Undoing Quantum Measurement: Novel Twists to the Physical Account of Time

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Since quantum measurement remains so ill-understood, its time-reversed version is bound to offer new insights. If undoing a quantum measurement is impossible in principle, it bears on the old problem concerning the origin of irreversibility. If it is possible, it gives new twists to basic notions like indeterminism and the uncertainty principle. We demonstrate this approach on the time-reversed version of the EPR experiment, where two entangled particles undergo measurements followed by "unmeasurements." Whereas Bell's theorem rules out local hidden variables, our experiment yields a complementary proof that even nonlocal hidden variables lead to observed violations of relativity. We are therefore left with either genuine randomness or a subtle time-asymmetry at the basis of quantum phenomena. Both options render the relativistic account of time incomplete. Genuine emergence and novelty turn out to be the most fundamental characteristics of physical reality.

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1. Introduction

Quantum measurement, after more than hundred years of research, remains the main obstacle to a better understanding of quantum theory. What about the time-reversed process? Is it possible in the first place? And whether the answer is positive or negative, what bearing has it on all the paradoxes besetting quantum mechanics?

Merely raising the question makes us aware that quantum measurement is deeply related to a broader physical riddle, namely, irreversibility and time-symmetry in general. This gives further incentive to study the issue.

This article communicates a work in progress. Some of its conclusions are tentative, hopefully to be made more rigorous in the future and stimulate further research.

2. The Physics of Time-Reversal

Consider an elastic collision between two particles. It is possible to reverse the process by reversing the momenta of the particles after the collision, such that the entire process would evolve backwards, retrieving the initial state from the final one. What about larger, macroscopic processes, involving myriad of particles? Mainstream physics holds that the question is merely technical. Given a suitable technology, so goes this majority opinion, every process can be reversed. No rigorous theoretical limit to reversibility has been pointed out so far.

3. Introducing 'Unmeasurement'

The quantum version of the reversibility question is even more intriguing. Can a quantum measurement be time-reversed such that a measured particle will resume its initial superposed state? While opinions are more divided on this issue, it is obviously akin to the issue of time-reversal in general. A few interpretations of quantum mechanics invoke the notion of "wave-function collapse," an abrupt change of the measured particle's state that is irreversible (see below). Other interpretations, however, avoid collapse, regarding measurement as reversible as any other process.

The issue is not entirely divorced from present-day technology. A procedure known as "quantum erasure" (Scully, Englert & Walther, 1991) purports to time-reverse quantum measurement. In the commonest version of this method, a particle undergoes a double-slit experiment, but while it passes through the slits it is entangled with another particle. Measurement of the latter particle can reveal which path was taken by the former. Consequently, the original particle's interference is destroyed. However, by subjecting the other particle to an appropriate measurement analogous to interference, each particle gives a "key" that enables observing the other's interference.

A closer inspection, however, reveals that no real undoing of measurement takes place in this method because no real measurement was made in the first place. Rather, entanglement was employed, later to be countered (but not undone) by a more subtle measurement.

Elitzur and Dolev (2001) proposed a different method of unmeasurement based on interaction-free measurement. They showed, for the first time, that just like measurement, unmeasurement too exerts a non-local effect in the EPR experiment. Another advance of their technique is that it is not subject to the No-Trace Restriction (see Section 5 below). However, the method works only for partial measurements, and its success becomes increasingly improbable as the measurement's outcome approaches certainty.

Other methods, still far from technical feasibility, have been studied (Peres, 1980; Greenberger & YaSin, 1989). They indicate that, just like earlier famous gedankenexperiments, deriving novel predictions gives an incentive to experimentalists to turn them into real experiments.

Unmeasurement, then, is of enormous importance for theoretical physics. *If quantum measurement turns out to be irreversible for some basic physical reason, then the age-old problem of the origin of irreversibility and time-asymmetry* (Savitt, 1995) *will get a fresh answer. If, on the other hand, quantum measurement turns out to be reversible, several surprising results would follow, bearing on other fundamental questions.*

4. Collapse entails Fundamental Irreversibility

What is measurement in the first please? Rather than implicating human observers, consciousness, etc., let us adopt Bohr's simple definition 'an irreversible act of amplification.' The meaning of 'irreversible' naturally, will be the bone of contention.

Next, a closely related term needs to be considered. 'Collapse of the wave-function' is a process that several interpretations of quantum mechanics invoke in order to explain the strange nature of measurement. It is important to realize that this collapse, if it indeed occurs, is irreversible *in principle*, regardless of technology.

Consider a wave-function of a single photon being split by a beam-splitter, each half going to another detector. One detector clicks will the other remains silent. In other words, the particle is detected in one of its two possible locations and turns out not to be in the other. The collapse interpretation holds that, while the wave-function initially went to both locations, measurement has made it materialize in one and totally vanished from the other location. Can the entire process be time-reversed? As long as we are talking at the gedanken level, it is possible to make the detector that clicked eject back the particle it has detected. But what about the other detector? Obviously, it cannot eject back the 'nothing' that it did *not* absorb. Consequently, the wave-function will not return to its original state, failing, for example, to exhibit interference. Wave-function collapse, then, entails a fundamental form of irreversibility, perhaps the most fundamental one.

So, does collapse occur? Our own belief is that it does, thereby providing the microscopic basis to all macroscopic manifestations of irreversibility. But of course, 'belief' is no substitute for a rigorous proof. Hence we shall henceforth study quantum measurement as if collapse does not occur. Rather, we shall follow hidden-variables theories and assume that some 'guide wave' always remains where the particle turns out not to be. It is such hidden variables that make the retrieval of the entire wave-function possible.

5. The Sacrifice: No Record of the Measurement's Outcome must be Left

Annoyingly, undoing a quantum measurement carries a peculiar price: *Unmeasurement necessitates complete elimination of any record of the measurement's outcome, including the observer's memory and knowledge.* We must remain oblivious of the outcome that has been erased, as even the smallest trace of a measurement left unreversed would ruin the entire procedure.

Is there any point, then, to considering quantum unmeasurement if the outcome to be undone must never be known? Fortunately, the answer is a resounding yes in the EPR case. We do not need to know the outcomes of the measurements that we seek to undo. Suffice it that we can see whether, following the unmeasurement, the two particles are entangled again.

6. Unmeasurement in the Context of the EPR Experiment

The EPR experiment (Einstein, Podolsky & Rosen, 1935) gave rise to one of physics' most famous paradoxes, in that it helped prove that quantum mechanics involves interactions that violate, albeit indirectly, the relativistic prohibition on velocities greater than light. Consider an atom with spin 0 ejecting two spin-$1/2$ particles that fly far apart towards two measuring devices that measure whether each particle's spin is $1/2$ ("spin up," $\uparrow$) or $-1/2$ ("spin down," $\downarrow$). Conservation laws oblige the two spins to be opposite: $\uparrow\downarrow$ or $\downarrow\uparrow$.

Is the correlation between the spins pre-established, having been fixed when the particles left the atom? A celebrated proof by Bell (1964) ruled out just that: The correlation can be established only upon the particles undergoing measurement. Hence, each particle must somehow "know" which measurement the other particle is undergoing and what the outcome is, in order to maintain the appropriate correlations even when the two measurements are orthogonal.

Now let *unmeasurement* be considered in this case. Straightforwardly:

Let two EPR particles, A and B, undergo measurements. Then let the measurements be time-reversed. Would the two particles resume their entangled state, being capable of manifesting again Bell-inequality violations upon consecutive measurements?

This, of course, is only a gedankenexperiment, as was initially the EPR itself. Present-day technology is far from capable of time-reversing any large-scale process, let alone the ill-understood quantum measurement.

None of this should concern us here. We envisage an idealized, very small and perfectly isolated laboratory, within which the particle pair undergoes a pair of measurements and then the entire process is "undone" without inspecting the measurements' outcome (see 4 below for the reason for this avoidance). Then let the two particles come out of the laboratory and be subjected to yet another pair of new measurements, this time to be fully inspected. Would these later measurements manifest Bell-inequality violations?

The stakes, no doubt, are high. *A negative answer would be nothing short of a theoretical proof that quantum measurement is inherently irreversible, likely the source of all larger-scale irreversibilities.*

What about a positive answer? Here, two assumptions need to be made in order to allow unmeasurement, and the result is far-reaching.

7. First Restriction: Reversibility entails Determinism

It is almost a tautology that, for a process to be reversible, it must be strictly deterministic. To retrieve the process's final conditions from the initial ones, each and every one of the intermediate stages must strictly determine the next one. And when the process involves numerous molecules, the slightest deviation from determinism will result in the time-reversal's failure (Elitzur & Dolev, 1999). For the EPR experiment to be reversible, therefore, we must assume, in line with the "hidden variable" theories, that the spin values yielded by the two measurements are not genuinely random but rather determined by causal factors, merely unknown yet objectively existent.

Apparently, our quest should end at this point with the desired conclusion. Has Bell's theorem not ruled out hidden variables? Experimental tests of the theorem show that the two particles could not have their spins fixed when they were emitted from the atom. *Q.E.D.*?

No, because Bell's theorem ruled out only *local* hidden variables, leaving it possible that nonlocal variables play a role (this was Bell's own belief). In other words, the process may be deterministic as long as an event can exert its causal effect on another spacelike-separated event, i.e. instantaneously.

The stakes, then, are even higher than a quantum origin of irreversibility: *If we rule out the exotic possibility, never challenged so far, that the particles' spins are determined by nonlocal deterministic causes, we shall banish determinism even from its last resort in quantum mechanics.*

8. Second Restriction: Quantum Determinism Entails Absolute Time

We assume, then, that for quantum mechanics to be reversible it must obey some hidden determinism, albeit of a nonlocal type. This leads to the second and last restriction: *Nonlocal* hidden variables entail an absolute time parameter.

Consider the presumed hidden factor, $F_\uparrow$ or $F_\downarrow$, that determines the spin direction. Where can such a factor reside? Bell's theorem has banished it from its natural place, namely, the common source of the particles, from which it could locally determine the particles' spins. It can therefore be present only in the measuring apparatus. Presumably, then, the presence of the factor $F_\uparrow$ or $F_\downarrow$ in the measuring advice causes the spin to be $\uparrow$ or $\downarrow$, respectively.

Now, in the EPR case, the same factor may often happen to be present in *both* measurements of the two particles A and B. By angular momentum conservation, it is impossible for both spins to be $\uparrow$. We must therefore assume that the causal priority goes to the "earlier" measurement, the "later" being able only to amplify the "already" determined spin.[a] The quotes around "earlier," "already" etc., remind us that the two EPR measurements are space-like separated, hence any temporal relations between

[a] A bolder assumption, namely that one EPR measurement can causally affect the *earlier* one, would immediately give rise to causal loops. Indeed, the retrocausal models, (Sheehan, 2006 and references therein) assume that measurement affects the particle's entire history backwards down to its emission, but these models are understandably very careful not to invoke any deterministic mechanism that would lead to such causal loops.

them can exist only within an absolute reference frame. Indeed, an absolute time parameter (say, that of the entire Universe's rest frame) is the inevitable consequence of any nonrelativistic theory that allows effects to propagate faster than light.

With this minimum of two restrictions, let us proceed to the unmeasurement experiment.

9. Time-Reversing Nonlocal Hidden Variables enables Distinguishing Absolute Motion

Let, then, two EPR particles A and B undergo spacelike separated measurements M_1 and M_2, respectively, with a small time interval between them (in the absolute time frame), such that M_1 occurs slightly "before" M_2. Suppose now that the presumed spin-determining factor $F_\uparrow$ happens to be present in both M_1 and M_2. As M_1 is slightly "earlier" than M_2, only M_1 affects A's spin to be $\uparrow$, thereby forcing B to be $\downarrow$, in compliance with conservation laws. Consequently, M_2 can only amplify the $\downarrow$ result imposed by M_1, despite the presence of $F_\uparrow$ in M_2 too.

Next, let the entire experiment be time-reversed. Let two unmeasurements $\cancel{M}_1$ and $\cancel{M}_2$ be performed on the two particles. By our above second Restriction of Determinism, we assume that the spin-determining factor $F_\uparrow$ that resides in both measuring devices also takes part in the two unmeasurements. As M_1 occurred before M_2, $\cancel{M}_2$ must now occur before $\cancel{M}_1$. This, by definition, is true for every deterministic time-reversal. The proof for this requirement is simple, given in Appendix (1), Fig. 1 depicts the experiment.

So far so good. Things do not go well, however, when the frame is a *moving* one, within which the experimental setup must obey Lorentz transformations. These transformations, in turn, clash with the absolute time-parameter which, by the above Absolute Time Restriction, is supposed to govern the nonlocal correlations.

The clash arises as follows. Let the entire experiment – the spin measurements and their time-reversal – be carried out in some inertial frame moving at near-c velocity with respect to the observer. Fig. 2 reveals the crucial twist brought by this motion: The simultaneity plane t' of the moving frame becomes slanted proportionately to the frame's velocity, deviating from the absolute simultaneity plane t. Consequently, the time-interval between the spacelike-separated M_1 and M_2 merely dilates, but the $\cancel{M}_2$-$\cancel{M}_1$ interval is *reversed*. This will ruin the overall time-reversal of the EPR experiment.

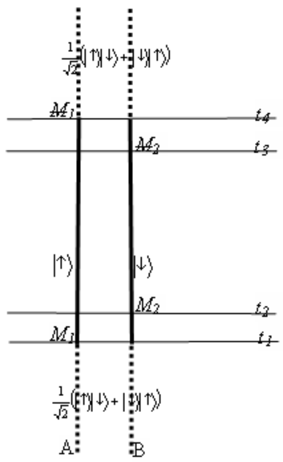

Fig. 1. **An EPR experiment undergoing time-reversal.** On each particle's world-line, the dotted segment represents the time interval during which the particle is superposed whereas the solid segment depicts its having a definite spin.

Conversely, if the reference frame moves to the opposite direction, the "unmeasurements" will maintain the same absolute time order as in the absolute time, but the measurements themselves will suffer the same order-exchange, leading again to the failure of time-reversal.

One escape hypothesis, albeit far-fetched, may be proposed here instead of the Absolute Time Restriction: Perhaps, in a moving frame, the nonlocal hidden variables do not operate in absolute time but obey the Lorentz transformations too? This possibility has been considered long ago (Elitzur, 1996) and shown to clash with conservation laws (see Appendix 2). The clash arises when the moving frame reverses its motion during the time interval between the two EPR measurements: The presumed cause-effect relations between the measurements must reverse, enabling anomalous cases of '↑↑' or '↓↓' spins to occur, in defiance of angular momentum conservation.

10. The Alternative Left: Genuine Randomness

What, then, have we achieved in the above analysis? Bell's theorem ruled out local *hidden* variables. We have now proved that nonlocal hidden variables are equally impossible.

One way out of the dilemma is offered by the collapse theories: If there is something inherently irreversible to measurement, no distinction between

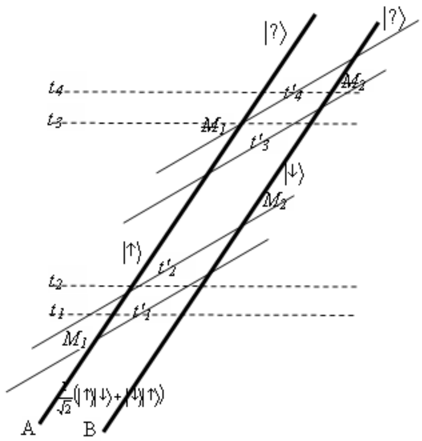

Fig. 2. The same experiment in a moving frame.

rest and motion will be possible in the first place. In other words, *perhaps unmeasurement, the very subject-matter of this paper, is simply impossible.* But, once again, we have no decisive proof for this option, although we favor it. Let us, then, consider the alternative and show that it has equally intriguing consequences.

We assume, then, that measurement is reversible. In this case, a measurement's outcome is genuinely random, but a subtle time-asymmetry emerges. *Quantum measurement is indeterministic in one direction and deterministic in the other: The transition from superposition to a definite value can lead to one out of several outcomes, but time-reversing each of these outcomes must lead to the same state of superposition.*

As far as we know, no observable reversibility can be derived from this asymmetry. Consider a process that contains some quantum spin measurements. Time-reversing the process ensures that the initial superposition states will be retrieved. Then, re-running the process must (by our above proof against nonlocal hidden variables) give rise to new spins, different from the earlier ones. Yet, by the No Record Restriction (Section 4), it is impossible to know what the initial spins were.

A slight change, however, enables us to derive a surprising prediction that is certainly observable.

11. The Consequence: Unmeasurements are Immune to Non-Commutation Laws

We have pointed out that genuine quantum randomness gives rise to a subtle asymmetry, in that measurement turns superposition into one out of many possible states *randomly*, while unmeasurement turns every possible state into superposition *with certainty*. Can this asymmetry be observed?

Yes. All we have to do in order to observe it is to make the two EPR measurements noncommuting, say, subject one particle to measurement of its spin along the x direction while the other's spin is measured along the y direction.

Here, time plays an observable role: *While the measurements of the spin directions are non-commuting, the unmeasurements do commute.*

The reason is simple. Consider a pair of EPR spin measurements, one of the x direction and one of the y direction. Bell's theorem proves essentially that the result of each particle's measurement depends on the choice of measurement to be performed on the other particle and its result. Hence, if x is performed before y, the following counterfactual holds: *The outcomes would be different have the measurements been made in a reverse order.* This is a direct consequence of Bell's theorem.

It is equally clear, however, that the same cannot be said about the *unmeasurements* of x and y, otherwise it will be possible to distinguish between motion and rest as in the case of nonlocal hidden variables in the previous section.

A subtle asymmetry between measurements and unmeasurements arises, which warrants an experimental test: *If unmeasurements turn out to be possible, they will be immune to non-commutation relations.*

12. Hawking's Information-Loss Conjecture Supported

Next we wish to point out a surprising consistency of our Genuine Randomness Conjecture with one of the most intriguing issues in present-day physics, namely, Hawking's (1976, see Preskill, 1993) information-loss paradox. True, Hawking himself has eventually retracted from his claim, but several physicists, we among them, remain unconvinced.

In essence, Hawking has shown that when a black hole swallows matter, the information associated with that matter is lost, and when the black hole evaporates, *new information is created at its event horizon.* This information seems to be genuinely new in that it appears to be unrelated to the matter swallowed earlier.

But this is precisely what the Genuine Randomness Conjecture holds to take place every time a measurement is made! If a particle is first measured, then unmeasured and then measured again, the outcome of the last measurement must not be determined by the first one. This is uncannily similar to the process in which empty space gives rise to virtual particle-pairs that form and then mutually annihilate. When such a virtual pair becomes real,as in black hole evaporation, new information is created, not determined by any previous process. In mainstream physics today this result is regarded as disturbing and often dismissed as erroneous. Our analysis, in contrast, renders this genuine novelty, natural: *New information is generated with every quantum measurement.*

13. A New Twist to the Transactional Interpretation

Finally, let us assess our findings in terms of one of the most consistent and appealing interpretations of quantum mechanics, namely, the transactional interpretation (Cramer, 1986). It has gained a widening acceptance during the last decade, not the least because of its simplicity, elegance and explanatory power (see, e.g. Sheehan, 2006).

In the transactional interpretation, any quantum interaction is the result of two wave-functions, one retarded and the other advanced, going back and forth in time between the source and the absorber, eventually giving rise to a complete quantum exchange of a particle. EPR-Like effects get a very fresh explanation this way: *The back-and-forth wave-functions form a spacetime zigzag, connecting the two particles in the present through their common origin in the past.*

How, then, should an EPR experiment look like in this framework when the two particles undergo a pair of measurements and then a pair of unmeasurements? Again, the transactional interpretation faces the same choice as other interpretations: If it holds that unmeasurement is impossible, then it is pointing out the microscopic source of irreversibility. If, on the other hand, it allows unmeasurements, the resulting picture is very peculiar: *An entire spacetime segment undergoes 'revision', such that, the entire history of the EPR pair is 're-written'.* We have earlier (Elitzur & Dolev, 2006) derived a similar conclusion from the transactional interpretation with the aid of novel gedankenexperiments indicating that spacetime itself is subject to a subtler form of evolution, not yet accounted for in the present-day relativistic framework.

14. Summary

What, then, has unmeasurement added to our understanding of quantum mechanics? With due modesty, quite a lot. Our analysis indicates that measurement may be fundamentally irreversible, hence unmeasurement probably cannot take place. Quantum mechanics, presently held to be a time-symmetric theory, may turn out to be the source of all asymmetries.

Conversely, if unmeasurement is possible, measurement must be genuinely random. In order for unmeasurement not to lead to results that violate special relativity, the outcome of each and every measurement must not be determined by local hidden variables *neither by non-local ones*. The latter restriction is a novel result, making quantum randomness absolute. Every event of measurement must introduce a genuinely new bit of information into the universe.

Which of the two alternatives eventually turns out to be correct? We do not know yet, but a more decisive argument will hopefully be found.

As for the interpretation of quantum mechanics, we have shown that, within the transactional interpretation, unmeasurement indicates that two or more histories must be 'written' and then 're-written' on top of one another on the same time segment. Spacetime itself must therefore be subject to evolution in some higher time parameter. This is very likely the time of Becoming (Elitzur & Dolev, 2005a, 2005b), so missed in present-day physics (Davies, 1995).

It seems safe to conclude, therefore, that the famous 'uneasy truce' between relativity and quantum mechanics has never been uneasier. If there are hidden variables beneath the quantum level, then, by an earlier proof of ours (Elitzur & Dolev, 2005a), they must be 'forever-hidden variables' in order to never give rise to violations of relativity. But then, by the same reasoning that has lead Einstein to abolish the aether, they probably do not exist. Indeed, it has been proved long ago (Elitzur, 1992) that God *must* play dice in order to preserve relativistic locality. Hence, randomness, novelty and emergence, which for luminaries like Parmenides, Spinoza and Einstein were mere epiphenomena to be explained away, are likely the Universe's very mode of existence.

Appendix 1: The Order of the "Unmeasurements" must be Precisely Opposite to that of the Measurements

The world-lines of particles A and B are as in Fig. 1: The dotted segments represent superposition while the solid segments represent definite spins. Each double-line represents the world-line of the measuring instrument that carries first the measurement, and then its undoing, on the same particle.

On the left is a correct time reversal of the two measurements. Although the deterministic $F_\uparrow$ factor is present in both measurements, M_2 fails to force particle B to have the $\uparrow$spin because of the priority of M_1. During the time-reversal, whatever causal influence M_2 had, it is undone by the time M_1 occurs. Now read the whole experiment backwards in time: Every unmeasurement becomes a measurement and *vice versa*. Everything seems equally consistent.

On the right is the same procedure without being strict with reversing the order of the unmeasurements. Here, the backward-reading of the experiment is clearly odd: Why should $\cancel{M}_2$, now turned into a measurement, fail to turn the superposed particle into a $\uparrow$, getting $\downarrow$ instead? The rest of the evolution is equally inconsistent.

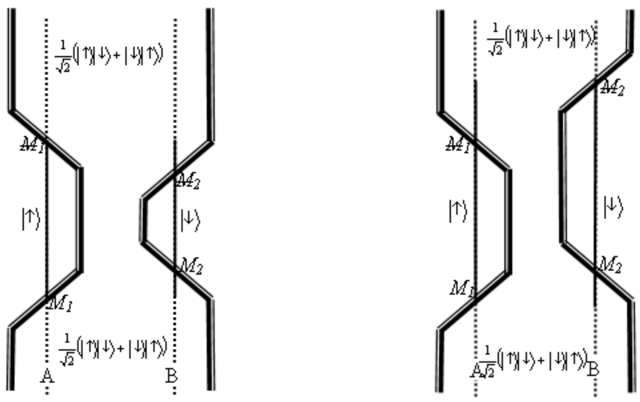

Fig. 3.

Appendix 2: Relativistic Nonlocal Effects Lead to Conservation Laws Violations

Consider the following hypothesis: The nonlocal effects observed in the EPR experiment are exerted in accordance with special relativity, that is, the simultaneity plane changes in accordance with the system's motion.

Next, consider an EPR experiment carried out in a frame that moves at a near-c velocity in one direction and then in the opposite direction. Let the two measurements be carried out with a slight time-interval, one before and one after the velocity reversal. In this case, a measurement that resided in the other measurement's 'future' prior to the reversal will suddenly shift to the 'past'. The presumed nonlocal effects would therefore fail to occur, giving rise to spin conservation violations.

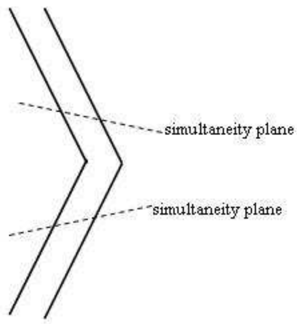

Fig. 4.

References

1. Bell, J. S. (1964) On the Einstein-Podolsky-Rosen Paradox. *Physics*, **1**, pp 195–200.
2. Cramer, J. G. (1986) The transactional interpretation of quantum mechanics. *Rev. Mod. Phys.* **58**, pp 647–687.
3. Davies, P. C. W. (1995) *About Time: Einstein's Unfinished Revolution.* New York: Simon & Schuster.
4. Einstein, A., Podolsky, B., & Rosen, N. (1935) Can quantum-mechanical description of physical reality be considered complete? *Phys. Rev.* **47**, 777–780.
5. Elitzur, A. C. (1992) Locality and indeterminism preserve the second law, *Physics Letters A*, **167**, 335-340.
6. – (1996) Time anisotropy and quantum measurement: Clues for transcending the geometric picture of time, *Astrophysics and Space Sciences* (special issue), **244**, 313-319.
7. Elitzur, A.C., & Dolev, S. (1999) Black hole evaporation entails an objective passage of time, *Foundations of Physics Letters*,**12**, pp 309–323.

8. Elitzur, A.C., & Dolev, S. (2001) Nonlocal effects of partial measurements and quantum erasure, *Phys. Rev. A* **63**, 062109-1—062109-14.
9. Elitzur, A.C., & Dolev, S. (2005a)Quantum phenomena within a new theory of time, In Elitzur, A.C., Dolev, S., & Kolenda, N. [Eds.] *Quo Vadis Quantum Mechanics?* , pp 325–350. New York: Springer.
10. Elitzur, A.C., & Dolev, S. (2005b) Becoming as a bridge between quantum mechanics and relativity, In Saniga, M., Buccheri, R., and Elitzur, A.C. (Editors) *Endophysics, Time, Quantum and the Subjective*, pp 589–606. Singapore: World Scientific.
11. Elitzur, A.C., & Dolev, S. (2006) Multiple interaction-free measurement as a challenge to the transactional interpretation of quantum mechanics, In Sheehan, D. [Ed.] *Frontiers of Time: Retrocausation – Experiment and Theory. AIP Conference Proceedings,* **863**, pp 27–44.
12. Greenberger, D. M. & YaSin A. (1989) "Haunted" measurements in quantum theory, *Foundation of Physics*, **19**, pp 679–704.
13. Hawking, S. W. (1976) Breakdown of Predictability in Gravitational Collapse, *Physical Review D,* **14**, pp 2460–2473.
14. Preskill, J. (1993) Do black hole destroy information?, *International symposium on black holes, membranes, wormholes and superstrings.* World Scientific, River Edge, NJ.
15. Peres, A. (1980) Can we undo quantum measurements?, *Phys. Rev. D* **22**, pp 879–883.
16. Savitt, S. (1995) *Time's Arrow Today*, Cambridge: Cambridge University Press.
17. Scully, M. O., Englert, B.-G., and Walther, H. (1991) Quantum optical tests of complementarity, *Nature* **351**, 111–116.
18. Sheehan, D. [Ed.] (2006) Frontiers of Time: Retrocausation – Experiment and Theory, *AIP Conference Proceedings* , **863**.