The Quantum Liar Experiment in Cramer's Transactional Interpretation

R. E. Kastner
University of Maryland, College Park
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ABSTRACT. Cramer's Transactional Interpretation (TI) is applied to the "Quantum Liar Experiment" (QLE). It is shown how some apparently paradoxical features can be explained naturally, albeit nonlocally (since TI is an explicitly nonlocal interpretation). At the same time, it is proposed that in order to preserve the elegance and economy of the interpretation, it may be necessary to consider offer and confirmation waves as propagating in a "higher space" of possibilities.

"Why will you refuse to listen to reason? I had hoped to find in you–as being a man of sense and an accomplished mathematician–a fit apostle for the Gospel of the Three Dimensions, which I am allowed to preach only once in a thousand years; but now I know not how to convince you." -The Sphere, Edwin A. Abbott, Flatland

1. Introduction

The Quantum Liar Experiment is an ingenious gedanken experiment first suggested by Elitzur, Dolev and Zeilinger [2002], based on pioneering work by Elitzur and Vaidman [1993] on "interaction free measurements" (IFM) and ensuing work by Hardy [1992]. Much has been written already about such experiments,[1] and deservedly so, since they exhibit very clearly the nonclassical nature of quantum events. This paper will consider the QLE and related experiments in the light of the Transactional Interpretation (TI) of John G. Cramer, first proposed in 1980 and presented in a comprehensive manner in his [1986].

It is this author's view that TI is a seriously underappreciated interpretation that offers the most natural and elegant approach to the many conceptual challenges of quantum theory, albeit at the price of a profound paradigm change.

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[1]Some of the many papers on IFM will be discussed and referenced in what follows.

Key features of the new paradigm are (1) time-reversed influences and (2) physical processes that operate at a level of possibility rather than at the level of actualized reality. Yet TI merits due consideration since the former is implicit in the quantum formalism. Moreover, Feynman's elegant and powerful sum-over-histories approach explicitly suggests the latter (i.e., that a lot of important activity seem to go on "behind the scenes" in any quantum process). Moreover, there is ample evidence of a need for such a paradigm change when we look at the outright contradictions and inconsistencies that arise in the context of many recent proposed experiments that make the EPR experiment seem tame by comparison.

We should first note that Cramer's analysis of IFM [Cramer, 2006] emphasizes that TI is an explicitly nonlocal and atemporal interpretation, and that it makes no attempt to give a "local" account on the level of determinate particles (because according to TI, these are not fundamental anyway). TI is considered causal, however, to the extent that wave functions are seen as functioning dynamically in physical interactions with each other and with the experimental apparatus in the form of retarded (normal time sense)"offer waves" (OW) and time-reversed "confirmation waves" (CW), identified as $\psi(x)$ and $\psi^*(x)$, respectively. For example, Cramer's account of Elitzur-Vaidman's [1993] interaction-free detection of a bomb in one of two arms of a Mach-Zender Interferometer [MZI] has offer waves going along both paths even though one might be blocked. The information obtained in the experiment is attributed specifically to this nonlocal character of a wave associated with a 'potential' particle but yet not giving rise to a detected particle in that location. I should also note here that in his (1986), Cramer applied TI to the Hanbury-Twiss effect which EDZ utilize in a version of the QLE in their (2002). Cramer's interpretation of the H-T effect will be addressed in connection with this version of the QLE in part 4.

2. A quantum "bomb".

Before dealing with the QLE, we first consider a simpler setup: Hardy's twist on the original Elitzur-Vaidman IFM, in which a bomb or other obstruction is placed inside one arm of an MZI. Recall that in the E-V version, the MZI is

tuned so that one of the detectors, which we will call D, will never activate unless something is obstructing one of the paths. In Hardy's version, the bomb or other macroscopic object is replaced by a quantum system: a spin one-half atom. The atom is prepared in a state of "up along x" which is then subject to a magnetic field gradient along the z direction and spatially separated so that it could be found in either of two boxes, one of which ("up along z" or $|z\uparrow\rangle$) is carefully placed in one path of the MZI. (refer to Figure 1.)
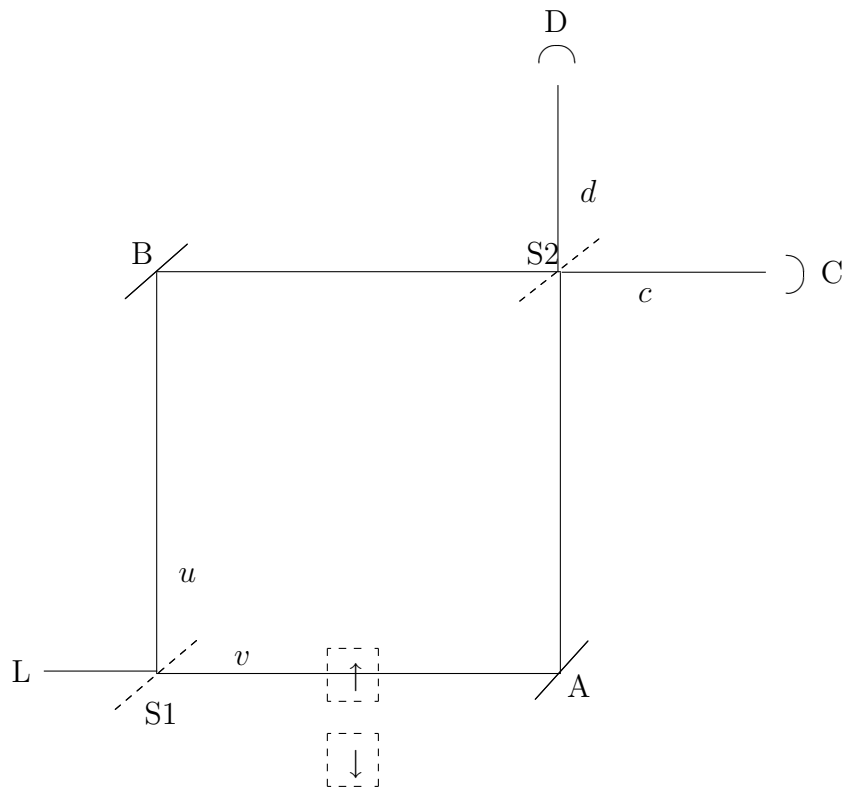

Figure 1. Hardy's version of the Elitzur-Vaidman Interaction Free Measurement with an atom replacing the bomb.

As noted in Hardy's discussion and by Elitzur, Dolev and Zeilinger, the surprising feature of this experiment is that when detector D is activated, the atom is determined to be in the box intersecting path v in a well-defined spin state $|z\uparrow\rangle$, yet seemingly the photon did not interact with it since the latter was detected at D. How is this possible? Hardy's discussion is centered around the idea of "empty waves," i.e., Bohmian guiding waves in which the particle is

clearly absent yet the wave appears to have real effects. It is not our purpose here to address the Bohmian "empty wave" picture but to show that TI gives a very natural and revealing account of this experiment.

The atom is understood to be in its ground state $|0\rangle$ unless otherwise specified. The atom's excited state is denoted as $|1\rangle$. The state of the combined system of {photon, atom} starts out as:

$$|\Psi\rangle_i = |s\rangle \otimes \frac{1}{\sqrt{2}}[|z\uparrow\rangle + |z\downarrow\rangle]. \tag{1}$$

After passing through the first beam splitter S1, the photon's state becomes $\frac{i}{\sqrt{2}}(i|u\rangle + |v\rangle)$, so at this point the total system state is:

$$|\Psi\rangle = \frac{1}{2}(i|u\rangle + |v\rangle) \otimes [|z\uparrow\rangle + |z\downarrow\rangle]$$

$$= \frac{1}{2}[i|u\rangle|z\uparrow\rangle + |v\rangle|z\uparrow\rangle + i|u\rangle|z\downarrow\rangle + |v\rangle|z\downarrow\rangle].$$

Now, under TI this is considered to be an offer wave (OW). The second term involves a potential transaction corresponding to the photon definitely being on path v and the atom definitely being in the intersecting box. Under the idealized assumptions of the experiment, the actualization of this transaction will result in absorption of the photon by the atom. But this can only occur in the presence of an atomic confirmation wave in the excited state $\langle z\uparrow, 1|$. So TI needs to allow for a hierarchy of transactions in which those with a shorter spacetime interval have the opportunity to form or fail before other transactions can enter the competition, so to speak. Cramer discussed this feature of TI in a powerpoint presentation (2005).

If the absorption transaction does not occur, the remaining photon OW proceeds through the final beam splitter S2 and the system state evolves at the detector region into the final state

$$|\Psi\rangle_f = -\frac{1}{2\sqrt{2}}|d\rangle|z\uparrow\rangle +$$

$$\frac{i}{2\sqrt{2}}|\,c\rangle|\,z\uparrow\rangle + \frac{i}{\sqrt{2}}|\,c\rangle|\,z\downarrow\rangle \tag{2}$$

The terms involving detection at C involve ambiguous states of the atom; we disregard these and focus our attention on the interesting case which is detection at D, represented by the second term in (2). When the photon component of this offer wave is absorbed by D, a photon CW is produced of the same initial amplitude, $\frac{1}{2}\langle d|$. The combined system OW also carries with it a factor of $\frac{1}{\sqrt{2}}$ given the original OW for the atom (which had an amplitude of $\frac{1}{\sqrt{2}}$ for that component of the state).[2]

The photon CW component propagates back along path u through the two beam splitters, acquiring another factor of $\frac{1}{2}$ along the way, while the atom CW picks up another factor of $\frac{1}{\sqrt{2}}$ as it proceeds back to the source (which was prepared in state $|x\uparrow\rangle$), for a total CW amplitude at the photon and atom emitters of $[\frac{1}{4}][\frac{1}{2}] = \frac{1}{8}$, in agreement with standard predictions. Note that it is assumed that a measurement is made on the atom (or at least that it is ultimately absorbed) and an atomic CW is produced. The form of the combined OW ensures that a D transaction can only occur in the presence of an atomic CW in the state $\langle z\uparrow, 0|$, which helps to explain why the atom's initial superposition must be "collapsed" whenever the photon is detected at D.

3. The Quantum Liar Experiment.

We now turn to a similar TI-based analysis of the QLE. This experiment adds to the previous one a second atom prepared in the same way as the first, but with its intersecting box placed in the way of the other arm of the MZI, and corresponding to the state $|z\downarrow\rangle$ for the second atom. (Refer to Figure 2).

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[2]In a private correspondence, A. Elitzur has raised the issue of a stationary superposed atom's OW as possibly needing some attention. For now, we just observe that for any massive particle with speed less than c, there will be some frame in which the particle is at rest. Presumably, in the particle's rest frame, the OW 'propagates' along the time axis only.
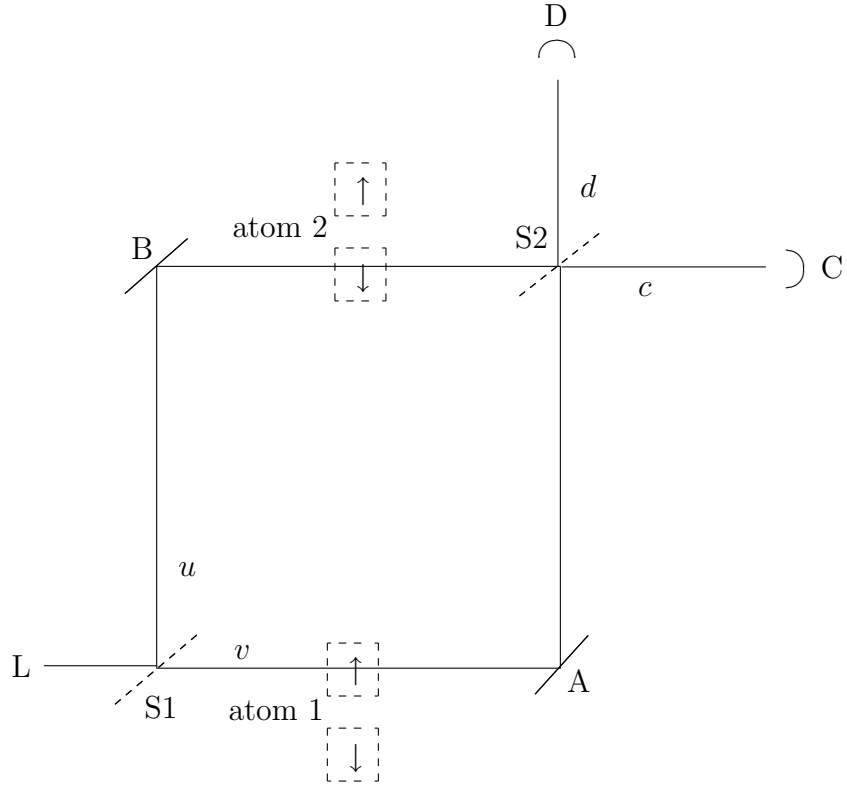
Figure 2. The Quantum Liar Experiment (QLE).

We first note that Elitzur and Dolev (2005) present this experiment as an example of what they describe as a situation "analogous to a Schrodinger cat found to be dead alongside scratches and droppings within the box that indicate that it has been alive all the time." [p. 341] In other words, according to the usual way of retrodicting trajectories for a photon based on the known state of the system and detections at one place or another, a seeming inconsistency arises within the description of the history of the system. However, we will see that under TI no such inconsistency arises.

The initial state of the system, in obvious notation, is[3]:

$$|\Psi\rangle = |s\rangle \otimes \frac{1}{\sqrt{2}}[\,i|z\!\uparrow\rangle_1 + |z\!\downarrow\rangle_1\,] \otimes \frac{1}{\sqrt{2}}[\,i|z\!\uparrow\rangle_2 + |z\!\downarrow\rangle_2\,] \qquad (3)$$

After the photon (or in this case OW) propagates through the first beam

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[3]The factors of i for the spin "up" states yield a more convenient form of the EPR state.

splitter S1, the state is:

$$|\Psi\rangle = \frac{1}{2\sqrt{2}}[i|u\rangle + |v\rangle] \otimes [\,i|z\uparrow\rangle_1 + |z\downarrow\rangle_1\,] \otimes [\,i|z\uparrow\rangle_2 + |z\downarrow\rangle_2\,] \qquad (4)$$

This product yields eight terms corresponding to eight total system OW components. In the following we adopt the shorthand $|z\uparrow\rangle_1|z\uparrow\rangle_2 = |++\rangle$, etc. The photon will be absorbed in transactions corresponding to OW components with atomic states $|+-\rangle$ and for single components $|u\rangle\,|--\rangle$ and $|v\rangle\,|++\rangle$ in a process very similar to the single-atom case above.

For now, we consider only the remainder, reviewing the conventional account :

$$|\Psi\rangle = \frac{1}{2\sqrt{2}}[-i|u\rangle\,|++\rangle \;-\; |u\rangle\,|-+\rangle \;+\; i|v\rangle\,|-+\rangle \;+\; |v\rangle\,|--\rangle\,] \qquad (5)$$

After the photon passes through the second beam splitter, with the evolution

$$|v\rangle \;\rightarrow\; \frac{1}{\sqrt{2}}(|d\rangle \;+\; i|c\rangle\,), \qquad |u\rangle \;\rightarrow\; \frac{1}{\sqrt{2}}(|c\rangle \;+\; i|d\rangle\,),$$

the state becomes

$$|\Psi\rangle = \frac{1}{4}(|d\rangle\,|++\rangle \;+\; |d\rangle\,|--\rangle \;+\; i|c\rangle\,|--\rangle \;-\; i|c\rangle\,|++\rangle \;-\; 2|c\rangle\,|-+\rangle\,). \quad (5)$$

If we now select only those photons detected at D, indicating the presence of an atom in an intersecting box, we have:

$$|\Psi\rangle_D = \frac{1}{4}|d\rangle\,(|++\rangle \;+\; |--\rangle\,) \qquad (6)$$

That is, the atoms are now entangled in an EPR state, where, in the words of EDZ, "the only common event in [the atoms'] past is the single photon that has 'visited' both of them." (2002, 454) EDZ then go on to present a version of the experiment in which even the common past event seems to be eliminated, by exploiting the Hanbury-Twiss effect (to be discussed in more detail in part 4).

There are now some apparently strange and paradoxical implications of this result for the atoms for which photons were detected at D. If we choose to open

one of the boxes, this will constitute a measurement of the z spin of that atom, and according to $|\Psi\rangle_D$, the other atom must always be found with the same spin. The usual account is that this means that the photon must definitely have traveled along the unblocked arm; but that would mean that it didn't interact with the atom on the other arm, so how could it have brought about any kind of correlation between the atoms?

Elitzur and Dolev refer to this as the "quantum liar" experiment because, in their words: "The very fact that one atom is positioned in a place that seems to preclude its interaction with the other atom leads to its being affected by that other atom. This is logically equivalent to the statement: 'This sentence has never been written.'" (ED p. 344)

Moreover, if we choose to measure the atoms' spins along other directions (by bringing the boxes back together and then separating them along other spin directions), we find that such outcomes violate the Bell inequality. Therefore, neither atom was really in a definite z spin state, so there was no definite "silent detector" (blocking box) and the photon could not have gone only along one path or another. This contradictory situation is analogous to the schizophrenic Schrodinger cat who, upon opening the box, is found to be dead but with evidence of a cat having been alive for the entire time (scratches and droppings in the box).

Let us now examine the QLE under TI. We will follow the notational convention in Cramer (2006), which traces an OW component from the source to a detector, and a CW from a detector back to the source. (The photon source, a laser, is denoted by L. Reflections at beam splitters resulting in a phase change of $\frac{\pi}{2}$ are underlined.)

First we limit the discussion to OW resulting in photon detection at D. Such detections arise from total system OW components with matching spin values, since the photon OW corresponding to the remaining nonmatching atomic spin state ($|-+\rangle$) cancel out at D due to destructive interference:

$$|L - \underline{S1} - A - \underline{S2} - D\rangle + |L - S1 - B - S2 - D\rangle = 0 \qquad (7)$$

So the only offer wave components that can give rise to transactions are

$$|L - \underline{S1} - B - \underline{S2} - D\rangle| + +\rangle \qquad (8a)$$

and

$$|L - S1 - A - S2 - D\rangle| - -\rangle \qquad (8b)$$

Now, under TI we have to consider the atomic CW that are present in cases where the photon is detected at D (see Figure 3). First, suppose that the box along path v is opened after a photon is detected at D, thus measuring the z spin of atom 1. A detection of atom 1 revealing its z spin generates CWs of the form $\langle z \uparrow |, \langle z \downarrow |$. We assume that atom 2 will eventually be absorbed (it doesn't matter how far in the future this happens), also generating CWs. [4] The available total system offer waves constrain possible transactions to those in which CWs from both atoms match, with the photon OW corresponding to the states of the atoms as in (8a,b).

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[4]If no specific detection point for a particular offer wave component is specified, TI still assumes that ultimately there will be some absorber for that offer wave component, leading to the possibility of a transaction.
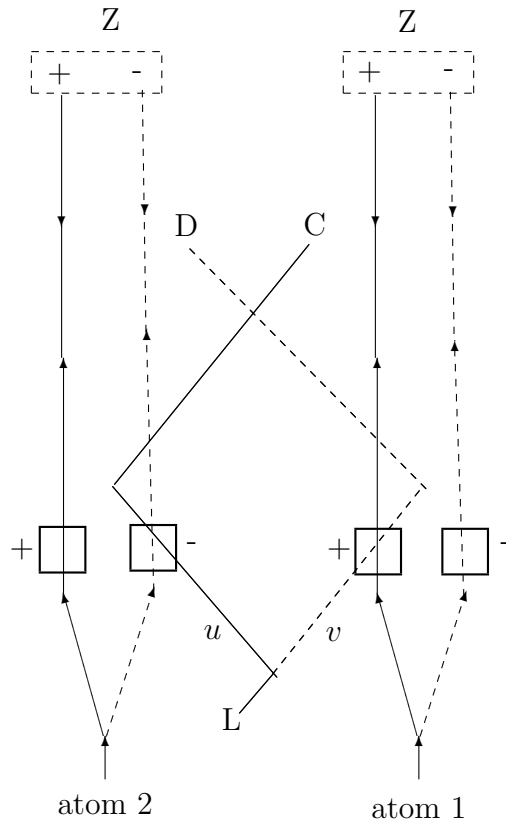
Figure 3. The QLE with a measurement of the atoms' spins along z.

Thus, if it turns out that atom 1 was in the intersecting box, the realized transaction is the one with an atomic component corresponding to $|++\rangle$, and the photon component corresponding to path u (8a). The situation is exactly reversed if atom 1 is found not to be in the box when it is opened; in this case the realized transaction is the one corresponding to path v and atomic state $|--\rangle$ (8b).

On the other hand, what happens if we decide not to open a box, but instead bring them back together and measure the atomic spins along some other direction, say y (using the usual Stern-Gerlach apparatus)? (See Figure 4). This will generate atomic CW of the form $\langle y\uparrow|$, $\langle y\downarrow|$. Each of these contains equal amounts of the z-spin eigenstates, which will separate according to the earlier z-oriented Stern-Gerlach field at the location of the MZI. For the atoms to be found in either eigenstate of spin along y, equal OW and CW components of each atom's spin along z is required, so possible transactions involve superpositions of the states (8). These will yield no "fact of the matter" either for the atoms'

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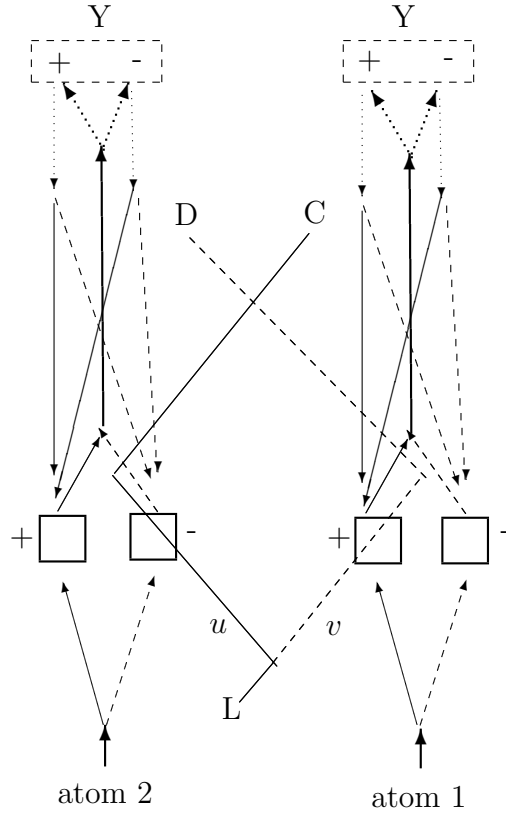whereabouts in the boxes nor for the photon's whereabouts on either path.

Figure 4: The QLE with a later measurement of the atoms' spins along y. Thick lines represent the state $|x \uparrow\rangle$. Thin solid lines represent the state $|z \uparrow\rangle$; thin dashed lines represent the state $|z \downarrow\rangle$. Dotted lines represent either spin state in the y direction. Arrows indicate whether these are offer or confirmation waves, with increasing time in the upward direction on the diagram.

Elitzur and Dolev [2006] have argued that this situation presents a challenge for TI, for the following reason. It seems that the first transactional opportunities are for the photon OW to encounter either atom OW and to be absorbed by one or the other atom. (These transactions correspond to the four terms we omitted from the state (5)). In the single-atom case we simply account for this with a hierarchy: if the transaction corresponding to the term $|v\rangle\,|z \uparrow\rangle$ fails, then that term is out of contention and other terms come into play. But in this two-atom version, absorption can fail for the corresponding terms $|v\rangle\,|++\rangle$ and $|v\rangle\,|+-\rangle$

(and their counterparts on path u) and yet these terms still remain in play for transactions involving superpositions, such as for absorption at D in a superposition of $|v\rangle\,|++\rangle$ and $|u\rangle\,|--\rangle$. So it might seem that if transactions involving absorption of the photon by either atom fail, the photon OW has to "try again" and head back out to see if a superposition is available, i.e., through a transaction involving a superposition of states $|++\rangle$ and $|--\rangle$. This sounds rather cumbersome and not in keeping with TI's usual elegant account.

We can avoid this "go back home and try again tomorrow" behavior of the photon OW by expanding our notion of the space of transactions to correspond to the configuration space of the combined system. In this account, we have to consider the entire system OW together, so that the photon OW doesn't just propagate along in ordinary physical space and encounter an atom OW in the same physical space. The "larger" space permits different levels of transactions: those which project out a portion of the total system (i.e., absorption of the photon at the location of atom 1 or atom 2), or those which encompass the entire system (e.g., superpositions of the photon/two-atom states).

Thus the QLE forces us to face head-on the issue sometimes raised in objections to TI: how can the OWs and CWs be "physically present in space"(as Cramer says in his (1986)) in situations involving more than one particle? It is suggested here that, rather than consider this a problem for TI, we should consider it an opportunity. Clearly, when we consider experiments like the QLE in the usual conceptual way, we encounter nothing but paradoxes and contradictions, which are always the hallmark of a constraining paradigm. We can break through the impasse by viewing offer and confirmation waves not as ordinary physical waves but rather as "waves of possibility" that have access to a larger physically real space of possibilities.

Another advantage of this picture is its harmonious accomodation of the idea of "quantum wholeness." This ontology assumes that all offer and confirmation waves should be considered as product states of all the particles in the universe, therefore having access to the entire range of transactional possibilities present in that space. Normally we don't need to consider that whole space because we are only dealing with experiments involving a tiny subset of the universal system (e.g., 1 or 2 particles in a simple product state with the rest of the universe), and

transactions only project out phenomena involving the one or two particle(s). (Thus, the account given in part 2, using language such as "the photon CW component propagates back along path u," needs to be understood as a kind of shorthand dealing only with a projection of the total system CW which actually resides in a larger space.) When we get into more complex experiments with larger numbers of entangled particles, the available transactions become more numerous and complex as well. But the point is that the wholeness implicitly exists, at least in the form of a product space of all emitted particles, until particles are absorbed at a particular location in a transaction.[5]

4. The Hanbury-Twiss Effect in the QLE

As noted earlier, several authors[6] note that the EPR correlations obtaining between the atoms when detector D clicks can be achieved by using two spatially separated photon sources. This is seen as creating a situation where the EPR correlations are brought about not by any event in the atoms' past but by an event in their future (the detection of the photon at D). The analysis offered here indicates that the correlations are created by the joint effect of the indeterminacy of the photon's emission point and the detection at D, so there is a pre- and post-selection aspect. Under TI, the same features would seem to be present in the 2-laser case; i.e., this would be seen as functionally equivalent to a photon from a single laser being split at S1. So transactionally, the two versions of the QLE are essentially equivalent in the functioning of the subsystems (photon and atoms) involved. We can see this by reviewing Cramer's account of the H-T effect.

As Cramer explains in his 1986 paper, under TI, "particles transferred have no separate identity apart from the satisfaction of [the] quantum mechanical boundary conditions." (1987, 678). In the H-T effect, each source (in this case an astronomical object) emits OWs that travel to the two detectors (used to make the relevant measurements). Each detector receives a composite OW and responds with a matching CW. For incoherent sources, the probability of a transaction is very small but still possible. Whether one uses coherent or

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[5]This in turn suggests that particle creation corresponds to the creation of possibility.
[6]E.g., EDZ (2002) and Silberstein, Stuckey and Cifone (2005).

incoherent sources, the effect is the same: there is no "fact of the matter" about the photon's origin, since the photon is a nonlocal transaction satisfying boundary conditions. As Cramer notes of the H-T effect: "...neither of the photons detected can be said to have originated uniquely in one of the two sources. Each detected photon originated partly in each of the two sources. It might be said that each source produced two half-photons and that fractions from two sources combined at a detector to make a full-size photon."

5. Conclusion

The Transactional Interpretation has been applied to various interaction-free measurements (IFM), including the "quantum liar experiment" (QLE). It has been argued that TI continues to provide an elegant and natural account of quantum phenomena, provided that we consider offer and confirmation waves as residing in a "higher" physical space corresponding to the configuration space of all particles involved. This space can be considered as a physically real space of possibilities; thus "real" is not equivalent to "actual."[7] This is admittedly a bold new ontological picture in the context of quantum theory interpretations, but it should be seriously considered because it accomodates the formalism of quantum theory, including its implicit time-symmetric aspects, in a natural way. As a side-benefit, it also provides further insight into the origins of "quantum wholeness." In this picture, actualized phenomena constitute just the "tip of the iceberg" of a space of physically real possibilities. Furthermore, this proposal seems harmonious with Cramer's "transactional paradigm of time" (2005), in which he which discusses the "emergence of present reality from future possibility" and, in an engaging metaphor, compares this process to frost forming on a windowpane:

"In the transactional interpretation, the freezing of possibility into reality as the future becomes the present is not a plane at all, but a fractal-like surface that stitches back and forth between past and present, between present and future...the emergence of the unique present....is rather like the progressive formation of frost crystals on a cold windowpane. As the frost pattern expands, there is no clear freeze-line, but rather a moving boundary, with fingers of

[7]Thus this proposal can be characterized as a version of possibilist realism constrained by specific physical law.

frost reaching out well beyond the general trend...in the same way, the emergence of the present involves a lacework of connections with the future and the past, insuring that the conservation laws are respected..." (2005, 9)

The ontology proposed herein can be seen as a perhaps unexpected but necessary feature of the "stitching" of the present from possibilities, by acknowledging the structured set of all those possibilities as "too big" to fit into ordinary spacetime. Indeed, one could even suppose that the realization of these transactional possibilities helps to create spacetime, as in the picture proposed by ED (2005, 346):

> "The wave function evolves beyond the 'now', i.e., outside of spacetime, and its 'collapse,' due to the interaction with the other wave functions, creates not only the events but also the spacetime within which they are located in relation to one another."

Some further remarks are probably in order regarding the often-heard objection that a multidimensional configuration space must be considered "unphysical": when it was first discovered that there were half-integral solutions to the eigenvalue equation for the angular momentum operator, these might well have been considered unphysical. Indeed there is no ordinary spatial way to understand half-integer spin values–in particular the spin one-half value for the electron, which is supposedly a point particle. This serious conceptual problem is dealt with by calling electron spin an "internal" angular momentum, with the vast majority of phyicists not batting an eye over the obvious conceptual inconsistency of a point particle having an "internal" degree of freedom. It seems to this author that the decision to take as physically real an *"internal" angular momentum of a particle that has no interior* is no less problematic than taking multi-particle offer and confirmation waves as physically real. The former assumes there is some hidden and inaccessible "internal space" that is nevertheless real, while the latter assumes that there is some "larger" and inaccessible space (corresponding to the dimensions of the relevant configuration space) that is nevertheless real. If one is willing to consider the "internal space" of electron spin as physically real, then it seems inconsistent to rule out the ontology proposed here on the grounds that it does not coincide with ordinary spacetime.

Interestingly, one could see this further elaboration of Cramer's original 1986

interpretation as consistent with a quotation he provides therein from C. F. von Weizsaecker: "What is observed certainly exists; about what is not observed we are still free to make suitable assumptions. We use that freedom to avoid paradoxes." (1986, 650)

Finally, to return to the QLE: under TI, at no time was one or the other atom "really" in the way of a photon traveling as a corpuscular blob down an arm of the MZI, so we avoid the paradoxes and contradictions that arise in the usual pseudo-classical account of the QLE as in the above description of the Schrodinger cat's schizophrenic history and the E-D 'quantum liar' linguistic trap. TI is a relativistically consistent interpretation which sees particles as field quanta, not as little classical corpuscles moving along trajectories. Thus, under TI the EPR state is brought about through the interactions of offer and confirmation waves which make possible several distinct transactions. When one of those is actualized, discrete transfers of energy and other physically detectable quantities occur, which we like to characterize as "particles."

Perhaps the most intriguing aspect of the QLE is this: that the boundary conditions for a D transaction can be satisfied by having the atoms in a superposition of "silent detectors", as long as each term in the superposition allows a silent detector on one arm and a vacant box on the other. It is these superpositions that come into transactional play when the atoms' spins are measured along a direction other than z. Clearly we cannot think of the atoms as physically confined in either of their boxes in such cases, which underscores the value of a quantum ontology involving a larger physical space.

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