The Inexhaustible Source of Insights Revealed by every Photon

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"Mehr licht!" ("More light!")
Göthe, on his deathbed

ABSTRACT

We present several quantum mechanical experiments involving photons that strain the notions of space, time and causality. One for these experiments gives rise to the "quantum liar paradox," where Nature seems to contradict herself within a single experiment. In the last section we propose an outline for a theory that aspires to integrate GR and QM. In this outline, i) "Becoming," the creation of every instant anew from nothingness, is real. ii) Force-carrying particles, such as photons, do not merely mediate the interaction by propagating in some pre-existing, empty spacetime; rather, they are the very progenitors of the spacetime segment within which the interaction takes place.

Keywords: Interaction-free measurement; EPR; Quantum entanglement; Quantum liar paradox; Spacetime

1. INTRODUCTION

Ever since Newton waged his ferocious wars against Huygens and the wave theory proponents, light kept being the delight as well as the nightmare of theorists and experimentalists alike. While theoretical advance has been slow during the last few decades, several experiments have been proposed that keep offering intriguing clues for any future theory. Accordingly, this paper presents a few simple experiments that we believe show that a photon is a much more elusive and odd entity than most physicists are willing to believe. The first of these experiments has already been carried out, the others still being gedankenexperiment, which we hope will pose challenges to experimentalist to carry out too. The last experiment gives rise to the Quantum Liar Paradox. With all due modesty we argue that this paradox is more acute than all the traditional quantum paradoxes such as EPR or Schr?dinger's cat. This is because the conflict it reveals is not only between quantum and classical mechanics or relativity theory. Rather, Nature seems to *logically* contradict herself within a single experiment. Finally, in the last section we shall take the liberty of speculating how the photon will look like within the long waited-for Unified Field Theory, in which quantum mechanics and relativity theory will be merged.

2. GETTING AWAY WITH SUPERSENSITIVE-BOMB TESTING

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[1] 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.

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:

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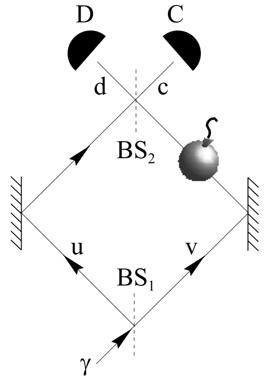

Figure 1. Interaction Free Measurement. BS_1 and BS_2 are beam splitters. In the absence of the obstructing bomb, there will be constructive interference at path c (the detector C will click) and destructive interference on path d (detector D never clicks).

- 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.*[2] refined it so as to save nearly 100% of the bombs. Other applications of IFM range from quantum computation[3] to imaging.[4]

3. HYBRIDIZING IFM WITH EPR

Apart from its technological applications, IFM is extremely efficient for experiments that aim to give better understanding of the nature f the wave-function. One such an experiment has been proposed by us[5] for studying the EPR effect. Consider a particle split not only to two parts, as in the ordinary MZI, but to 100. Then measure one of the wave-function's parts. In most cases, no detection would occur. This is a weak IFM that changes the wave-function only slightly. Rather than the abrupt transition from superposition to position, the likelihood of the particle to be in a certain state has increased or decreased. This is partial measurement. Next consider an EPR pair whose particles undergo partial measurements. Here, some intriguing effects occur:

1. Partial measurement on one particle yields a partial nonlocal effect on the other particle;
2. The other particle can then undergo another partial measurement and exert its own slight effect back on the first.
3. Partial measurement can be totally time-reversed, returning the wave-function to its original superposition, giving rise to a new kind of quantum erasure.

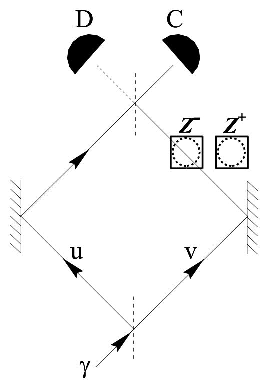

Figure 2. Mutual IFM, where the “bomb” is also quantum-mechanical.

4. This erasure nonlocally erases the previous partial nonlocal effect on the distant particle.
5. This way, the particles may keep “talking” to one another for a long time, unlike the ordinary EPR in which they become disentangled after one measurement.

This method, and the ones describe below, have this feature in common. Quantum measurement is ill-understood and abrupt. If one makes it gradual, some novel features of the measuring process emerge.

4. MAKING IFM MUTUAL: SUPERPOSED PARTICLES MEASURE ON ANOTHER

Next we study more advance variants. To understand their intriguing nature, 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,[1] Elitzur and Vaidman mentioned the possibility of an IFM in which both objects, the measuring one as well as 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.[6,7] He considered an EV device (Fig. 2) similar to that described in Section 2, 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!

5. STRAINING SEQUENTIALITY

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[8] and Pagonis[9] argued that the result is no less consistent with the "collapse" interpretation. Griffiths,[10] 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.*[11] reached the same conclusion using Bohmian mechanics.

Rather than taking a side in this debate, we pointed out[12] 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:

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

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

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

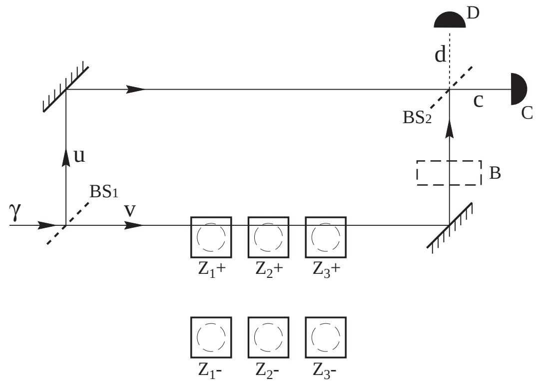

Figure 3. One photon MZI with several interacting atoms. Here too, introducing the blocking object B will prevent the predicted result.

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

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

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

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

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.[8, 9]

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):

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

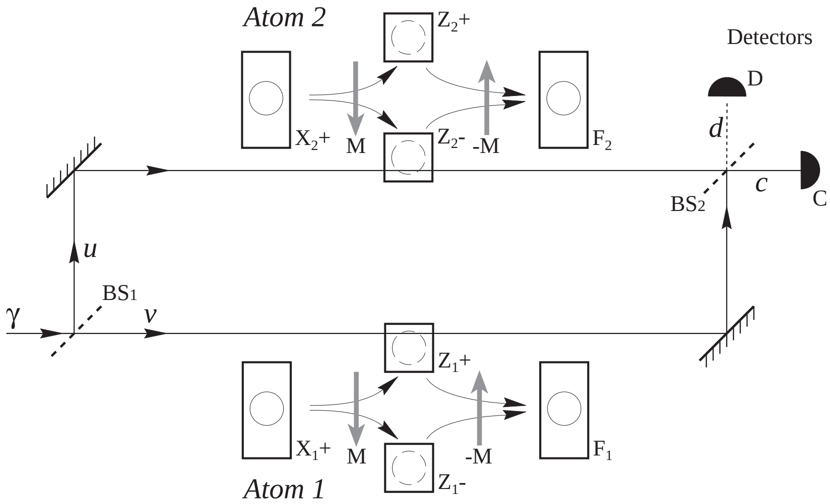

Figure 4. Entangling two atoms that never interact.

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.

6. EPR EFFECTS BETWEEN PARTICLES THAT NEVER INTERACTED IN THE PAST

Another elegant experiment by Hardy[6] 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).

Let again a single photon traverse a MZI. Now let *two* Hardy atoms be prepared as in Section 4, 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:

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

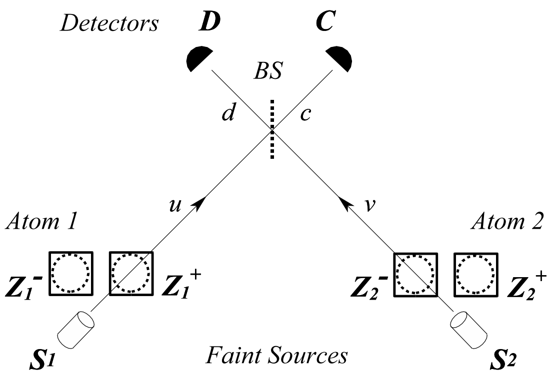

Figure 5. Entangling two atoms.

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

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

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

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

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.

7. EPR UPSIDE DOWN

Hardy's abovementioned experiment[6] inspired us to propose a simpler version[13] that constitutes an inverse EPR. 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, 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.

8. NATURE CAUGHT CONTRADICTING HERSELF

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[14] 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

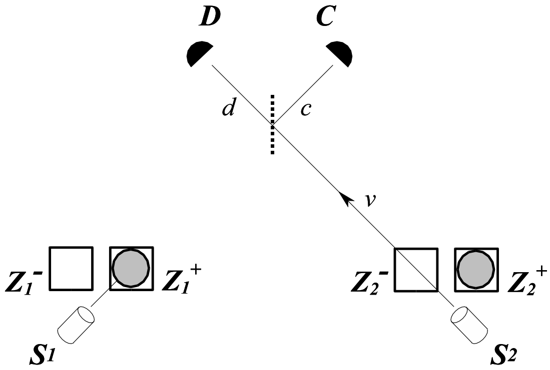

Figure 6. Entangling two atoms.

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 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.

9. THE QUANTUM LIAR PARADOX SIMPLIFIED

An even simpler version of the above experiment can be devised. This time let us consider two excited atoms, out of which only one can emit a photon within a given time interval. The atoms thus become entangled with respect to their excited/ground state. Here too, the measurement of one atom may show it to be excited, implying that it has never emitted a photon and thus could never become entangled was the other atom. But here again, by Bell's Inequality, this result must be effected by the other, supposedly non-entangled atom! All one has to do to make such a clear-cut experiment possible, is to chose another variable that is orthogonal to the ground/excited state and then randomly employ the two measurements on a series of atom pairs. This gedankenexperiment, just like all the others described above, is technically feasible and we urge experimentalists to carry it out.

10. WHAT, THEN, IS A PHOTON?

It is only natural to try to make some sense of the above experiments. Of course, the formers' validity does not depend on our favorite interpretation. They pose a challenge to any interpretation of QM.

Let us bear in mind that the photon is so strange because it belongs to three of physics' most notorious crime families. It is, at the same time,

1. a quantum object, like electrons, neutrons and atoms, hence its motion is governed by the wave-function, an odd entity that defies ordinary notions of space and time;
2. a relativistic object, like gravitons, whose velocity is invariant, appearing the same for any observer; and
3. a force-carrying particle, like gravitons, gluons and W and Z bosons, whose interchanges between bodies alter, in yet unknown ways, their relative motions.

Most likely, an explanation for all these peculiarities amounts to no less than the long sought-for unified field theory, not a modest task. Is there any point trying? Well, *is there any point trying to say what is a photon without trying?* Let's aim high!

We believe that solving the photon's riddle requires physics to face another, long-neglected question, that of the very nature of time. Mainstream physics denies any objective reality to time's "passage," viewing it as an illusion. Our model's[15] basic assumption is just the opposite: Time "flows" in a way that makes spacetime, together with its events and world-lines, "grow" in the future direction.

Once spacetime itself is granted evolution, then all the wave-function's peculiarities may be looked at in an entirely new way: *Perhaps the wave-function is more fundamental than spacetime. Rather than proceeding as an extended wave within an empty spacetime and then "collapsing" to a localized particle, perhaps wave-function collapse gives rise not only to the particle's position within spacetime but to the entire spacetime region associated with it.*

If the wave-function is more fundamental than spacetime, so should be the interaction between wave-functions. When two particles interact with one another, being in their privileged "now," reside on the very "edge" of spacetime. Beyond this "edge" lies the ultimate nothing, that is, not even spacetime, just as the Big-Bang model portrays the "outside" of the universe.

The wave-functions interact, then, "outside" spacetime, and this interaction gives rise not only to the particle's future relative locations. The quantum interaction creates the entire new spacetime region within which the particles interact. Whether they will be closer to one another (attraction) or further (repulsion), is thus determined by their pre-space interaction.

This speculation offers novel ways to think about interactions and the very notions of motions and forces. Can it fruit into a precise and testable theory? We hope to be able to answer this question in the affirmative one day. About one thing we are sure: Enough with the prevailing straight-jacket approach of "Shut up and calculate!"

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