INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF OPTICS B: QUANTUM AND SEMICLASSICAL OPTICS

J. Opt. B: Quantum Semiclass. Opt. **4** (2002) S351–S357 PII: S1464-4266(02)37814-5

An amusing analogy: modelling quantum-type behaviours with wormhole-based time travel

Stéphane Durand

Centre de Recherches Mathématiques, Université de Montréal, CP 6128,
Succ. Centre-ville, Montréal, Qc, Canada H3C 3J7

E-mail: durand@crm.umontreal.ca

Received 15 December 2001
Published 29 July 2002

Abstract
When backward time travel through wormholes is taken into account, classical physics loses its determinism and allows simulation of some quantum behaviours. We show how it is possible to simulate a non-local wavefunction reduction-type effect, i.e. we present a mechanical analogy for the collapse of the wavefunction of an entangled state of two removed particles. This situation can be seen as the simplest EPR situation, i.e. the situation where there is just one direction to measure along the spin (or the correlated properties). We present no rigorous results here, just a different point of view about something that is generally thought to be impossible: modelling a quantum indeterministic and non-local behaviour with a mechanical system.

Keywords: Wormhole, time travel, EPR correlations, quantum entanglement, indeterminism, non-locality

1. Introduction

We generally think that classical physics is deterministic and local, while quantum mechanics is indeterministic and non-local. But when backward time travel through wormholes is taken into account, classical physics loses its determinism and allows a 'classical' understanding of some quantum behaviour. For instance, it is possible to picture something analogous to a non-local wavefunction reduction, i.e. it is possible to imagine a mechanical analogy for the collapse of the wavefunction of an entangled state of two removed particles. This situation can be seen as the *simplest* EPR situation, i.e. the situation where there is just one direction to measure along the spin; this situation being the only one possible in two dimensions (our wormhole model is two-dimensional). Of course, it is the general case, the three-dimensional Bell's case, that is crucial from an experimental point of view, *but not from a conceptual point of view* since the quantum *formalism* is indeterministic and non-local even in two dimensions. Moreover, when reformulated in terms of wormhole machinery, the non-local aspect of the 'wavefunction reduction' becomes Lorentz covariant since it uses retro-causation[1] instead of ('spooky') action-at-a-distance as in orthodox quantum mechanics (and also because wormhole physics should be part of general relativity). Note also that if only microscopic wormholes could exist (or if they were stable only at a microscopic scale), this 'quantum' behaviours would disappear at the macroscopic level. So, even with its limitation, we think the present model is worth noticing as part of a reflection about the 'mysteries, puzzles and paradoxes in quantum mechanics'.

Since the work of Morris *et al* [2], it is known how to construct a time machine from any wormhole: it suffices to move one mouth of the wormhole away from the other at high speed and then to bring it back, the two mouths acting like the two members of the twins paradox. Then, crossing the wormhole one way generates travel forward in time, and backward in time the other way. So, if stable wormholes can really exist, time machines can also. Of course backward time travel, when applied to human beings, invariably leads to

---

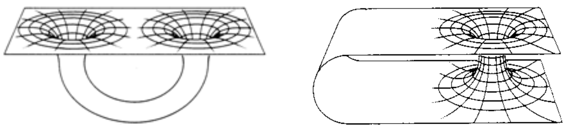
[1] Note that the present idea is totally different from the work of [1] which relies on hidden variables. Here we keep the indeterminism as a fundamental aspect.

deeply paradoxical situations; but not necessarily when applied to inanimate objects. For it is the conflict between *free will* and travelling back in time which yields paradoxes; for instance, going backward in time and killing one's younger self, i.e. changing the past[2]. In contrast, a particle (which has obviously no free will!) can return to its past and interact with a younger copy of itself in a consistent way. Therefore, if only microscopic wormholes could exist, i.e. if only elementary particles could use them and travel into the past, there would be no unresolvable paradox.

It is known [3] that when such wormholes are taken into account, classical physics loses its determinism. We will show here that it is possible to generalize the idea in order to imagine a classical mechanical analogy for a quantum phenomenon which is both indeterministic and non-local, such as the one involved in the wavefunction collapse of an entangled state. We emphasize again, however, that we present no rigorous results here, but just a new way of looking at some quantum behaviours.

2. Wormhole and time travel

To be self-contained, let us recall the work of [3]. We will first see how an inanimate object can travel to the past and interact with a younger copy of itself in a consistent way. Figure 1(*a*) shows a 2D wormhole embedded in a fictitious 3D space. (The same wormhole can equivalently be represented as in figure 1(*b*).) In the following, we will limit ourselves to the simpler situation where the sizes of the wormhole's mouths are negligible, so that the mouths can be treated as pointlike. In others words, we will consider only radial motions into and out of the wormhole. We will also neglect the recoil of the wormhole when the particle traverses it. With these approximations the rules governing the trajectories of a particle (also pointlike) entering a wormhole are very simple. As indicated in figure 2 (where the two circles represent the wormhole's mouths of figure 1(*a*) seen from the top), if the particle enters the right mouth of the wormhole from *a* (respectively *b*, *c* and *d*), it leaves the left mouth as in a' (respectively b', c' and d'). These rigorous results [3] can be intuitively understood from the wormhole's geometry (figure 1). Now, suppose we transform this wormhole into a time machine [2], allowing for instance a 2 h jump forward or backward in time: as seen by an observer outside the wormhole, an object entering from the right emerges from the left 2 h earlier; conversely, entering by the left it exits from the right 2 h later. From the object's point of view, however, time still flows toward the future during the traversal. (The same as for a human being who at the age of 70 in year 2000 used a time machine to travel 50 years backward in time; he will come out the machine in 1950 but at the same age or slightly older.) If the wormhole's throat is very short, the object enters and exits the wormhole at (almost) the same *proper* time, i.e. at the same age. Note that the wormhole's throat can be 'short' even if its two mouths connect two distant regions according to the exterior space. In that respect, embedding diagrams are misleading since the two situations depicted in figures 1(*a*) and (*b*) are mathematically equivalent (according to general relativity). Since we are only interested here in backward time travel, we will limit ourselves to the situation with the particle entering the right mouth.



(*a*) (*b*)

Figure 1.

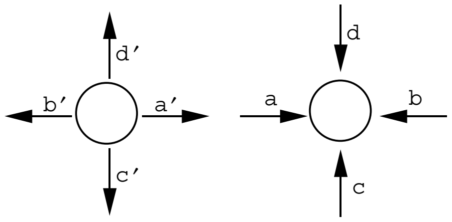
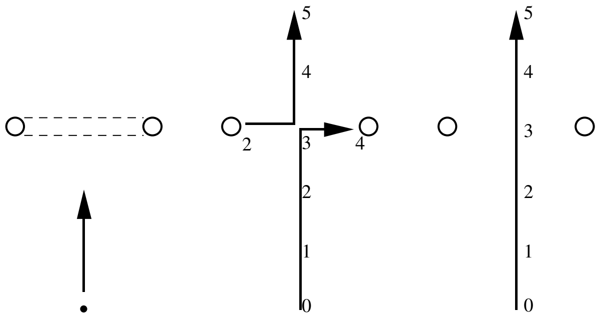


Figure 2.



(*a*) (*b*) (*c*)

Figure 3.

In figure 3(*a*), a particle is moving toward such a time-machine wormhole. Figure 3(*b*) shows a situation with a self-interaction; the details of the motion are as follows. Suppose that the wormhole allows a step back 2 s in the past, and suppose that the particle's speed is constant through the whole process. (Only the exterior time is depicted in the figure.) The particle, which we can imagine acting as a small billiard ball, comes from the bottom. At time $t = 3$ s, it reaches the middle point between the two mouths. At that moment, it gets hit by a second particle coming from the left. The collision deflects the first particle at a right angle toward the wormhole's right mouth, while the second particle is deflected toward the top. At $t = 4$, the first particle enters the wormhole by the right mouth. It emerges from the left mouth 2 s sooner, that is at $t = 2$. Then, at $t = 3$ it hits the particle coming from the bottom. The collision is thus between the particle and itself (self-collision): the particle returns to the past, meets its younger self (i.e. collides with), then carries on its evolution. (More precisely, supposing the particle was created at $t = 0$, it is a collision between a 5 s old copy and a 3 s old copy of the particle, if we suppose that the particle exits the wormhole at the same age it enters.)

As we see, such an experience is entirely coherent. Of course, if at $t = 3.5$ s the particle 'decides' to change its

---

[2] Of course, if free will (this liberty we feel to have to take decisions and make actions) is just an illusion, such paradoxes would not necessarily occur.

trajectory in order to miss the right mouth and therefore not enter the wormhole, a contradiction will follow: from where, then, did the other particle which hit it come? This is exactly the kind of paradox which would appear if objects with free will could travel backward in time. But for inanimate objects, 'forced' to follow the rules of the game (i.e. the rules of physics), no paradox occurs[3].

3. Classical indeterminism

We will now see why determinism is lost in the presence of wormholes. Compare figure 3(*b*) with 3(*c*) which depicts the same wormhole and the *same initial condition*, i.e. a particle coming from the bottom reaching the middle point between the two mouths at $t = 3$. But, then, the particle simply follows its straight motion toward the top. Both possibilities (figures 3(*b*) and (*c*)) are perfectly allowed. In other words, the same initial condition may lead to two different evolutions (collision or no collision). The choice between both evolutions must be made at $t = 2$: at that moment, either a particle comes out the left mouth (leading to a collision), or no particle comes out (and the first particle follows its straight motion). The future is thus settled at this very moment. But how to decide between the two evolutions? Impossible! The choice must be made at random. Genuine indeterminism is at work here. We thus have a mechanical model for a pure indeterministic process.

Let us now push the example a little further. In both situations of figure 3, the particle arrives at the same final position at the same moment and at the same speed. For instance, at $t = 5$ both in figures 3(*b*) and (*c*) the particle is at the same point. In this example there is no difference between the final states. The difference lies only in the intermediate motion. Nevertheless, we can suppose that the collision produces a permanent effect on the particle, cracking it for instance. In that case, the same initial condition may produce two different final situations: cracked or not cracked. Thus, by analogy with quantum mechanics, we can describe the state of the particle before its arrival near the wormhole (actually, before $t = 2$) by the following 'superposed state':

$$|\Psi\rangle = |c\rangle + |n\rangle$$

where $|c\rangle$ means cracked and $|n\rangle$ means non-cracked *at the end of the process*, i.e. where $|\Psi\rangle$ is written in terms of the final possible outcomes. (Normalization factors are of no importance here and throughout the rest of the paper.) Then, at $t = 2$, a 'measurement' is made on the particle, say by its interaction with the wormhole (implying that either a second particle comes out or not from the wormhole's left mouth), and the state 'collapses' randomly into either $|c\rangle$ or $|n\rangle$. So, in some sense, this process can be seen as a sort of 'wavefunction reduction'. Note that the process of figure 3(*b*) is irreversible. Indeed, if we reverse it, the particle coming from the top and entering the left mouth would travel 2 s *forward* in time (instead of backward, because it is crossing the wormhole the other way), and would exit the right mouth too late to hit itself at the centre. (A variation on these points is made in the next section.) This simple example, then, can be seen as a mechanical model for a quantum measurement.

Actually, an indeterministic process could be split in two parts: (1) a single cause should be able to produce different effects; and (2) how does nature choose between these different effects? In general, these two points look intimately related. But we now see that it is not necessarily so. Indeed, we now 'understand' point 1, since we have a mechanism to explain it; but 2 is still mysterious: What is the meaning of a genuine random choice; how can a choice really be made at random? The wormhole-based model vividly emphasizes this point.

The situation depicted in figure 3 was originally put forward in [3]. However, it was not motivated in that work as an example of a mechanical model for an indeterministic process, as here (and no analogy with wavefunction reduction was made), but rather it appeared in the context of a discussion about the consistency of the physics of wormholes. These authors, then, use quantum ideas and semi-classical techniques (WKB approximation) to associate probabilities with each possibility in order to remove the ill-defined (classical) evolution of the particle, that is, the non-uniqueness of its classical solution. But, here, the philosophy is different. We do not want to justify wormhole physics with the help of quantum physics, but the reverse: we want to 'justify' quantum physics in terms of wormhole physics. That is, we want to use (microscopic) wormholes to model quantum behaviours; and, in particular, in section 5 we will modify figure 3 in order to model *non-local* quantum measurements, i.e. a kind of simple EPR-type situation.

4. 'Spin'-type effects

The previous example was an easy one since no calculation was needed to follow the particle's motion. Indeed, we approximated the particle by a point and neglected the dimension of the wormhole's mouth. An even more striking example would be to consider the general case. One can show [3], taking into account the size of the mouths, that different trajectories *inside* the wormhole are possible for the same initial trajectory (figure 4): in situation (*a*), the particle coming from the bottom (in black) is slightly deflected to the right by the collision with itself (in grey) on its left rear side, while in situation (*b*) it is slightly deflected to the left by a collision on its front right side, thus entering the wormhole's right mouth at a slightly different position. Entering the wormhole in a different way, the particle leaves it also in a different way, thus explaining why the angle of the collision was different. In this new example, the same initial trajectory can evolve into two *different* final trajectories. This is reminiscent of a Stern–Gerlach experiment, in which a spin-half particle is deflected in one of two ways. If the 'Stern–Gerlach' apparatus is switched off, that is if the wormhole is removed, the particle is not deflected and continues along a straight line. Note that here both processes of figure 4

---

[3] Of course, it is possible to imagine inconsistent situations even for inanimate objects. But the important point is that for these objects there is a class of phenomena which are consistent while for entities with free will *every* situation is potentially inconsistent. Non-contradictory situations, for inanimate objects, are said to satisfy the principle of self-consistency which states that 'the only solutions to the laws of physics that can occur locally in the real universe are those which are globally self-consistent' [3]. In this paper, we will consider only situations satisfying this principle. Note that it may actually be possible to reconcile free will and backward time travel if one is willing to introduce the idea of parallel universes, see [4].

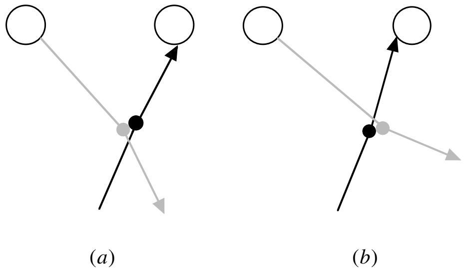


Figure 4.

are irreversible: in both figures the particles travelling in the reverse direction would cross the wormhole in the wrong way to allow them to travel into the past. So, by analogy with spin behaviour, let us call $|-\rangle$ and $|+\rangle$ the final trajectories in grey (i.e. the final states) of figures 4(*a*) and (*b*) respectively. Thus, before the collision the particle is in the 'superposed state'

$$|\Psi\rangle = |+\rangle + |-\rangle$$

and the interaction with the wormhole collapses it to either $|+\rangle$ or $|-\rangle$.

In this view, then, spin would be a purely gravitational effect. A spin measurement being actually the result of an interaction with a magnetic field, the wormhole would represent the effect of the magnetic field (and the non-existence of macroscopic wormholes would forbid any classical analogue of spin)[4]. Of course this is a very limited model for spin. Moreover, it will not work for particles with spin other than one-half nor for two successive measurements. Nevertheless, the purpose here is not to find a model for spin but rather for the collapse of the wavefunction of two-state systems and, as we will see in the next section, to its extension to an entangled pair of particles.

5. EPR-type correlations

It is easy to see that quantum formalism is non-local, i.e. that it predicts the existence of (implicit) instantaneous influences, though the experiences to prove that are much more involved. Let an EPR pair of spin-half particles be in the following state:

$$|\Psi\rangle_{12} = |+\rangle_1|-\rangle_2 - |-\rangle_1|+\rangle_2. \tag{1}$$

Here, we will restrict ourselves to situations where the same spin component is measured on both particles, i.e. we will not consider the rotation of one detector compared with the other one. At the moment of the first observation (of particle 1 or 2) the entangled state (1) collapses randomly into either $|+\rangle_1|-\rangle_2$ or $|-\rangle_1|+\rangle_2$. That is, the observation of *one* particle collapses the state of *both* particles, no matter how far apart they may be. The second observation (measuring the same spin component on the other particle) just reads the already collapsed state, it does not perturb it. We thus see that the formalism predicts the occurrence of an 'instantaneous influence' (or in Einstein's words, a 'spooky action-at-a-distance') because (i) each particle's state, $|+\rangle$ or $|-\rangle$, is not fixed before the first measurement *and* (ii) both measured particle's states must be (anti-)correlated[5]. We can see that the reduction process is not Lorentz covariant since, the interval between observations 1 and 2 being time-like, the temporal order between them can be different in different Lorentz frames: in one reference frame the collapsing is produced by detector 1, and in another it is produced by detector 2. So the reduction process is not made by the same detector depending on the reference frame! Hence, taken literally, the reduction postulate contradicts special relativity. But the wavefunction reduction in itself being a non directly observable process, it yields no operational inconsistency, i.e. no *apparent* violation of causality (the experimental results by themselves do not violate causality). This is why it is said that quantum mechanics is in conflict only with the spirit of special relativity, though it seems to be a profound conflict[6].

Of course, if we measure the same spin component for both particles (the so-called basic situation), the experimental results are easily explainable classically, i.e. without any kind of superluminal influence, by supposing that the spin states are fixed *before* the first measurement. The 'magic' of Bell's theorem was precisely the demonstration that in some more complicated situations (which we will not discuss here) the experimental results predicted by the quantum theory are not explainable classically or, more precisely, are not explainable with a local realistic model. But the point here is that even in the basic case, for which the *experimental* results are explainable classically, the *formalism* itself predicts a non-local effect (a non-local wavefunction reduction), and we will now see how wormhole physics can simulate it.

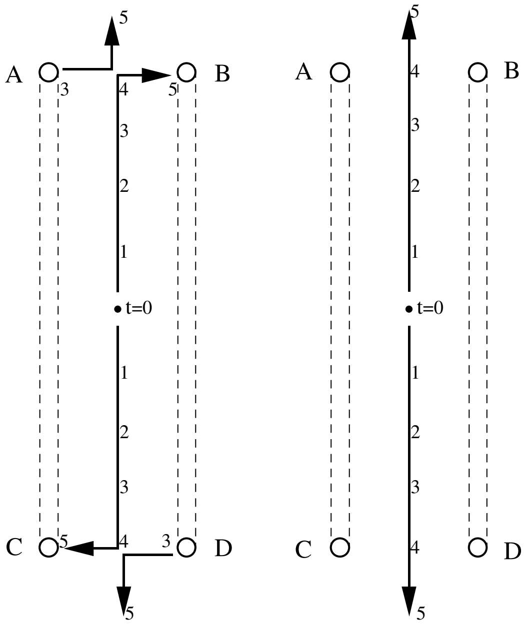
To simplify the discussion, we will only consider situations analogous to figure 3, i.e. with the same final trajectories, and we will consider that the two possible final particle's states are cracked and non-cracked. Figure 5(*a*) shows two long wormholes in dotted lines. Each one allows 2 s backward time-travel, either from B to D or from C to A. In between, at the centre (where $t = 0$), two identical particles are emitted at the same speed, in opposite directions. Let us follow the one moving upward: at $t = 4$ it gets hit on its left, at $t = 5$ it enters the wormhole at B, it then moves

---

[4] Note that considering a magnetic dipole as a wormhole is not a new idea. In other contexts, such an idea has been advocated by Wheeler [5], Feynman [6] and Sorkin [7]. Furthermore, note that this type of spin model would imply that spin is not an intrinsic characteristic of the particle: it would be an environment-dependent characteristic, the mere result of an interaction. Without a wormhole around, spin would have no meaning. That is, spin would be defined (not only known but defined) only by making a measurement of it. But is that not exactly what quantum mechanics says (in its pure Copenhagen interpretation)? (This environment-dependent characteristic reminds us of a different attempt [8] to classically model another property of a spin-$\frac{1}{2}$ particle: its rotational behaviour under rotation, i.e. the fact that it needs not only one but two full 360° rotations to restore its initial configuration. See also [9] for a different approach to an environment-dependent characteristic for spin)

[5] We stress that this 'instantaneous effect' cannot be used to communicate since the collapse of the state is done randomly. Note also that this 'instantaneous effect' is only implicit, and not explicit as in Bohm's pilot-wave theory.

[6] The wavefunction cannot be seen as merely a mathematical trick representing our knowledge of the system since it leads to pure non-classical experimental results: interaction-free measurements, for instance [10]. Note that the non-local character of quantum mechanics is also at work when only one particle is involved. Indeed, according to the standard formalism, a measurement at some point may instantaneously collapse a wavefunction at some other point. For instance, a measurement in one of the two arms of an interferometer may instantaneously collapse the wavefunction in the other arm. This phenomenon underlies the so-called interaction-free measurement just cited. However, unlike EPR-type situations, it is not possible to experimentally confirm this non-local process when only one particle is involved.



(*a*) (*b*)

Figure 5.

2 s backward in time to emerge from D at $t = 3$, finally at $t = 4$ it gets hit from the top and deflected downward. On the other hand, the other particle (starting downward) also gets hit at $t = 4$, enters the wormhole in C at $t = 5$, moves 2 s backward in time to exit from A at $t = 3$, gets hit again at $t = 4$ and deflected upward. No contradiction! Another possibility is shown in figure 5(*b*): no particle uses any wormhole, no collision occurs, both particles move in straight motion. Both evolutions of figure 5 are coherent and could happen.

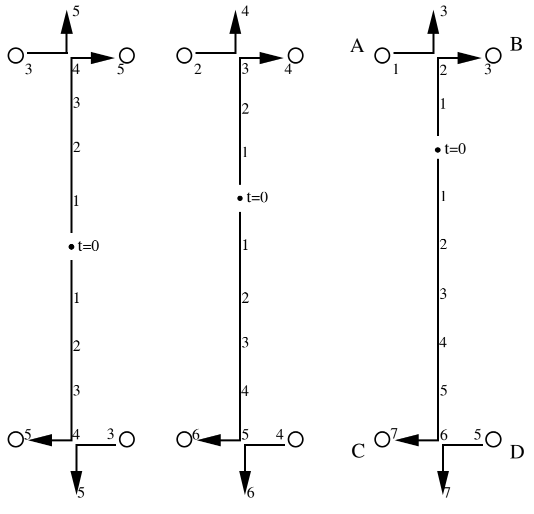
Since a collision at one end implies a collision at the other end, at the conclusion of the experience either both of the particles are cracked or neither of them is cracked: the final states are thus correlated. However, just after the emission of the particle, and actually until $t = 3$, nothing is decided: it is impossible to predict any particle's final state (cracked or non-cracked). The choice is made at $t = 3$: at that moment, either no particle emerges from the mouths A and D, or a particle emerges from each mouth. Therefore, the outcomes of this experience are at once indeterministic (one cannot predict if the particles will be cracked or not) and correlated (both particles will be in the same state). Exactly as in an EPR-type experience.

So, by analogy with state (1) we can describe the system before $t = 3$ by the 'entangled' state

$$|\Psi\rangle_{12} = |c\rangle_1|c\rangle_2 + |n\rangle_1|n\rangle_2 \qquad (2)$$

where, as before, $|c\rangle$ means cracked and $|n\rangle$ means non-cracked at the end of the process, i.e. for $t > 4$. (The fact that (2) represents correlated states while (1) represents anti-correlated states is of no importance.) Then, at $t = 3$, the state (2) 'collapses' into $|c\rangle_1|c\rangle_2$ or $|n\rangle_1|n\rangle_2$. (To transpose this example to 'spin', we could imagine duplicating and symmetrizing figure 4 instead of 3.)

Now suppose, as shown in figure 6(*c*), that the particles are emitted at $t = 0$ closer to the mouths AB than the mouths CD.



(*a*) (*b*) (*c*)

Figure 6.

This means that the 'measurement' in the AB area is achieved before the 'measurement' performed in the CD area. Until $t = 1$, both evolutions are potentially present and the system is described by (2). Then, a choice is made at $t = 1$: a particle exits or not from A. This fixes the evolution ('reduction of the state vector') at *both* ends, even if an observer at the other end will see or not a particle emerging from D only 4 s later, i.e. at $t = 5$. For him, the 'measurement' will only occur after $t = 5$, but everything was decided since the time $t = 1$. His measurement therefore fixes nothing (no choice involved), it only reveals a prefixed state. Note that in this case the particle travels toward the *future* in the wormhole BD. Figure 6(*a*) simply reproduces figure 5(*a*), and 6(*b*) shows an intermediate situation.

Despite the analogy we proposed with wavefunction reduction, and unlike the orthodox interpretation of quantum mechanics which asserts that the particle's location *is not defined* before the measurement, here we have concrete particles with well-defined motions and following real trajectories at all times. The only uncertainty is a dilemma between using a wormhole or not.

Another 'amusing' feature is that the whole process seems Lorentz covariant. Indeed, there is no need here for an instantaneous propagation (implicit or explicit) of some influence from one observer to the other as in the usual quantum formalism. Instead, we have retro-causation which, being everywhere space-like, is totally in agreement with the relativistic structure of spacetime. Also, wormhole physics should be part of general relativity[7]. However, even if nothing here propagates instantaneously between the ends AB and CD, there is the equivalent of an instantaneous effect as seen from outside the wormholes. From a conceptual point of view, we thus can compare an indeterministic non-local (usual quantum mechanics with implicit action-at-a-distance) and an indeterministic local (wormholes with retro-causation)

---

[7] Actually, the rules governing the trajectories of a particle entering a wormhole were calculated in [3] only for non-relativistic particle speeds (though the spacetime was Lorentzian). Whether or not the same rules apply for relativistic speeds is apparently still an open question.

explanation of the same phenomenon. Note that if only microscopic wormholes could exist (or if they were stable only at a microscopic scale), such retro-causation behaviours would be impossible at the macroscopic level. So, the wormhole analogy permits us also to understand why some 'quantum' behaviours should disappear at large scale.

Of course, we just modelled the simplest type of EPR correlations (what we called the basic case). As we said, the experimental outcomes for this situation can be reproduced with pure classical deterministic physics. It suffices to suppose that the particles' states are fixed *before* the first measurement, the pairs of particles being emitted half in the state $|c\rangle_1|c\rangle_2$ and half in the state $|n\rangle_1|n\rangle_2$ (or in any other fractions adding to one). Indeed, in that case there is no indeterminism and no non-local effect involved, though the outcomes are correlated. *On the contrary, the wormhole model simulates a genuine indeterministic and non-local process, i.e. exactly what the quantum formalism tells us.* In order to model more complicated situations, such as those underlying Bell's theorem, one should symmetrize figure 4 instead of 3, and allow the segments AB and CD of figure 5 not to lie in the same plane. But to analyse the dynamics of such situations, one should first generalize the results of [3] to the case of three-dimensional motion[8].

6. From quantum to classical

Since wormholes can always be transformed into time machines, if a human being could use them it would invariably lead to temporal paradoxes (supposing free will is not just an illusion). To preserve the consistency of History, this should be forbidden. But how? A plausible answer seems the following: macroscopic wormholes are unstable, so that macroscopic objects cannot use them. Such an answer (admitting its truth) yields however another question: why are entities big enough to have a consciousness (and free will) precisely too big to use a wormhole?

So, for the rest of this section let us try a different answer. In both figures 3(*b*) and (*c*), at the end of the process the particles reach the same point at the same time and at the same speed. If the particles have no (elaborated) internal structure, the final states in both cases are thus identical. But this is no longer true if the particles have an internal structure since the internal states will be modified by the collision (cracking of the particle, for instance). Similarly, if we take into account the ageing of the particles there will be a difference between the two final situations. Denote the particles' proper time by τ, and look again at figure 3(*b*). Suppose that the wormhole throat is infinitely short, so that the particle's proper time is the same at the entrance and at the exit of the wormhole. At the beginning: $t = \tau = 0$. The collision occurs at $t = \tau = 3$, and the particle enters the wormhole at $t = \tau = 4$. It emerges 2 s earlier according to the exterior time, i.e. at $t = 2$, but with the same proper time, i.e. with $\tau = 4$. The collision occurs at $t = 3$ and $\tau = 5$. The collision is therefore the 'meeting' of the young particle ($\tau = 3$) coming from below and the old particle ($\tau = 5$) coming from the left. The particle reaches the final position at the top of the figure at $t = 5$, at 7 s old ($\tau = 7$). On the other hand, if there is no collision (figure 3(*c*)), the proper time keeps identical with the exterior time: the particle reaches the final position at $t = \tau = 5$, i.e. at 5 s old. Hence, the particle's final states of figures 3(*b*) and (*c*) differ by their proper time (7 s old versus 5 s old).

In the context of classical mechanics, Newton's and Lagrange's approaches are equivalent even if they quite differ from a conceptual point of view. Newton's approach is local (causal): from the initial conditions, the evolution is generated step by step according to differential equations. Lagrange's approach is non-local (non-causal)[9]: from the initial *and* final conditions, the evolution is given from a variational principle as some *global* optimal motion. In general the two approaches are equivalent, but when time travel is taken into account this is no longer necessarily so. Indeed, taking into account the proper time, the final states of figures 3(*b*) and (*c*) are not identical ($\tau = 7$ in one case and $\tau = 5$ in the other), and so for *given* initial and final conditions there is only *one* solution. Or, supposing that a collision cracks the particle, if we look for solutions with an uncracked final particle, there is only one solution (figure 3(*c*)). There is no need, therefore, to make an indeterministic choice.

But for a (stable) particle there is no difference between being young and being old! For an electron, for instance, proper time means nothing since there is no internal structure, or at least no internal evolution. For an electron, the two final states of figure 3 are identical. But as soon as an object acquires a somehow elaborated internal structure, its proper time becomes significant (the object evolves intrinsically) and the solutions with time travel are no longer on the same footing as the ordinary ones. Hence, from a Lagrangian perspective one should make a distinction between a structureless object and a more complex one. For the former, there are two possibilities and an indeterministic choice must be made. For the latter, only one solution is allowed and everything is deterministic. *In other words, when the proper time becomes significant the classical behaviour is recovered.* The proper time is significant not only for living entities but for almost any 'macroscopic' object since such objects intrinsically evolve simply by interacting with the environment or else by the cumulative effect of the gravitation on their structure. (Note that a structureless object means both without internal evolution and pointlike, since for an extended object the two final trajectories of figures 3(*b*) and (*c*) would not be exactly the same due to the non-pointlike character of the collision.)[10]

---

[8] One approach would then be the following. In [3], it is claimed that the authors have developed a sum-over-self-consistent-histories formulation of nonrelativistic quantum mechanics for the self-interacting billiard ball of figure 3, and have found that it gives a unique, self-consistent set of probabilities for the two possible outcomes: 50% probability for each one. One thus should try to apply this technique to the situation of figure 5 (basic EPR case), or rather to the one constructed by duplicating figure 4, and then to the situation with the segments AB and CD not lying in the same plane (Bell's case), and compare the associated probabilities.

[9] Non-local here does not have the same meaning as before.

[10] Actually, there exist other solutions corresponding to the initial conditions depicted in figure 3, in which the particle is deflected downward [3]. We neglected these possibilities here; in any case, from the Lagrangian approach they are excluded since they do not correspond to the same final conditions. Moreover, according to some claims made in [11], in the context of the WKB semi-classical approximation these extra solutions have very small associated probabilities.

7. Conclusion

Of course, we do *not* necessarily have to 'understand' quantum mechanics. That is, we do not have to be able to explain quantum phenomena with a mechanical model. It may simply be impossible—and maybe this is precisely all the panache of the quantum theory. It seems nevertheless curious that some quantum behaviours can be simulated by wormhole-based time travel. But, is it that curious? The existence of a connection between quantum theory and motion backward in time is by no means a new idea. For instance, according to Feynman's approach to QED, an anti-particle can be interpreted as a particle going backward in time [8]. Whether or not this is just a mathematical equivalence is still an open question. However, even if Feynman's point of view about anti-matter is wrong there must be 'at some level' a connection between quantum theory and backward time travel, for quantum non-locality implies 'some kind' of superluminal effect (except maybe if we consider many-worlds type models), and from special relativity there is of course a connection between superluminal speeds and motion backwards in time. So, in some sense, 'travels' backward in time are intrinsically underlying the quantum nature of reality. In this perspective, it becomes less surprising to try to explain quantum processes with a time machine. It is interesting to note how the wormhole machinery stresses the intimate connection between non-locality and indeterminism since to model indeterminism we need wormholes, and wormholes imply non-locality (as seen from outside the wormholes).

A last comment in closing. According to the orthodox interpretation of quantum mechanics, there are no such things as concrete particles at the microscopic level. An electron, for instance, is not a tangible corpuscle following a trajectory. It is a much more abstract entity, which is *completely* described by the wavefunction. The image of a particle as pointlike is just the 'side effect' of some interaction with a macroscopic device (or with the environment). In other words, the position of the particle is not defined (and not just not known) until it is measured. It is commonly said that there is no element of reality associated with the position before the measurement. (The same is generally true for the spin.) Such an interpretation yields the following question: How can tangible objects (tables, walls, etc) be made of non-tangible ones (electrons, protons, etc)? At first sight, this appears to be a typically quantum mystery. But, actually, such a troubling fact is already present at the heart of special relativity. Indeed, according to $E = mc^2$, pure motion can be transformed into matter. For instance, in the reaction $\mathrm{p} + \mathrm{p} \rightarrow \mathrm{p} + \mathrm{p} + \mathrm{p} + \bar{\mathrm{p}}$, two new particles are created from the pure (lost in) motion of two others. How can motion, which is definitively not something, be transformed into something?

On the other hand, according to the wormhole model discussed here (and some others, such as the pilot-wave theory) a particle is regarded as a real concrete corpuscle and has a pointlike behaviour at all times whether or not it is measured. In return, to reproduce quantum behaviour we take into account explicit motion backwards in time. But if we consider that a particle is a concrete and tangible entity, how can we explain the creation of particles from the vacuum (an electron–positron pair, for instance)? But wait! If we accept backward time travel, Feynman's approach with its positron travelling backward in time is no longer so strange; and according to Feynman, precisely, there is no creation and annihilation of particles, there are just rebounds backward and forward in time!

Therefore, there seems to be a duality between, on the one hand, the usual interpretation of relativistic dynamics (with its creation and annihilation of particles) and the orthodox interpretation of quantum mechanics (with its non-tangible particles), and, on the other hand, Feynman's interpretation of relativistic dynamics (without creation and annihilation of particle) and a wormhole-type interpretation of quantum mechanics (with its concrete particles travelling backward in time).

Acknowledgment

This work is supported by the Fonds pour la Formation de Chercheurs et l'Aide à la Recherche (FCAR) of Québec.

References

[1] Aharonov Y, Botero A and Scully M 2001 Locality or non-locality in quantum mechanics: hidden variables without spooky action-at-a-distance *Proc. 3rd Workshop on Mysteries, Puzzles and Paradoxes in Quantum Mechanics (Gargnano, Italy, Sept. 2000) Z. Naturf.* A **56** 5–15

[2] Morris M S, Thorne K S and Yurtsever U 1988 Wormholes, time machines and the weak energy condition *Phys. Rev. Lett.* **61** 1446–9

[3] Echeverria F, Klinkhammer G and Thorne K S 1991 Billiard balls in wormhole spacetimes with closed timelike curves: classical theory *Phys. Rev.* D **44** 1077–99

Friedman J *et al* 1990 Cauchy problem in spacetimes with closed timelike curves *Phys. Rev.* D **42** 1915–30

[4] Deutsch D 1991 Quantum mechanics near closed timelike lines *Phys. Rev.* D **44** 3197

See also

Deutsch D and Lockwood M 1994 The quantum physics of time travel *Sci. Am.* **March** 68

[5] Wheeler J A 1962 *Geometrodynamics* (New York: Academic)

[6] Feynman R P 1995 *Feynman Lectures on Gravitation* (New York: Addison-Wesley)

[7] Sorkin R 1977 *J. Phys. A: Math. Gen.* **10** 717

Sorkin R 1979 *J. Phys. A: Math. Gen.* **12** 403

[8] Feynman's examples with the hand and with a ribbon in:

Feynman R P 1987 The reason for anti-particles *Elementary Particles and the Laws of Physics—The 1986 Dirac Memorial Lectures* (Cambridge: Cambridge University Press)

[9] Zurech W H 1982 Environment-induced superselection rules *Phys. Rev.* D **26** 1862

[10] Elitzur A and Vaidman L 1993 Quantum mechanical interaction-free measurements *Found. Phys.* **23** 987

Kwiat *et al* 1995 Interaction-free measurement *Phys. Rev. Lett.* **74** 4763

[11] Thorne K S 1994 *Black Holes and Time Warps* (New York: Norton)