THE TOO-LATE-CHOICE EXPERIMENT: BELL'S PROOF APPLIED TO A TIME-REVERSED SETTING

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In the EPR experiment, each measurement addresses the question "What is the particle's spin value along this direction?" We propose a modified experiment where this question is reversed: "Along which direction does the particle have this spin value?" To enable that, each particle's interaction with a beam-splitter at t_1 leaves its spin direction superposed. At t_2, the experimenter uses Interaction-Free Measurement to select an "up" or "down" outcome regardless of the direction. By Bell's theorem, it is now the earlier "choice" of spin direction that must be nonlocally transmitted between the particles. This lends support to time-symmetric interpretations of QM, namely the Transactional Interpretation (TI) and the Two State-Vector Formalism (TSVF). We conclude with a brief comparison between these interpretations and their traditional alternatives, Copenhagen, Bohmian mechanics and the Many Worlds Interpretation.

Quantum nonlocality [1], for which rigorous proofs exist like the Bell [2] and GHZ [3] theorems, has a temporal counterpart, where causal effects appear to go in the backwards time direction [4]. Unlike non-locality, however, non-temporality was never considered a pivotal issue, let alone requiring rigorous proof. This neglect is inappropriate, because some novel interpretations of quantum mechanics, mainly Cramer's [5] transactional interpretation (TI) and Aharonov's [6] two state-vector formalism (TSVF), render non-temporality the key for understanding QM's other unique features. Indeed, once effects are allowed to go sometimes backwards in time, effects that appear nonlocal in *space* turn out to be perfectly local in *spacetime*. TSVF further derives several surprising predictions [6], of which many won empirical support. Other quantum peculiarities, such as the uncertainty principle and the measurement problem, may be amenable to similar interpretational twists.

The outline of this paper is as follows. We begin with a brief review of quantum time-symmetric causality in Sec. 1. The essential features of the standard EPR experiment are briefly recounted in 2, followed in 3 by our "Too-Late Choice" variant. 4 specifies how the spin value rather than the spin direction can be chosen. 5 describes the unique entanglement resulting from this reversal of measurement stages. 6 concludes with a brief comparison between the way different schools of quantum mechanics respond to the challenge of apparent quantum retrocausality.

1. Can A Quantum Effect Precede its Cause?

The first suggestion of quantum non-temporality seems to be Wheeler's delayed choice experiment [7], where the experimenter's last-minute decision is argued to determine whether a photon coming from a very far source came, all along, as a wave or a particle. Yet Wheeler himself did not argue that the experimenter's decision really determines the particle's past. On the contrary, following the Copenhagen school, he preferred to question the notion of reality in all times ("No phenomenon is a phenomenon until it is an observed phenomenon" [7]). Leggett and Garg [8] pointed out that the correlations between consecutive measurement values of the same system deviate from classical case similarly to the nonlocal correlations on which Bell's theorem was based. Neither did they, though, go as far as to invoke temporal anomalies.

Elitzur and Dolev's [4] went a step further in their Quantum Liar experiment, where the retrocausal argument was based on Bell's proof. Using a time-reversed EPR ("RPE"), they employed the standard setting where each particle undergoes spin measurement along one out of three directions, with one crucial difference: One of these three measurements was replaced with one that asks, "*Is this particle entangled with the other one?*" In half of the cases, the outcome must be "No." Yet this very outcome is imposed by entanglement just like those of the standard spin measurements, leaving Nature, so to speak, caught blushing in self-contradiction. Several comments on this gedankenexperiment, *e.g.* [9-11], indicate that the employment of Bell's theorem indeed makes time-symmetric causality harder to dismiss. For consecutive Bell-like settings for testing retrocausality, with strong/weak measurements, in the spirit of TI/TSVF, see [6, 12-16].

A similar move is proposed below. We gedankenly apply Bell's theorem to an EPR-Bell setting where the spin measurement's two stages, namely, the choice of spin direction to be measured and then the final value thereof, are made in reversed order. Bell's proof in this case seems to inject the nonlocal influence into the particles' past.

2. The EPR Experiment: "What is the Particle's Spin Value along this Direction?"

Recall first the standard EPR-Bell setting.

i. A particle pair is prepared in the state $\frac{1}{\sqrt{2}}\left(\left|\uparrow\right\rangle_A\left|\downarrow\right\rangle_B - \left|\downarrow\right\rangle_A\left|\uparrow\right\rangle_B\right)$. Each particle (A/B) travels far away from the other (see Fig. 1).

ii. Then for each particle, one out of three spin directions (*α/β/γ*) is chosen by the experimenter to be measured. This is the spin measurement's preparation, made by the particle's entrance into the appropriately aligned SG magnet.

iii. Measurement is then completed by detectors placed at the SGM's two exits. Upon the particle's detection, a spin value (↑/↓) is obtained along the chosen direction.

iv. Over many times, correlations are expected within each A/B pair of values (↑/↓), which in turn depend on the two directions (*α/β/γ*) chosen an instant earlier.

v. Local realism may naively account for these correlations as pre-existing spin values along all directions, only passively revealed by measurements.

vi. However, Bell's theorem proves that no such pre-existing values can accommodate with the experimenters' simultaneous choices of spin directions. It is therefore these choices, as well as their random outcomes, that nonlocally affected the distant particle's spin value.

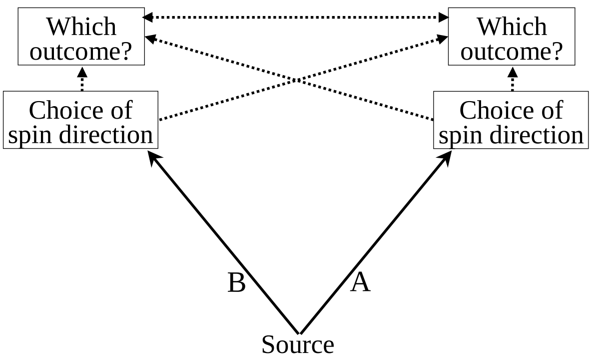

Fig. 1. An EPR-Bell experiment

3. The Too-Late-Choice Experiment: "Along which Direction does the Particle have this Spin Value?"

In the above standard setting, each particle's spin value turns out to be determined by a) the spin direction measured on the other particle – freely chosen at the last moment by the distant experimenter – plus b) that measurement's outcome – randomly imposed by quantum uncertainty. Our temporal twist should then be as follows: Make (b) somehow subject to the experimenter's free choice. Then, it would be (a) that Bell's theorem obliges to be nonlocally affected.

So here it goes:

i. A particle pair is prepared as in (I*i*).

ii. For each particle, the spin direction (I*ii*) is left undecided by the particle's own interaction with a beam-splitter, which makes its momentum superposed ($p_1/p_2/p_3$) towards the SG magnet pre-aligned along ($\alpha/\beta/\gamma$). The superposed particle thus goes through all three magnets.

iii. A spin *value* (↑/↓) is chosen to be imposed (see next section) on each particle as the measurement's final outcome. Only then is measurement completed to reveal the spin *direction* to which the imposed value pertains.

iv. Nonlocal correlations are expected between the spin directions just as they were with spin values in (I).

v. Local realism appears to account for these correlations by the earlier momenta randomly[1] assigned for each particle. Post-selection, so the argument goes, passively picked those momentum pairs, which merely happened to be correlated.

vi. However, by Bell's proof, (I*vi*), it is now these spin directions that cannot be ascribed to previously-chosen pairs of magnets. Rather, these directions depend on each experimenter's choice of the value to impose on their particle.

vii. It is therefore the momentum pairs of $p_1/p_2/p_3$, otherwise uncorrelated, and for which *any choice seems to be too late*, which become nonlocally correlated by virtue of the later, familiar correlations between the spin values.

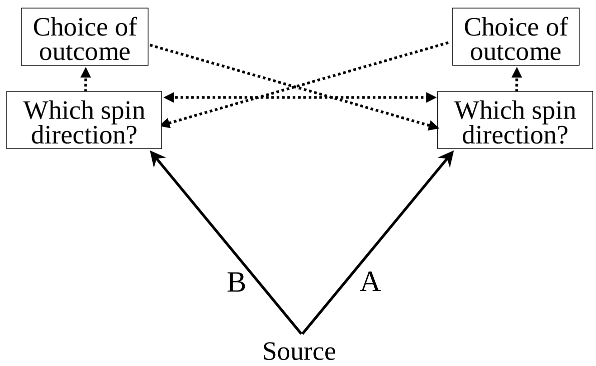

Fig. 2. The Too-Late Choice experiment

4. But how can the Spin Value be Arbitrarily Chosen?

Of course, it is the above "somehow" that must be specified in order to make the experiment even loosely feasible. How can one *choose* whether the measurement would yield "up" or "down"?

IFM [17] neatly comes to our help: Simply post-select for this value. Let three detectors be placed next to all "down" exits of the three SGMs that the particle traverses in superposition. In 50% of the cases, none of the detectors would click. We

[1]Or crypto-deterministically a-la Bohm.

have thus attained the desired state: We know that this particle's spin is "up," but still ignorant about the direction to which this "up" pertains. Repeat this procedure with the other particle. In 25% of the cases, you will succeed too.

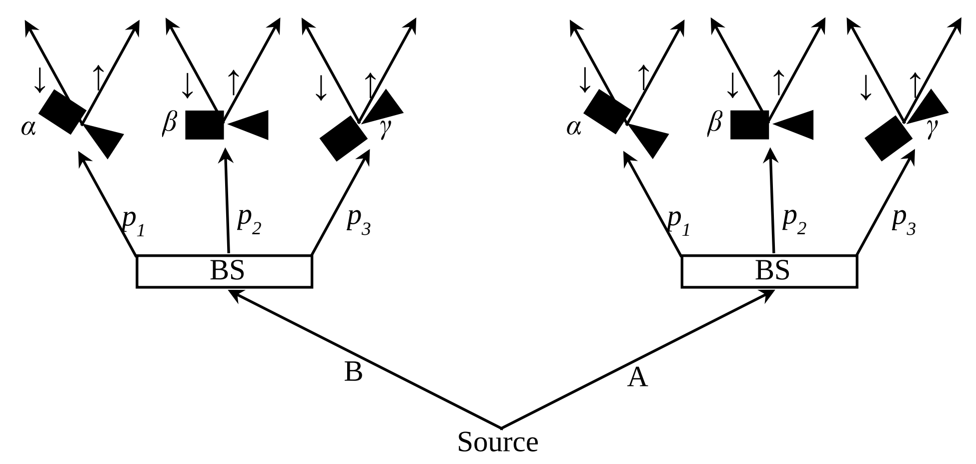

Fig. 3. The modified EPR experiment. For each particle, a three-port BS sends it towards one of three SG magnets. The particle's detection in one out of the six final exits thus determined not only its spin value, but also what was its earlier "decision" which of the three SGMs to enter.

Notice that the experimenters' freedom spans here over the four choices ↑↑/↑↓/↓↑/↓↓.[2] Let us focus on the same-value choices ↑↑ or ↓↓, of which our predictions' deviation from the local account are maximal. We have, then, two EPR particles whose spins are "up" along unknown directions.

Finally, complete the measurement for each particle: Place detectors on the remaining three "up" SGM exits. This time, a click is bound to occur in one of them, adding the actual spin direction to the "up" value.

Intuitively, one correlation is immediately expected: If particle A's "up" is along, say,*α*, B's "up" must *not*. Other correlations between the spin directions similarly follow from the familiar cosine correlation function, as shown in the next Section.

Naïvely, one may argue that these correlations can be explained on the basis of purely local post selection. Perhaps, so the argument goes, we are merely picking those cases where the two particles where directed by the two BSs towards the appropriate SG magnets, hence the remaining correlations. Dismissing this local alternative can be done similarly to the way Elitzur and Dolev [18] analyzed an EPR experiment involving incremental partial measurements. In that case, the nonlocal effects go back and forth between the two particles, piecemeal. Bell's proof can be applied even to these partial stages. Similarly for the present experiment: Bell's proof can be used to

[2] The temporal order by which these detectors are placed –whether on α, β or γ first, also has nonlocal consequences, but we focus here on the straightforward causal efficacy of the choice between overall "up" and "down"

show that each stage in the measurement's preparation, as well as each stage in its completion, nonlocal effects went back and forth between the particles. Our discussion only focused on the most conspicuous stage, namely the final detection.

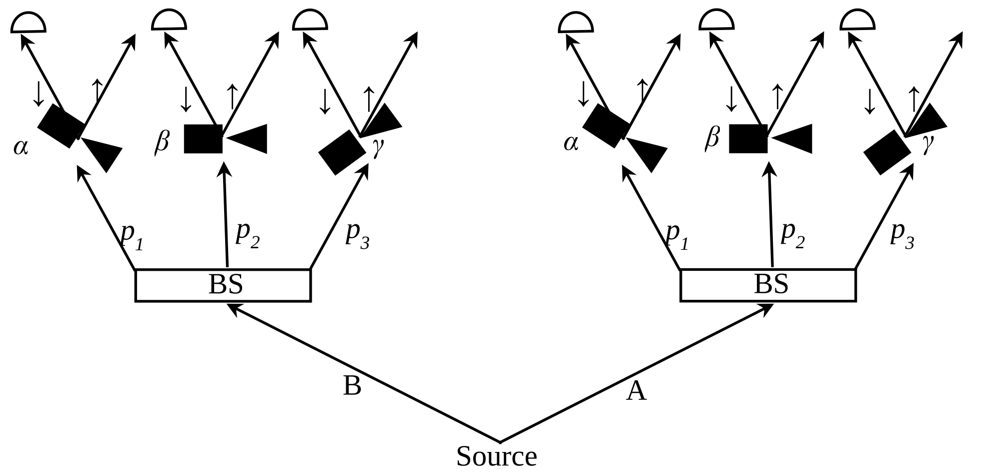

Fig. 4. The IFM post-selection. In cases where all six detectors positioned on all the "down" exits failed to click, both particles possess spin "up" in whatever direction they were prepared, imposing a new kind of correlation between their earlier histories.

5. The Too-Late Entanglement

Let us define the state arising from the above procedure. Unlike the superposition in the spin value in the standard EPR-Bell, here the spin *direction* remains superposed. So, for spin "up,"

$$|\psi\rangle_\uparrow = \frac{1}{\sqrt{3}}\left(|\alpha\rangle_\uparrow + |\beta\rangle_\uparrow + |\gamma\rangle_\uparrow\right),$$

and for "down",

$$|\psi\rangle_\downarrow = \frac{1}{\sqrt{3}}\left(|\alpha\rangle_\downarrow + |\beta\rangle_\downarrow + |\gamma\rangle_\downarrow\right),$$

modifying the EPR state into

$$|\text{TooLate}\rangle = \frac{1}{\sqrt{2}}\left(|\psi^A\rangle_\uparrow |\psi^B\rangle_\downarrow - |\psi^A\rangle_\downarrow |\psi^B\rangle_\uparrow\right),$$

where the familiar cosine-like correlations between results between outcomes are expected.

6. Summary: Why Go Time-Symmetric?

Before summarizing the lesson of this Too-Late Choice version of the EPR, it should be pointed out that the time-symmetric interpretations' merits have long ago been best illustrated on the ordinary EPR. The latter famously intrigues us by showing that Alice's choice of spin direction somehow affects Bob's outcome and *vice versa*. This feat, however, seems to be best elucidated if each measurement determines not only the particle's present state but its earlier history as well. Then, via the resulting spacetime zigzag, "nonlocal" turns out to be local in four dimensions (see also [15]).

But this account does more than mitigate the conflict between QM and special relativity. It also rids the poor particle from other daunting tasks imposed on it by hidden-variables models. How, for example, can the nonlocal effect travel from the particle without being attenuated by distance? And how can it precisely locate the particle's twin, no matter where it went, how far, and among how many zillions of otherwise identical particles? *Even if the relativistic prohibition on supraluminal effects did not exist, the EPR correlations would still be disturbing because of these neglected thermodynamic-like oddities*. The time-symmetric account's answer to these questions, however, is just as elegant [19].

Our reasons for opting for the time-symmetric interpretations is also based on our critical examination [20] of the prevailing interpretations, which we classify into two major groups: *i*) abandonment of ontology *vs*. *ii*) excessive ontology. In the first group, there are Copenhagen school [21], QBism [22] and their like, which eschew the very notion of objective reality. There are, so they argue, only data, information, "knowledge," "beliefs," *etc.*, as the essential ingredients of the quantum formalism. Consequently, no matter how unique and surprising is a certain effect predicted by QM, under "shut up and calculate" they are stripped of any mystery. At the same time, however, physics is denied the motivation account for apparent anomalies, resolve conflicts and search for better models.

In the second group, schools like Many Worlds [23] and Bohmian Mechanics [24] amend physical reality with entities that are unobservable almost in principle. For example, the parallel universes, numbering as many as all the possible outcomes of each and every quantum interaction anywhere in this universe, are inaccessible by definition. Similarly for Bohm's "guide wave": It must remain undetectable, otherwise violations of the uncertainty principle and SR would inevitably ensue ("hidden variables must be hidden forever" [25]). Worse, under simple situations involving mutual IFM between two particles, it turns out that position and momentum, which in Bohmian mechanics were supposed to regain their objective reality, exist not in physical space but in some configuration space, where particles can go through one another without interaction [20]. Comparing this resort into mathematics to the Copenhagen school's dismissal of objective properties, one cannot help asking whether the medicine is any better than the disease.

Where do the time-symmetric interpretations belong according to the above classification? They are certainly ontological, arguing that spacetime has some unfamiliar properties, yet this ontology is by no means excessive. If, at the quantum realm, causal effects proceed on both time directions, then appropriate experiments should be able to reveal them. Indeed TSVF already boasts some verifications of this kind, and further surprising theoretical and empirical results can be expected.

This of course comes with a price. It implies that there is something very profound about time which is still unknown to physics, absent even in the revolutionary accounts of general relativity and quantum field theory, and even in more speculative models. But, after a century of pondering quantum nonlocality and non-temporality, haven't we been made acutely aware of this ignorance all along?

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