Multiple Interaction-Free Measurement as a Challenge to the Transactional Interpretation of Quantum Mechanics

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Abstract.
Cramer's analysis of interaction-free measurement in terms of his Transactional Interpretation is critically reviewed. Next we attempt to apply it to some varieties of IFM that have been devised during the last decade, pointing out the challenges posed by such attempt. We then discuss the possible bearings of these experiments on the Transactional Interpretation as well as on the nature of spacetime.

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1. INTRODUCTION

Cramer's [1, and this volume] transactional interpretation (TI) provides a simple, elegant and lucid explanation to some of quantum mechanics' most counterintuitive results. Its advantage has been demonstrated even in cases that its author did not consider [2, 3]. It is therefore no surprise that its application [4] to interaction-free measurement (IFM) [6] presents the same merits. And if a personal note is allowed, one of us (AE) is indebted to Cramer's stimulus for it was through Cramer's 1986 classic that he has learned about Reninger's negative-result experiment, the ancestor of IFM.

This article explores the promises and difficulties related to this interface. In Section 2 we briefly present the basic elements of the TI. In Section 3 IFM is introduced. In Section 4 we present Cramer's application of his interpretation for explaining IFM, whereas Section 4 offers a critical comment concerning the issue of temporality. Sections 5 points out one issue about which the TI remains undecided. In Sections 6-10 we present some new variants of IFM that we believe strain the TI. Finally in Section 11 we conclude with some unorthodox reflections on the nature of spacetime.

2. OUTLINE OF THE TRANSACTIONAL INTERPRETATION

Cramer succinctly summarized the TI in [4]. Any quantum event that involves the exchange of conserved quantities (energy, momentum, angular momentum, etc.), and that can be represented by a matrix element, is considered to have been formed in three stages:

1. An "offer wave" (the usual retarded wave function ψ or Dirac "ket" state vector $|a\rangle$) originates from the "source" (the object supplying the quantities transferred) and spreads through space-time until it encounters the "absorber" (the object receiving the conserved quantities).
2. The absorber responds by producing an advanced "confirmation wave" (the complex conjugate wave function ψ^* or Dirac "bra" state vector $\langle a|$) which travels in the reverse time direction back to the source, arriving with an amplitude of $\psi^*\psi$.
3. The source chooses between the possible transactions $\{i\}$ based on the strengths of the $\psi_i^*\psi_i$ echoes it receives, and reinforces the selected transaction repeatedly until the conserved quantities are transferred and the potential quantum event becomes real.

An important and still open issue that immediately ensues from this description concerns temporality. The TI appears to involve a sequential process, during which stages 1-3 and the repeated reinforcements occur "one after another." Since this is a process that takes place along time, does the TI implies that spacetime itself is subject to change? Cramer's early paper [4] strongly objected to this implication, adhering to the "block universe" picture of time. Yet his more recent view [5] reflects a bold switch to the unorthodox picture of "becoming." This issue will turn out to be highly relevant to the experiments discussed in the next sections.

3. INTERACTION-FREE MEASUREMENT

A few years after the publication of Cramer's interpretation, a new quantum experiment was devised. Consider a super-sensitive bomb with which even the slightest interaction possible leads to its explosion. Can one detect the bomb's presence at a certain location without destroying it?

Elitzur and Vaidman [6] posed this question with a new answer in the positive. Their solution was based on the device known as Mach-Zehnder Interferometer (MZI), shown in Fig. 1. A single photon impinges on the first beam splitter, the transmission coefficient of which is 50%. The transmitted and reflected parts of the photon wave are then reflected by the two solid mirrors and then reunited by a second beam splitter with the same transmission coefficient. Two detectors are positioned to detect the photon after it passes through the second beam splitter. The positions of the beam splitters and the mirrors are arranged in such a way that (due to destructive and constructive interference) the photon is never detected by detector D, but always by C.

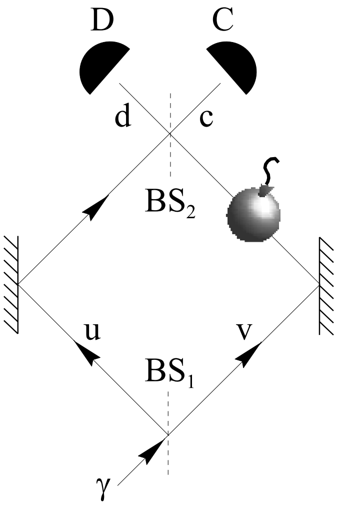

FIGURE 1. Interaction Free Measurement. BS_1 and BS_2 are beam splitters. In the absence of the obstructing bomb, there will be constructive interference at path c (the detector C will click) and destructive interference on path d (detector D never clicks).

In order to test the bomb, let it be placed on one of the MZI's routes (v) and let a single photon pass through the system. Three outcomes of this trial are now possible:

- The bomb explodes,
- Detector C clicks,
- Detector D clicks.

If detector D clicks (the probability for which being 1/4), the goal is achieved: we know that interference has been disturbed, *ergo*, the bomb is inside the interferometer. Yet, it did not explode.

The problem can be formulated in an even more intriguing way: Can one test whether the supersensitive bomb is "good" (better say: "bad") without bringing about its explosion? Again, all one should do is to place the bomb on one of the MZI's routes such that, if the photon passes on that route, the bomb's sensitive part can be triggered by absorbing only some of the photon's energy. Here too, the bomb constitutes a "which way" detector: Just as its explosion would indicates that the photon took the bomb's route, its silence indicates that it took the other route. And again, interference is destroyed by the bomb's mere non-explosion, indicating that the bomb *is* explosive.

Since the EV paper, numerous works, experimental and theoretical, have elaborated it and expanded its scope. Zeilinger *et. al.* [7] refined it so as to save nearly 100% of the bombs. Other applications of IFM range from quantum computation [8] to imaging [9]. Elitzur and Dolev [10] devised an IFM-EPR hybrid for an intriguing variant of the EPR experiment in which the entangled particles keep "talking" even after the first measurement.

4. THE TRANSACTIONAL INTERPRETATION OF INTERACTION-FREE MEASUREMENT

As the TI boasts so elegant explanations to some of the most intriguing quantum-mechanical experiments, it was only natural to expect an application of it to IFM. Such an analysis has indeed been proposed [4], and it is as attractive as the TI's analyses of the double-slit and EPR experiments. Here too, the process takes the familiar stages:

- The source sends an "offer wave"
- which is then split by the first BS,
- half of which arrives to the second BS and then splits again into two halves that go to the two detectors.
- The detectors respond with "confirmation waves" back to the source,
- part of which is blocked by the bomb's back side.[1]
- The bomb itself, too, responds with a "confirmation wave" of its own.
- The source thus receives three "confirmation waves" of different magnitudes,
- and then randomly chooses one out of them with which to complete the final "handshake."

5. DO ALL THE TRANSACTION'S STAGES OCCUR "AT ONCE"?

It is with respect to the role of time that we must raise our first critical comment on the TI. Notice that the time interval between the photon's possible interaction with the bomb and its final interaction with the detectors can be made arbitrarily long by delaying the photon's wave-function on the other arm. Once the interaction time with the bomb is over and no explosion occurred, two facts need to be addressed:

1. The wave-function is radically changed, now giving probability 1 that the photon is in the other MZI path.
2. One can remove the second BS and the detectors in a "delayed choice experiment [11]" fashion, preventing the final interaction altogether.

Now, if the TI insists that the "confirmation waves" from the bomb and from the detectors arrive to the source *together*, the resulting account cannot properly handle these intermediate stage. And since Cramer has recently distanced himself from the "block universe" picture [5], a more "dynamic" explanation is worth considering.

Such an alternative is one of the main proposals of this paper. The bomb responds with a "confirmation wave" immediately upon the wave-function's interaction with it, not waiting for the entire process to be completed within the MZI. In other words, *the*

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[1] In our opinion this part of the transaction is invalid. The confirmation wave must not enter route v on its way back and hit the bomb's back side. First, interference of the confirmation waves from the two detectors should cancel their parts that go to that path. Second, the alleged loss of a part of the confirmation wave will skew their intensities upon arriving back to the source, and consequently the probabilities predicted by this account will deviate from the standard QM calculation.

source receives the "confirmation wave" from the bomb while the rest of the wave-function proceeds on the MZI's other arm. Upon the reception of the wave, the source begins the negotiation towards a transaction, between the transmitted wave (50% of the beam) on the *v* path, and the rest of the beam (50%) that is still advancing freely on the *u* path. The final "decision" whether to complete the transaction between the source and the bomb is therefore made *before* the rest of the wave-function reaches the detectors. Thus, if the source and bomb "decide" to complete the transaction, an explosion occurs. But then, the other half of the wave-function must be "updated" by some "cancellation wave" going after it from the source, so as not to produce another photon against conservation laws. Equally, the negotiation may end in "no deal!" rather than with a "handshake," and no explosion will occur. Then, the other half of the wave-function must be updated so as to increase the probability of detection to 100%. This occurs regardless of whether the second BS is removed or not.

One surprising outcome of this variant of the TI concerns the notion of "collapse." This enigmatic transition involves a disappearance of the wave-function from all the sites in which the particle is not eventually found. How does this disappearance happen? Here the TI offers a very simple idea. Recall that Maxwell's equations allow advanced waves, yet they are never observed. In the TI, this absence is explained by destructive interference between offer and confirmation waves. We submit that "collapse" may occur due to the same mechanism: The "cancellation wave" proposed above destructively interferes with those parts of the wave-function that should vanish once transaction with one absorber has been completed. Similarly, in the case of no explosion, a "reinforcement wave" strengthens the remaining part of the wave-function by constructive interference.

We are acutely aware, on the other hand, that this account implies a time quite different from that given by present-day physics. It necessitates "time-outs" during which the intermediate transactions are performed in some Deeper time. Physical theory does not acknowledge such a feature of time, but in what follows we will try to show that it might be just such an extension of the theory that is needed for a better understanding of quantum phenomena.[2]

6. THE CHALLENGE OF MUTUAL IFM: A "HARDY ATOM" REPLACING THE BOMB

Cramer's analysis addresses the original IFM plus Zeilinger's improvement. There are, however, several variants of this experiment which pose a greater challenge to the TI, a challenge still unmet.

To understand the intriguing nature of these experiments, recall that the uniqueness of IFM lies in an exchange of roles: The quantum object, rather than being the subject of measurement, becomes the measuring apparatus itself, whereas the macroscopic detector is the object to be measured. In their original paper [6], Elitzur and Vaidman mentioned the possibility of an IFM in which both objects, the measuring one as well as

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[2] Just recall the many "curled" extra spatial dimensions that current superstring theories invoke. Wouldn't one hidden time dimension be able to account more simply for many more intriguing phenomena?

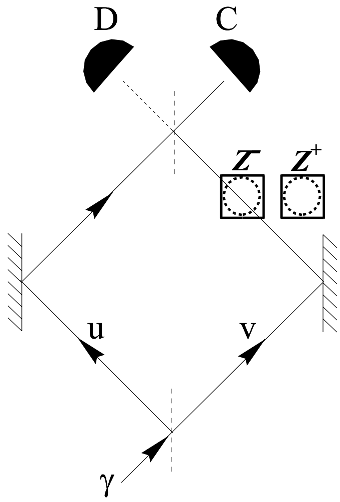

FIGURE 2. Mutual IFM, where the "bomb" is also quantum-mechanical.

the one being measured, are single particles, in which case even more intriguing effects can appear. This proposition was taken up in a seminal work by Hardy [12, 13]. He considered an EV device (Fig. 2) similar to that described in Section 3, but with a more delicate "bomb," henceforth named a "Hardy atom."

This atom's state is as follows. Let a spin $\frac{1}{2}$ atom be prepared in an "up" spin-x state (x^+) and then split by a non-uniform magnetic field M into its z components. The two components are carefully put into two boxes Z^+ and Z^- while keeping their superposition state:

$$\Psi = |\gamma\rangle \cdot \frac{1}{\sqrt{2}}(iZ^+ + Z^-). \tag{1}$$

The boxes are transparent for the photon but opaque for the atom. Now let the atom's Z^- box be positioned across the photon's v path in such a way that the photon can pass through the box and interact with the atom inside in a 100% efficiency.

Next let the photon be transmitted by BS_1:

$$\Psi = \frac{1}{\sqrt{2}}(i|u\rangle + |v\rangle) \cdot \frac{1}{\sqrt{2}}(i|Z^+\rangle + |Z^-\rangle). \tag{2}$$

Discarding all these cases of the photon's absorption by the atom (25% of the experiments) removes the term $|v\rangle|Z^-\rangle$, leaving:

$$\Psi = \frac{1}{2} \cdot (-|u\rangle|Z^+\rangle + i|u\rangle|Z^-\rangle + i|v\rangle|Z^+\rangle). \tag{3}$$

Next, reunite the photon by BS_2:

$$|v\rangle \xrightarrow{BS_2} \frac{1}{\sqrt{2}} \cdot (|d\rangle + i|c\rangle) \tag{4}$$

$$|u\rangle \xrightarrow{BS_2} \frac{1}{\sqrt{2}} \cdot (|d\rangle - i|c\rangle), \tag{5}$$

so that

$$\Psi = \frac{i}{\sqrt{2}^3} \cdot [|c\rangle \cdot (i|Z^+\rangle + 2|Z^-\rangle) - |d\rangle|Z^+\rangle]. \tag{6}$$

After the photon reaches one of the detectors, the atom's Z boxes are joined and a reverse magnetic field $-M$ is applied to bring it to its final state $|F\rangle$. Measuring F's x spin gives:

$$\begin{aligned}\Psi &= \frac{1}{4} \cdot |d\rangle \cdot (-i|X^+\rangle + |X^-\rangle) \\ &\quad + \frac{1}{4} \cdot |c\rangle \cdot (-3|X^+\rangle + i|X^-\rangle).\end{aligned} \tag{7}$$

In 1/16 (6.25%) of the cases, the photon hits detector D, while the atom is found in a final spin state of $|X^-\rangle$ rather than its initial state $|X^+\rangle$. In every such a case, both particles performed IFM on one another; they both destroyed each other's interference. Nevertheless, the photon has not been absorbed by the atom, so no interaction seems to have taken place.

Hardy's analysis stressed a striking aspect of this result: The atom can be regarded as EV's "bomb" as long as it is in superposition, and its interaction with the photon can end up with one out of three consequences:

- The atom absorbs the photon – this is analogous to the explosion in EV's original device.
- The atom remains superposed – this is analogous to the no-explosion outcome.
- The atom does not absorb the photon but looses its superposition – a third possibility that does not exist with the classical bomb and amounts to a delicate form of explosion.

Hence, when the last case occurs, it appears that the photon has traversed the u arm of the MZI, while still affecting the atom on the other arm by forcing it to assume (as measurement will indeed reveal) a Z^+ spin!

7. MULTIPLE MUTUAL IFMS

Hardy argued that this result supports the guide-wave interpretation of QM. His reasoning was that the photon took the u arm of the MZI while its accompanying empty wave took the v arm and broke the atom's superposition. However, Clifton [14] and Pagonis [15] argued that the result is no less consistent with the "collapse" interpretation. Griffiths [16], employing the "consistent histories" interpretation, argued that the result indicates that the particle might have taken the v arm as well, and Dewdny *et. al.* [17] reached the same conclusion using Bohmian mechanics.

Rather than taking a side in this debate, we pointed out [18] a more peculiar case for which all the above interpretations seem to be insufficient. Consider the setup in Fig. 3. Here too, one photon traverses the MZI, but now it interacts with, say, *three* Hardy atoms rather than one. Formally:

$$\Psi = |\gamma\rangle|X_1^+\rangle|X_2^+\rangle|X_3^+\rangle. \tag{8}$$

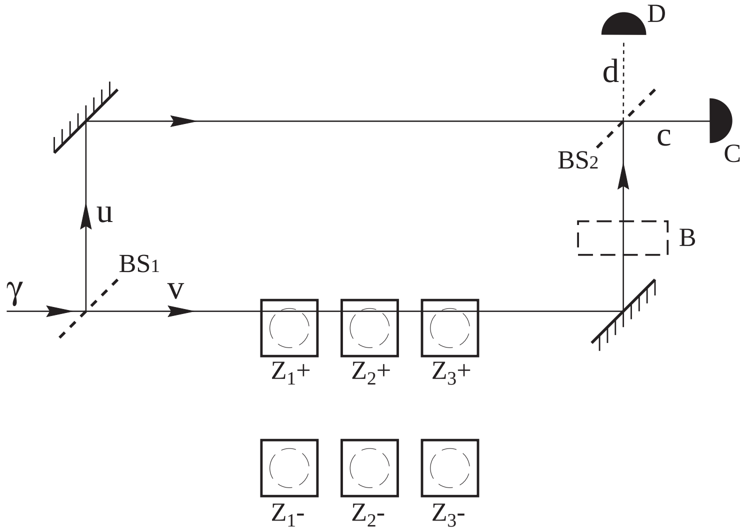

FIGURE 3. One photon MZI with several interacting atoms. Here too, introducing the blocking object B will prevent the predicted result.

After the photon's passage through BS_1 and the atoms splitting into their z spins:

$$\begin{aligned}\Psi &= \frac{1}{4}\cdot(i|u\rangle+|v\rangle)\cdot(i|Z_1^+\rangle+|Z_1^-\rangle)\\ &\quad\cdot(i|Z_2^+\rangle+|Z_2^-\rangle)\cdot(i|Z_3^+\rangle+|Z_3^-\rangle). \end{aligned} \tag{9}$$

As in the previous experiment, we discard all the cases (44%) in which absorption occurred:

$$\begin{aligned}\Psi &= -\frac{1}{4}\cdot[-|v\rangle|Z_1^-\rangle|Z_2^-\rangle|Z_3^-\rangle \\ &\quad +|u\rangle(+i|Z_1^+\rangle|Z_2^+\rangle|Z_3^-\rangle+i|Z_1^+\rangle|Z_2^-\rangle|Z_3^+\rangle\\ &\quad +|Z_1^+\rangle|Z_2^-\rangle|Z_3^-\rangle+i|Z_1^-\rangle|Z_2^+\rangle|Z_3^+\rangle\\ &\quad +|Z_1^-\rangle|Z_2^+\rangle|Z_3^-\rangle+|Z_1^-\rangle|Z_2^-\rangle|Z_3^+\rangle\\ &\quad -i|Z_1^-\rangle|Z_2^-\rangle|Z_3^-\rangle-|Z_1^+\rangle|Z_2^+\rangle|Z_3^+\rangle)]. \end{aligned} \tag{10}$$

Now let us pass the photon through BS_2 and select the cases in which it has lost its interference, hitting detector D:

$$\begin{aligned}\Psi &= \frac{1}{4\sqrt{2}}\cdot|d\rangle\\ &\quad\cdot(i|Z_1^+\rangle|Z_2^+\rangle|Z_3^+\rangle+|Z_1^+\rangle|Z_2^+\rangle|Z_3^-\rangle\\ &\quad +|Z_1^+\rangle|Z_2^-\rangle|Z_3^+\rangle-i|Z_1^+\rangle|Z_2^-\rangle|Z_3^-\rangle\\ &\quad +|Z_1^-\rangle|Z_2^+\rangle|Z_3^+\rangle-i|Z_1^-\rangle|Z_2^+\rangle|Z_3^-\rangle\\ &\quad -i|Z_1^-\rangle|Z_2^-\rangle|Z_3^+\rangle). \end{aligned} \tag{11}$$

Measuring the 3 Hardy atoms' spins now will yield, with a uniform probability, all possible results, except the case where all the atoms are found in their $|Z_i^-\rangle$ boxes, which will never occur. This is only logical, since if the atoms were all in their $|Z_i^-\rangle$ boxes, the photon would not have been obstructed, and the interference would have remained intact.

Next, reuniting the atoms' Z boxes and measuring their x spin will yield all possible combinations of X^+ and X^- in uniform probability, except the case of all three atoms measuring X^+ which has a higher probability. That is also natural, as these atoms are supposed to have interacted either with the guide wave, or with the real particle itself, or with the uncollapsed wave function, depending on one's favorite interpretation [14, 15].

Let us, however, return to the intermediate stage prior to the uniting of the Z boxes (as per Eq. (11)). We know that at least one atom must be in the $|Z^+\rangle$ box to account for the loss of the photon's interference. Let us, then, measure atom 2's spin, and proceed only if it is found to be $|Z_2^+\rangle$ (57% of the cases):

$$\Psi = \frac{1}{4\sqrt{2}} \quad \cdot|d\rangle\cdot(-i|Z_1^-\rangle+|Z_1^+\rangle) \\ \cdot|Z_2^+\rangle\cdot(i|Z_3^+\rangle+|Z_3^-\rangle). \tag{12}$$

Now unite the z boxes of atoms 1 and 3 and apply the reverse magnetic field $-M$:

$$\Psi = \frac{1}{2\sqrt{2}}\cdot|d\rangle\cdot|X_1^+\rangle\cdot|Z_2^+\rangle\cdot|X_3^+\rangle. \tag{13}$$

Surprisingly, atoms 1 and 3 will *always* exhibit their original spin undisturbed, just as if no photon has interacted with them. In other words, only one atom is affected by the photon in the way pointed out by Hardy, but that atom does not have to be the first one, nor the last; it can be *any* one out of *any* number of atoms. The other atoms, whose wave-functions intersect the MZI arm before or after that particular atom, remain unaffected.

Any attempt to reconstruct a comprehensible account from these correlations gives a highly inconsistent scenario. For, if it is the measurement of the second atom that have cancelled the photon's v term, then, for the photon to reach that atom, it must have first passed through the first atom, and, later, through the third as well. If one tries to visualize this result, then a single photon's wave function seems to "skip" a few atoms that it encounters, then disturb the m^{th} atom, and then again leave all next atoms undisturbed. Ordinary concepts of motion, which sometimes remain implicit within prevailing interpretations, are inadequate to explain this behavior.

Can, then, the TI account for this result? This is one of the challenges that need to be addressed.

8. A HYBRID MZI-EPR EXPERIMENT

Another elegant experiment by Hardy [12] brings together nearly all the famous quantum experiments, such as the double-slit, the delayed choice, EPR and IFM – all in one simple setup (Fig. 4).

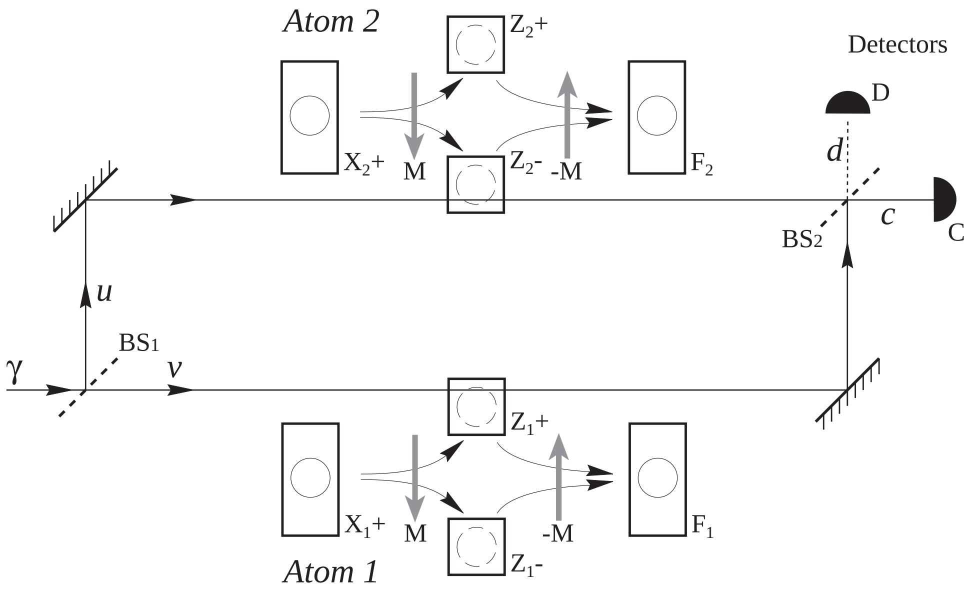

FIGURE 4. Entangling two atoms that never interact.

Let again a single photon traverse a MZI. Now let *two* Hardy atoms be prepared as in Section 6, each atom superposed in two boxes that are transparent for the photon but opaque for the atom. Then let the two atoms be positioned on the MZI's two arms such that atom 1's Z_1^+ box lies across the photon's v path and 2's Z_2^- box is positioned across the photon's u path. On both arms, the photon can pass through the box and interact with the atom inside in 100% efficiency. Now let the photon be transmitted by BS_1:

$$\begin{aligned}\Psi &= \frac{1}{\sqrt{2}^3} \quad (i|u\rangle + |v\rangle)\cdot(iz_1^+ + z_1^-) \\ &\quad \cdot(iz_2^+ + z_2^-). \end{aligned} \tag{14}$$

Once the photon was allowed to interact with the atoms, we discard the cases in which absorption occurred (50%), to get:

$$\begin{aligned}\Psi &= \frac{1}{\sqrt{2}^3}(\quad -i|u\rangle z_1^+ z_2^+ - |u\rangle z_1^- z_2^+ \\ &\quad +i|v\rangle z_1^- z_2^+ + |v\rangle z_1^- z_2^-). \end{aligned} \tag{15}$$

Now, let photon parts u and v pass through BS_2:

$$|v\rangle \xrightarrow{BS_2} \frac{1}{\sqrt{2}}\cdot(|d\rangle + i|c\rangle) \tag{16}$$

$$|u\rangle \xrightarrow{BS_2} \frac{1}{\sqrt{2}}\cdot(|c\rangle + i|d\rangle), \tag{17}$$

giving

$$\begin{aligned}\Psi &= \frac{1}{4}(\quad |d\rangle z_1^+ z_2^+ + |d\rangle z_1^- z_2^- \\ &\quad -i|c\rangle z_1^- z_2^+ - 2|c\rangle z_1^- z_2^-). \end{aligned} \tag{18}$$

If we now post-select only the experiments in which the photon was surely disrupted on one of its two paths, thereby hitting detector D, we get:

$$\Psi = \frac{1}{4}|d\rangle(z_1^+ z_2^+ + z_1^- z_2^-). \tag{19}$$

Consequently, the atoms, which never met in the past, become entangled in an EPR-like relation. In other words, they would violate Bell's inequality. Unlike the ordinary EPR, where the two particles have interacted earlier or emerged from the same source, here the only common event in the two atoms' past is the single photon that has "visited" both of them.

This experiment's accordance with the Transactional Interpretation is very natural. It is the final click in the D detector that produces the desired result, namely, the entanglement of the two atoms. If the photon is not allowed to reunite at BS_2, the effect will not occur. In terms of TI, then, it is the "confirmation wave" from this detector that goes back to the two distant atoms and entangles them.

Notice, however, that the TI needs to be elaborated beyond its original form in order to account for such interactions. First, the atoms, being in a state of a superposition, should be represented by some kind of "offer wave." Then, the "offer wave" from the source must query the atom on each of its possible superposition branches separately (as opposed to TI explanations hitherto, where the superposition branches were negotiated concurrently). The source should first negotiate the options for the photon going on one path. If there was no agreement on absorption of the photon by the atom, then the source should negotiate the situation where the photon goes on the other path. If there was no transaction regarding absorption there either, then the source must issue a new offer for the full entanglement – that is, $|v\rangle|Z_1^-\rangle|Z_2^+\rangle$ superposed with $|u\rangle|Z_1^+\rangle|Z_2^-\rangle$. All parties must now agree on this complex state together... In our opinion, this kind of negotiation is very cumbersome. A more elegant account should be sought.

In addition, the Transactional Interpretation is somewhat evasive concerning one of QM's most disturbing questions, namely, What is the size limit for a superposed object? Recent experiments have demonstrated interference not only with atoms but also with molecules as large as a "Bucky ball", *i.e.*, a molecule of 60 carbon atoms [19]. It may turn out that there is no theoretical limit to the size at which an object can be superposed; given a sufficient isolation that prevents the object from being "measured" by the environment, many physicists believe that even large objects such as cats can be superposed. If that turns out to be the case, the TI will have to give a clearer account of waves that represent not particles but macroscopic objects.

9. A TIME-REVERSED EPR

Hardy's abovementioned experiment [12] inspired us to propose a simpler version [20] that constitutes an inverse EPR, the bearing of which on the TI is straightforward.

Let two coherent photon beams be emitted from two distant sources as in Fig. 5. Let the sources be of sufficiently low intensity such that, on average, one photon is emitted during a given time interval. Let the beams be directed towards an equidistant BS. Again,

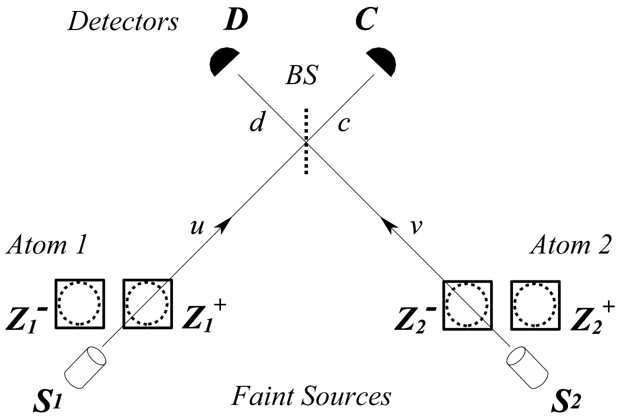

FIGURE 5. Entangling two atoms.

two detectors are positioned next to the BS:

$$\phi_{\gamma u} = p|1\rangle_u + q|0\rangle_u, \tag{20}$$

$$\phi_{\gamma v} = p|1\rangle_v + q|0\rangle_v, \tag{21}$$

$$\psi_{A1} = \frac{1}{\sqrt{2}}(iz_1^- + z_1^+), \tag{22}$$

$$\psi_{A2} = \frac{1}{\sqrt{2}}(iz_2^- + z_2^+), \tag{23}$$

where $|1\rangle$ denotes a photon state (with probability p^2), $|0\rangle$ denotes a state of no photon (with probability q^2), $p \ll 1$, and $p^2 + q^2 = 1$.

Since the two sources' radiation is of equal wavelength, a static interference pattern will be manifested by different detection probabilities in each detector. Adjusting the lengths of the photons' paths v and u will modify these probabilities, allowing a state where one detector, D, is always silent due to destructive interference, while all the clicks occur at the other detector, C, due to constructive interference.

Notice that each single photon obeys these detection probabilities only if both paths u and v, coming from the two distant sources, are open. We shall also presume that the time during which the two sources remain coherent is long enough compared to the experiment's duration, hence we can assume the above phase relation to be fixed.

Next, let two Hardy atoms be placed on the two possible paths such that atom 1's Z_1^+ box lies across the photon's u path and 2's Z_2^- box is positioned across the photon's v path. After the photon was allowed to interact with the atoms, we discard the cases in which absorption occurred (50%), getting

$$\begin{aligned}\Psi \quad &= \frac{1}{\sqrt{2}^3}(-i|v\rangle z_1^+ z_2^+ - |v\rangle z_1^- z_2^+ \\ &\qquad +i|u\rangle z_1^- z_2^+ + |u\rangle z_1^- z_2^-).\end{aligned} \tag{24}$$

We now post-select only the cases in which a single photon reached detector D, which means that one of its paths was surely disrupted:

$$\Psi = \frac{1}{4}|d\rangle(z_1^+ z_2^+ + z_1^- z_2^-), \tag{25}$$

thereby entangling the two atoms into a full-blown EPR state:

$$z_1^+ z_2^+ + z_1^- z_2^-.$$

In other words, tests of Bell's inequality performed on the two atoms will show the same violations observed in the EPR case, indicating that the spin value of each atom depends on the choice of spin direction measured on the other atom, no matter how distant.

Unlike the ordinary EPR generation, where the two particles have interacted earlier, here the only common event lies in the particles' future.

One might argue that the atoms are measured only after the photon's interference, hence the entangling event still resides in the measurements' past. However, all three events, namely, the photon's interference and the two atoms' measurements, can be performed in a spacelike separation, hence the entangling event may be seen as residing in the measurements' either past or future.

Here too, the result is only natural within the TI: A confirmation wave goes from detector D back to the two sources, retroactively entangling the two atoms.

10. THE QUANTUM LIAR PARADOX

A closer inspection of the abovementioned inverse EPR reveals something truly remarkable. Beyond the apparent time-reversal lies a paradox that in a way is even more acute than the well-known EPR or Schrödinger's cat paradoxes. It stems not from a conflict between QM and classical physics or between relativity theory; rather, it seems to defy logic itself.

The idea underlying the experiment is very simple: In order to prove nonlocality, one has to test for Bell's inequality by repeatedly subjecting each pair of entangled particles to one out of three random measurements. Then, the overall statistics indicates that the result of each particle's measurement was determined by the *choice* of the measurement performed on its counterpart. A paradox inevitably ensues when one of the three measurements amounts to the question *"Are you nonlocally affected by the other particle?"*

Let us, then, recall the gist of Bell's nonlocality proof [21] for the ordinary EPR experiment. A series of EPR particles is created, thereby having identical polarizations. Now consider three spin directions, x, y, and z. On each pair of particles, a measurement of one out of these directions should be performed, at random, on each particle. Let many pairs be measured this way, such that all possible pairs of x, y, and z measurements are performed. Then let the incidence of correlations and anti-correlations be counted. By quantum mechanics, all same-spin pairs will yield correlations, while all different-spin pairs will yield 50%-50% correlations and anti-correlation. Indeed, this is the result

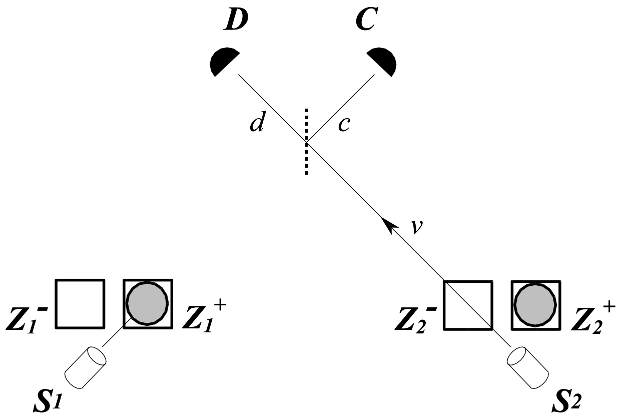

FIGURE 6. Entangling two atoms.

obtained by numerous experiments to this day. By Bell's proof, no such result could have been pre-established in any local-realist way. Hence, the spin direction (up or down) of each particle is determined by the choice of spin angle (x, y, or z) measured on the other particle, no matter how distant.

Let us apply this method to the abovementioned time-reversed EPR. Each Hardy atom's position, namely, whether it resides in one box or the other, constitutes a spin measurement in the z directions (as it has been split according to its spin in this direction). To perform the z measurement, then, one has to simply open the two boxes and check where the atom is. To perform x and y spin measurements, one has to re-unite the two boxes under the inverse magnetic field, and then measure the atom's spin in the desired direction. Having randomly performed all nine possible pairs of measurements on the pairs, many times, and using Bell's theorem, one can prove that the two atoms affect one another non-locally, just as in the ordinary Bell's test.

A puzzling situation now emerges. In 44% (*i.e.*, $\frac{4}{9}$) of the cases (assuming random choice of measurement directions), one of the atoms will be subjected to a z measurement – namely, checking in which box it resides. Suppose, then, that the first atom was found in the intersecting box. This seems to imply that *no photon has ever crossed that path, since it is obstructed by the atom*. Indeed, as the atom remains in the ground state, we know that it did not absorb any photon. But then, by Bell's proof, the other atom is still affected nonlocally by the measurement of the first atom. But then again, if no photon has interacted with the first atom, the two atoms share no causal connection, in either past or future!

The same puzzle appears when the atom is found in the non-intersecting box. In this case, we have a 100% certainty that the other atom is in the intersecting box, meaning, again, that no photon could have taken the other path. But here again, if we do not perform the which-box measurement (even though we are certain of its result) and subject the other atom to an x or y measurement, Bell-inequality violations will occur, indicating that the result was affected by the measurement performed on the first atom (Fig. 6).

The situation boils down to:

1. One atom is positioned in the intersecting box.
2. It has not absorbed any photon.
3. Still, the fact that the other atom's spin is affected by this atom's position means that something has traveled the path blocked by the first atom. To prove that, let another object be placed after the first atom on the virtual photon's path. No nonlocal correlations will show up.

Thus, the very fact that one atom is positioned in a place that seems to preclude its interaction with the other atom is affected by that other atom. This is logically equivalent to the statement "this sentence has never been written." We are unaware of any other quantum mechanical experiment that demonstrates such inconsistency.

11. ARE PAST AND FUTURE EVENTS EQUALLY REAL?

What, then, is the theoretical framework within which the peculiarities of multiple IFM can be best accounted for? Our proposal incorporates the TI within a broader theory [22, 23], which is admittedly far from current mainstream. The analogy we offer as a starting point may sound wild, but then, isn't the quantum world outrageous enough to justify wild analogies?

Rewriting history carries unfavorable associations. In old editions of *The Great Soviet Encyclopedia*, the entry on the Bering Sea was unusually lengthy. Why? Earlier editions reveal an intriguing reason. Lavrenty Beria, former Head of the Soviet secret services under Stalin, was regarded as "hero of the people" while in office. Then he was ousted and executed, and consequently had to be wiped out of public memory. Holders of the Encyclopedia were therefore instructed to hand the appropriate volume to the authorities for "updating." In order to keep the page numbers in order, the Bering Sea entry had to be expanded so as to fill the gap left by entry that was erased.

Can Nature be doing something similar at the quantum level? Our hypothesis is that spacetime, rather than being a mere dimension in Minkowski's four-dimensional universe, is in itself subject to dynamics, at least at the quantum level. *An entire evolution, in which a few particles interact, may sometimes undergo "reiteration" as part of the transactional process, leaving a few occasional inconsistencies.* The "time outs" we proposed in Section 5 above is the natural candidate for the physical arena in which quantum peculiarities develop.

Whether this interpretation is eventually accepted or not, the results we described in the previous sections warrant attention in themselves, as well as other results that further elaborations of multiple IFM would probably yield in the future.

Finally, there is a host of quantum experiment and effects revealed during the last two decades, such as teleportation [24] and quantum erasure [25], that warrant a thorough discussion in terms of the TI. Also, considerable similarities exist between the TI and Aharonov's "two-vector formalism" [26], which, although in perfect accord with quantum theory, has yielded several surprising predictions. Surely, a detailed comparison between the two models would prove to be most beneficial from both of them.

Without doubt, the issue of retrocausality will continue to advance quantum theory and experimentation.

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