reality

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Abstract

It has been argued that quantum state reduction is a gravitational effect. However, to make sense of it one needs to distinguish "Quantum Reality" from the more familiar "Classical Reality". This notion of quantum reality is developed here, indicating its curious relation to the normal flow of time, most strikingly in the Einstein-Podolski-Rosen type of phenomena.

1 Introduction

In the late 1960s and early 1970s, I used to have weekly discussions with Basil Hiley, in Birkbeck College, these being also attended by students and frequently by David Bohm. These discussions were on the foundations of quantum mechanics, most frequently on the mysterious phenomenon of wave-function collapse upon measurement. Eventually, after I had left Birkbeck to join the University of Oxford, Basil developed his own ideas in relation to those of Bohm, as finally presented in a very substantial book, Bohm and Hiley [1993].

My own ideas developed very differently, under the belief that quantum state reduction had to be a gravitational effect, where one needs to distinguish a "Quantum Reality" from the more familiar "Classical Reality". In this paper, I develop the ideas of quantum reality, indicating its curious relation to the normal flow of time, most strikingly in Einstein-Podolski-Rosen types of phenomena.

2 The Principle of Equivalence and Quantum Mechanics

The principle of equivalence asserts that, locally, the effect of the gravitational field is identical to that of an accelerating reference system. In quantum theory, this principle takes a curious form in that the effect of an acceleration on the quantum system is to introduce a term in the phase factor which involves the exponential of the cube of the time. Versions of this effect effect have been noted by various authors over the past century, as summarized in Bose et al. [2025], where an experiment is described which strikingly confirms this necessary feature for the principle of equivalence to extend to quantum systems.

These considerations refer simply to a background gravitational field and, specifically, to the Earth's gravitational field. However, we encounter difficulties when we try to extend these ideas to a gravitating body which is itself in a superposition of two separate locations, whose own superposed gravitational field needs to be taken into consideration. Such situations had been studied by the author; and can be found in Penrose [2016, 2022], and discussed in more detail in Howl et al. [2019] and Fuentes and Penrose [2018]. The general conclusion of these arguments is that there is a fundamental uncertainty in the mass-energy of such a system, leading to the expectation that such a superposition of gravitational fields will have a lifetime which is inversely related to this energy uncertainty, in accordance with the Heisenberg time-energy uncertainty principle. This may be compared with the half-lifetime of an unstable nucleus, which is inversely related to an uncertainty in its mass value, in accordance with this basic Heisenberg principle.

The lifetime so obtained is in agreement with a proposal made by Lajos Diósi years before on the basis of different theoretical considerations Diósi [1984, 1987, 1989]. In order to calculate the Diósi lifetime of a body in a quantum superposition of two separate locations, where one location is displaced from the other by a translational motion, we can imagine that two identical copies of the body are initially exactly in coincidence with each other, but then we pull one copy away from the other by a strictly translational motion, until the two are separated by the intended amount, and we calculate the energy that this would cost, considering only the gravitational energy cost of this displacement but ignoring all other forces such as electromagnetic or nuclear. This energy will be the Diósi energy, whose reciprocal provides essentially the lifetime for the superposition to collapse to one or the other location. The proposal presented above would provide essentially the same lifetime for such a superposition.

Later, Diósi considered what would be involved when his lifetime proposal was applied to the detailed motions of the constituents of large complicated material, within which such wave-function collapses ought to be taking place all the time on a small scale. This led him to the prediction that the superposition of movements of molecules in the system would have a tendency to collapse, leading to a spontaneous heating of the system as a whole. Recent experiments Donadi et al. [2021] appear to have disproved this theoretical prediction of a spontaneous increase in temperature, thereby ruling out particular models of this specific kind.

It would appear that such spontaneous heating effects might also disagree with the very precise observations of the motions of celestial bodies, since the spontaneous heating of such bodies would lead to the increase of their masses as time progresses, which seems very unlikely in view of the very precise measurements of the motions of celestial bodies.

A different picture is presented here in which such spontaneous heating effects are avoided completely, as a consequence of considerations of special relativity, at the expense of a seemingly retro-causal behaviour in the collapse picture.

3 Quantum state reduction in a space-time setting

Figure 1 describes a body being put into a quantum superposition of two locations which gradually separate as time progresses. The point O in the picture represents the start of the quantum displacement so that the broken lines on the left and the right emanating from the point O represent the two alternatives of the body in superposition. We suppose that the collapse takes place significantly after the two locations become well separated from each other. At a certain stage, collapse does take place and the body becomes located entirely in the left-handed location, as indicated by the left line becoming unbroken at Q^*, whereas the right-handed location disappears at Q. However,there is a problem with this picture if we look at it from the perspective of observers moving at great speed either to the right, observer

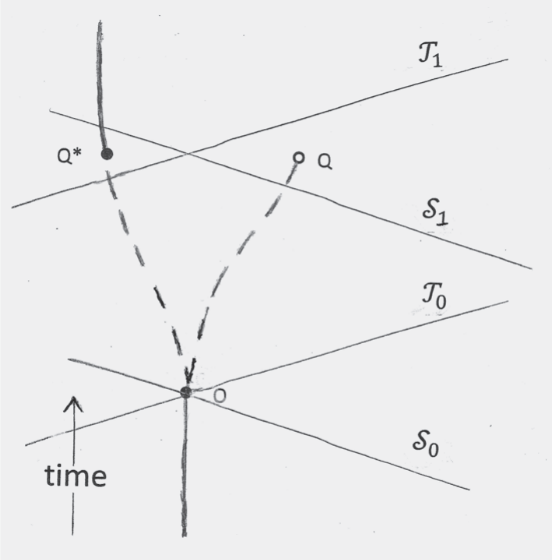

Figure 1: Quantum superposition of two locations

$\mathcal{T}$, or to the left, observer $\mathcal{S}$.

The moment O, according to observer $\mathcal{T}$, is represented on the line sloping to the right indicated as $\mathcal{T}_0$. For observer $\mathcal{S}$, the picture at the moment O corresponding to the start of the superpositon is indicated by the line $\mathcal{S}_0$ which is tilted up on the right hand side. As noted above, it is supposed that the collapse of the superposed state is to the left hand alternative so that the right-hand alternative disappears at the point Q, which in turn results in the quantum state being completely at Q^*, and then persisting in the unbroken line towards the top.

In contrast, according to observer $\mathcal{S}$, the total state of the body has become entirely located on the left-hand side at the intersection of the worldline with the plane $\mathcal{S}_1$. Yet, since the intersection of this surface of simultaneity according to $\mathcal{S}$ still intersects the broken line of the right-hand alternative, this means that there is still a probability, according to $\mathcal{S}$, that the body might appear at Q.

Even worse, on the surface of simultaneity of observer $\mathcal{T}$, the right-handed alternative has already disappeared when there is still a probability that the left-hand alternative may disappear also, leaving us with the absurdity of the body vanishing altogether.

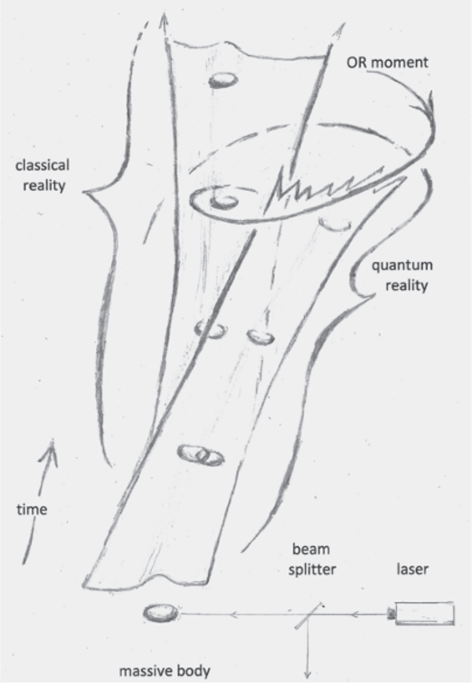

Figure 2: Quantum superposition of a massive body

Clearly this is an absurdity, and to make sense of the situation, it appears to be necessary to consider the possibility that the decision has already been made that the body will be in the left-hand branch right back at the point O. Accordingly, I take the viewpoint that despite the presence of a quantum-superposed state, the *actual* physical reality of the situation is representend in the picture by the left-handed route right up from the point O, including the broken line up to Q^*. The left-handed branch describes the entire 'classical reality' of the state of the body, whereas there remains a 'quantum reality´ in which both branches persist up until the termination of the right-hand branch at Q.

In figure 2, a somewhat more complete picture of such a situation is provided. In general terms, time progresses from the bottom of the picture to the top. At the very bottom, we see depicted a laser which aims a high-energy photon at a tiny material body, with a beam splitter in the path of the photon's path, so that upon encountering the beam splitter the photon's quantum state is put into a superposition of it going further along the horizontal path where it hits the tiny material body and the vertical downward path where the photon remains free. This puts the tiny body itself into a superposition of receiving the photon's impact and not receiving it. As we proceed upwards in the diagramme, the tiny body's superposed state of having been displaced and not having been displaced evolves in time. As the body has mass and given that according to the Einstein field equations the structure of space-time differs by the given quantity and location of a mass in space-time, each of the superposed states will bring about a slightly different space-time corresponding to the tiny massive body being in two different locations. Thus, space-time itself is put into a superposition. This persists as we move up the picture where the separation of the two space-times increases until the collapse occurs, whereby the left-hand branch by itself comes to represent the entire reality of the situation. The classical reality is represented as the left-hand branch which is entirely smooth without any sharp jump in the space-time. The quantum state reduction is described at the top of the picture where the right-handed branch is terminated, yet the classical reality remains smooth as described by the left-handed branch from bottom to top. The quantum reality retains both branches in superposition but that reality is terminated when the classical reality takes over.

I have eluded to the distinction between classical and quantum reality in Penrose [2016] but first spelt it out properly in Penrose [2022], p. 346. Einstein, Podolsky and Rosen (EPR) suggested a criterion for a given quantity to be an "element of reality", which I shall take as my starting point for spelling out the distinction between classical and quantum reality in the following. Einstein et al. [1935], p. 778-779, write:

> A comprehensive definition of reality is, however, unnecessary for our purpose. We shall be satisfied with the following criterion, which we regard as reasonable. *If, without in any way disturbing a system, we can predict with certainty (i.e;, with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.* It seems to us that this criterion, while far from exhausting all possible ways of recognizing a physical reality, at least provides us with one such way, whenever the conditions set down in it occur. Regarded not as a necessary, but merely as a sufficient, condition of reality, this criterion is in agreement with classical as well as quantum-mechanical ideas of reality.

So EPR regard this criterion as applying both to classical and quantum reality. However, as might be expected from a criterion that is supposed to be only a sufficient but not a necessary condition for something to be real, it does not exhaust all the differences between classical and quantum reality. These differences come particularly into focus in the case of entangled quantum systems, as we shall see in a moment. As elaborated in Penrose [2022], p. 346, the core difference between dealing with classical and quatum reality is that with respect to classical reality, one can ask the system in question "What is your state?", and the system can then legitimately respond (upon being measured): "My state is X" with certainty. In contrast, with regard to quantum reality, if one wants to obtain and answer with certainty, one has to be content with being able to ask the question "Is your state X?", and the system will (upon meaurement) answer "Yes, my state is indeed X" or "No, it is not". In other words, with regard to quantum reality, one must be content with confirming the state of a system rather than being able to ascertain it. However, this confirming or disconfirming will be done with certainty, and a quantum state thus confirmed fulfils EPR's criterion (which I called 'Einstein's dictum' in Penrose [2022]).

The implication of this point of view is brought to the fore when we consider the Einstein-Podolsky-Rosen experiment in Bohm's form but again taking the special theory of relativity into account, as depicted in figure 3. Here, Alice and Bob are space-travellers who at point O are each presented with a sealed box which contains a spin half particle, say an electron. The two electrons have been put into an entangled state by virtue of the fact that the two particles initiated from a spin 0 state before being parted and put into the two boxes handed to Alice and Bob, respectively. Now, after Alice and Bob have become separated by a great distance after point O, Alice chooses to measure the state of spin of the electron in her box. At point M_A, she essentially asks the electron "Are you in the state $|\nearrow\rangle$?", and the measurement disconfirms, so that Alice now knows that the state of her electron is instead $|\swarrow\rangle$. This has the implication that Bob's state must be opposite to what Alice has found, in order that the initial state can indeed have been spin 0.

Of course, from the point of view of special relativity, the notion of distant simultaneity does not make (objective) physical sense since it depends on what reference system is being adopted. As with the situation in figure 1, a reference frame taken with respect to observers moving rapidly to the right or to the left would provide us with a different assessment of which point on

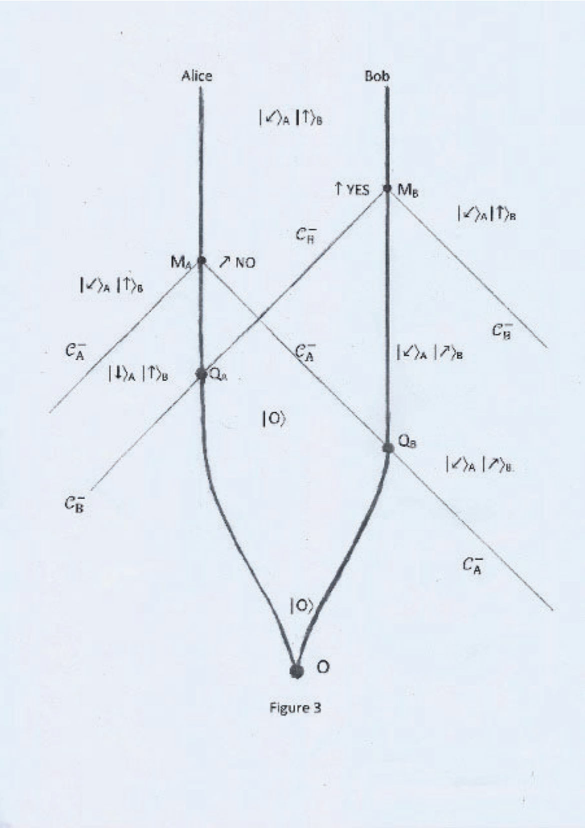

Figure 3: An EPR-type experiment taking special relativity into account

Bob's world-line is simultaneous with Alice's measurement. In the extreme case, the theoretical fast-moving observer moving rapidly to the left would cause Bob's state to be viewed as having become opposite to what Alice finds in her measurement at a point arbitrarily close to point Q_B, depending on the rapidity of the fast-moving observer's motion. As that motion approaches the speed of light, we find that the point taken to be simultaneous with Alice's measurement at M_A could provide the conclusion that the point is as close as we like to the point Q_B, which is the intersection of the past light-cone of M_A with Bob's world-line. Accordingly, we find that the spin state of Bob's electron must have been the opposite to what Alice finds, already at this point Q_B, even though he did not actually measure the state until much later, namely until point M_B. This provides a very curious picture of the quantum reality of this situation, particularly because we can reverse the roles of Alice and Bob to obtain the conclusion that by the time that Alice makes her measurement at M_A, the result of Bob's measurement, which essentially consists of him asking "Are you in the state $|\nearrow\rangle$?", receiving the answer "Yes!", from which he concludes that Alice's state must be $|\swarrow\rangle$ before *her* meaurement has been carried out at the point Q_A, which is the intersection of the past light-cone of M_B with Alice's worldline. Thus, what Alice eventually measures would have indeed been this state, which is consistent with her measurement disconfirming that her electron is in the state $|\nearrow\rangle$.

This is an extremely peculiar situation where "causality" considerations do not follow the ordinary classical rules. However, we are now talking about quantum reality, and the rules of quantum reality turn out to be very different from what would be expected from a classical picture. What is striking about this situation as depicted in figure 3 is that despite the peculiarity of the way in which quantum reality behaves, it does not appear to be actually inconsistent. It would be an interesting exercise to see if this lack of inconsistency is a universal feature of entangled states which one could find out by looking at more complicated scenarios than that depicted in figure 3, e.g. those summarised in Pan et al. [2012]. It is a question of whether this would clarify or confuse the deep questions concerning quantum reality as opposed to classical reality.

Where does this leave us? I had commented earlier that the way to avoid the consequence of the anticipated spontaneous heating in the Gran Sasso experiment is to take note of the fact that according to the Diósi proposal the individual quantum collapse events would feature a 'jump' in the state, which would, overall, have the effect of a heating. However, in the proposal being put forward here, classical reality is completely continuous, without any spontaneous heating at all, in accordance with the findings of the Grand Sasso experiment. In this way, we are to combine a quantum-mechanical collapse picture with the relativity of simultaneity as it appears in special relativity at the price of seemingly retro-causal behaviour. In accordance with figures 1 to 3, it is clear that it is only in this strange quantum reality, which cannot actually be ascertained, that these curious seemingly retro-causal effects can occur, although indirectly. However, they do have classical implications, such as the violation of Bell's inequalities Bell [1964], not considered here.

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