THE TOO-LATE-CHOICE EXPERIMENT: BELL'S PROOF WITHIN A SETTING WHERE THE NONLOCAL EFFECT'S TARGET IS AN EARLIER EVENT

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In the EPR experiment, each measurement addresses the question "What spin value has this particle along this orientation?" The outcome then proves that the spin value has been affected by the distant experimenter's choice of spin orientation. We propose a modified setting where the question is reversed: "What is the orientation along which this particle has this spin value?" It then turns out that the orientation is similarly subject to nonlocal effects. Each particle's interaction with a beam-splitter at t_1 leaves its spin orientation superposed. Later at t_2, the experimenter selects an "up" or "down" spin value for this yet-undefined orientation. Only after the particles undergo this procedure, the two measurements are completed, each particle having a definite spin value along a definite orientation. By Bell's theorem, it is now the choice of orientation that must be nonlocally transmitted between the particles upon completing the measurement. This choice, however, has preceded the experimenter's selection. This lends some support to the retrocausal interpretations of QM. We conclude with a brief comparison between these interpretations and their traditional alternatives, Copenhagen, Bohmian mechanics and the Many Worlds Interpretation.

Quantum nonlocality [1], rigorously proven by the Bell [2] and GHZ [3] theorems, has a few temporal counterparts, where the quantum effects appear to go in the backwards time direction [4]. Unlike non-locality, however, retrocausality was never considered such a pivotal issue, let alone requiring rigorous proofs. We believe this neglect is inappropriate, because some modern interpretations of quantum mechanics, mainly Cramer's [5] transactional interpretation (TI) and Aharonov's [6] two state-vector formalism (TSVF), render time-symmetric causality essential for a comprehensive understanding of QM. Once, for example, causality is allowed to go backwards in time, effects that appear nonlocal in *space* turn out to be perfectly local in *spacetime* [7]. In the EPR case, for example, the measurement's effect simply zigzags along the two particles' world-lines. TSVF further derives several surprising predictions [6], of which many have already won empirical support. Other quantum peculiarities, such as the uncertainty principle and the measurement problem, may be amenable to similar interpretational twists [7,8].

In this article we offer a novel and simple demonstration of quantum retrocausality. We begin in Sec. 1 with a succinct review of quantum time-symmetric causality. The essential features of the standard EPR experiment are then briefly recounted in 2, followed in 3 and 4 by our "Too-Late Choice" variant. It specifies how the spin value, rather than the spin orientation, can be chosen. Sec. 5 shows how spin value can be arbitrary chosen. Sec. 6 describes the unique entanglement resulting from this reversal of measurement stages. Sec. 7 utilizes a modification of the "Too-Late Choice" experiment to elucidate an apparent conceptual difficulty with the alternative account of Bohmian mechanics. Finally, Sec. 8 concludes with a brief comparison between the ways different schools of quantum mechanics respond to the challenge of apparent quantum retrocausality.

1. Can A Quantum Effect Precede its Cause?

We begin with a simple working definition. Let "Orthocausality" denote the ordinary temporal direction of causation, which in the quantum realm means that measurement determines the particle's state at that moment as well as the consecutive ones until the next measurement. "Retrocausality," then, asserts that the measurement also determines the particle's past, backwards until the preceding measurement.[1] Following are some arguments along these lines.

The foundations of time-symmetry in QM have been laid out by the work of Aharonov, Bergmann and Lebowitz (ABL), who used a symmetric construction of statistical ensembles (now known as pre- and post-selection) to suggest a time-symmetric probability distribution of measurement outcomes [9]. This finding was later generalized and broadened into a comprehensive interpretation of QM, namely the Two-State-Vector Formalism (TSVF). This school then predicted some surprising effects that, although perfectly consistent with standard quantum theory, emerged only within the TSVF framework.

The first experiment suggesting quantum retrocausality was Wheeler's "delayed choice" gedankenexperiment [10], later realized in [11]. In that setting, the experimenter's last-minute decision is argued to determine whether a photon coming from a very far source has come, *all along*, as a wave or a particle. Yet Wheeler himself did not argue that the experimenter's decision really determines the particle's

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[1] The two accounts are not equivalent. Orthocausality is often presented as exclusive, admitting only one time direction. Retrocausality, in contrast, always comes within a time-symmetric framework.

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"* [10]).

Elitzur, Dolev& Zeilinger [12] were more explicit in their analysis of a time-reversed EPR ("RPE"), where two excited atoms emit single photons towards a single beam-splitter. Suppose only one photon in detected, with no indication which of the two atoms emitted it. This uncertainty (reflected in the induced superposition of the atoms' states) suffices to entangle the two atoms into a full EPR-Bell state. A temporal novelty emerges: The entangling event seems to reside in the two atoms' *future* rather than past. Elitzur *et al*. also pointed out the "delayed choice" aspect in this setting: By choosing at the last moment whether or not to insert a BS, the experimenter is actually deciding whether or not the two atoms *have been entangled*.

This setting was later used by Elitzur & Dolev [13] for their Quantum Liar experiment, where the retrocausal argument was straightforwardly based on Bell's proof. Here too, a single photon is emitted from one out of two atoms, its origin remaining indeterminate. This entangles them into an EPR-Bell pair. On this pair, they employed the standard Bell setting where each atom undergoes a spin measurement along one of three orientations. There was, however, one crucial difference: One of these three spin measurements was replaced with a different measurement that amounts to asking, "*Is this atom entangled with the other one?*" In half of the cases, the outcome must be "No." Yet this outcome too, just like those of the two spin measurements, is imposed by entanglement, catching Nature, so to speak, blushing in self-contradiction. Several comments on this gedankenexperiment, *e.g.* [14-16], especially Kastner's "possibilist" version of TI [17], indicate that the application of Bell's theorem makes retrocausality merit serious consideration.

Elitzur & Cohen [18] reviewed these retrocausal approaches as well as several measurement methods they called "incomplete," *e.g.*, weak [19] and partial measurements [20]. They also proposed gedanken combinations of them to better elucidate quantum retrocausality.

Aharonov, Cohen & Elitzur [7] offered a novel twist to the EPR-Bell setting with the addition of weak measurements preceding the two final strong ones. Although the predicted results can be explained by normal causality, *i.e.*, arguing that the weak measurements have merely inserted some slight bias into the particle pair, which later affected the final strong measurements, Aharonov *et al*. argued that the more natural account would be that of the TSVF account, where the backwards evolving (post-selected) states determined the outcomes of the *earlier* weak measurements.

More recently, studying a simple quantum interaction that appears to violate momentum conservation, E&C showed that all nonevents can be traced back into a fundamental "Quantum Oblivion" effect, where a very brief virtual interaction ends up with "unhappening." Venturing further to theory, they proposed [21, 22] a retrocausal evolution that accounts for such self-cancellation, involving exchange of negative physical values between earlier and later events. These works offered a comprehensive framework for the study of both weak and strong measurements, with several intermediate phenomena that call for further study.

This is the background for the argument 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 orientation to be measured and then the final outcome 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 Orientation?"

Recall first the standard EPR-Bell setting (Fig. 1).

i. A particle pair is prepared in the singlet 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 (Fig. 1).

ii. Then, for each particle, one out of three possible spin orientations, *e.g.*, from the co-planer set $\{\alpha/\beta/\gamma\}$, is randomly chosen to be measured. Temporally speaking, this is the spin measurement's *preparation*, by the particle's entrance into the appropriately aligned Stern-Gerlach (SG) magnet.

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

iv. Over many times, correlations between the ↑/↓ values are expected within the A/B pairs. By Bell's theorem, each pair of spin values turns out to depend on the two orientations $\{\alpha,\beta,\gamma\}$, chosen an instant earlier.

v. Local realism may naively account for these correlations as pre-existing spin values, specified in advance for each possible orientation, to be only passively revealed by any future measurements.

vi. However, Bell's theorem proves that no such pre-existing values can be accommodated with the experimenters' simultaneous and independent free choices of spin orientations. It is therefore these choices, plus their random outcomes, that non-locally affected the distant particle's spin value.

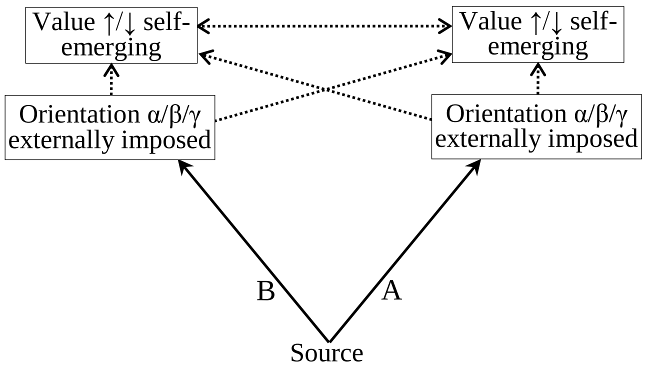

Fig. 1. The web of local and nonlocal correlations in the EPR-Bell experiment

3. A Slight Modification: Leave the Particle to "Choose" the Spin-Orientation to be Measured

To introduce our Too-Late version of the EPR, let us reconsider the measurement in the standard setting (stages 2*ii*-2*iii* above). Each particle's spin value turns out to be determined by *a*) the spin orientation measured on the other particle – freely chosen at the last moment by the distant experimenter – and *b*) that measurement's outcome – randomly imposed by quantum uncertainty (Fig. 1). On this combination Bell's proof rests.

Suppose however that the choice of spin-orientation is also left to the particle: A simple three-port beam-splitter sends it to one out of three SGMs, aligned along α, β, or γ. Only upon the final detection, then, will the particle "decide" which choice it was.

Does this modification make the non-locality proof weaker? Apparently, giving up the experimenter's free decision amounts to losing the outcome's "external" component, to be nonlocally transmitted between the particles. A closer look, however, shows that this component does not have to be external. First, the particles are not correlated for position and momentum. Moreover, the three positions of the SGMs can be arbitrarily placed for each BS. Therefore, *the particles cannot "conspire" in advance about their choices of spin orientation*. Hence they still have to inform one another, *non-locally*, about the spin orientation each particle eventually "chooses."

This simplification, therefore, leaves the non-locality proof intact while enabling the temporal exchange between the spin value and spin orientation outcomes.

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

Suppose, then, that we could somehow first obtain a certain spin value for each EPR particle and only then subject the pair to a question like "both spins are ↑, so to which orientations does this ↑ pertain for A and for B?" Then, it would be these orientations that Bell's theorem obliges to be non-locally affected.

Here, then, is the Too-Late Choice experiment (Fig. 2)

i. A particle pair is prepared as in (2*i*).

ii. For each particle, the spin orientation (2*ii*) is left undecided as the particle interacts with a three-port beam-splitter which makes its momentum superposed ($p_1/p_2/p_3$) towards the three SG magnets pre-aligned along ($\alpha/\beta/\gamma$). The particle thus goes through all three magnets superposed.

iii. With a special delicate measurement (see Sec. 5), each particle is measured only for its spin *value* (↑/↓), the orientation still left superposed.

iv. Only then is measurement completed to reveal the orientation to which this value pertains.

v. Nonlocal correlations are now expected between the spin orientations, just as they were with spin values in (2*iv*).

vi. Local realism may try to preserve the temporal order in the following way: The earlier choice of spin orientation, although not yet known to the observer, has already been decided by the particles earlier, then transmitted non-locally *at that* *time*. Therefore, the spin value obtained at (2*iv*) was by then pertaining to this unknown-yet-definite orientation.

vii. Here, however, Bell's inequality would not suffice to rule out the orthocausal alternative. Another falsification is given below by showing, through quantum interference, that the spin orientation was genuinely superposed even after spin value was determined.

viii. 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 non-locally correlated by virtue of the later, familiar correlations between the spin values.

5. 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 feasible. How can one measure a certain spin value for all orientations?

Suppose the two EPR particles going through the above setting are heavy atoms. Now delay each atom within its six possible paths ($\alpha/\beta/\gamma$)·(↑/↓) and send a photon along, say, the three "up" paths. Should the photon emerge unabsorbed, we know that the particle's spin is "down" without yet determining the orientation. Similarly for the case the photon *is* absorbed: the atom becomes, in addition, excited, but its spin value is certain while its superposition of orientation remains intact.

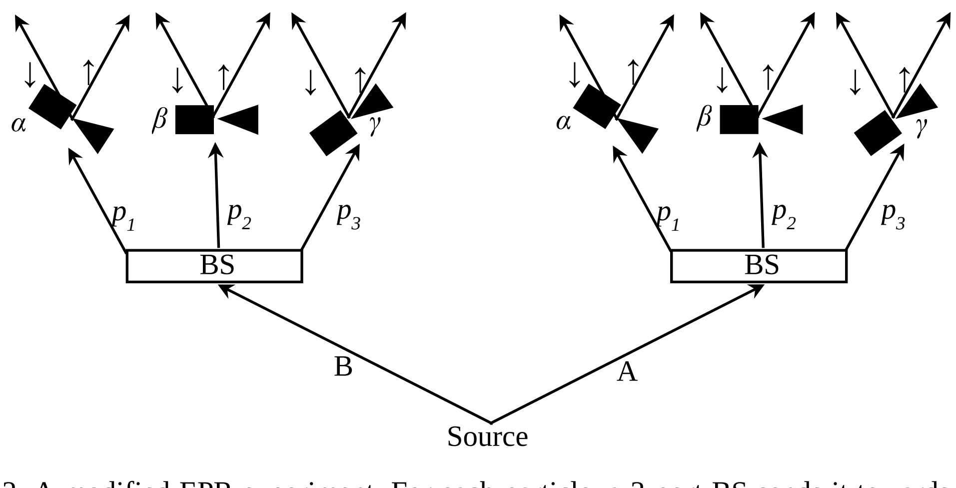

Fig. 2. A modified EPR experiment. For each particle, a 3-port BS sends it towards one of three SGMs. The particle's detection in one out of the six final exits thus determined not only its spin value, but also which SGM it has entered earlier.

Consider, then, the simplest case where the two measurements give same-value pairs ↑↑ or ↓↓. One (anti-)correlation is immediately expected: If particle A's "up" is later found to be along, say, *α*, then B's "up" must *not*. Other correlations between the spin orientations similarly follow from the familiar cosine correlation function, as shown in the next Section.

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 spin orientation to which the value pertains.

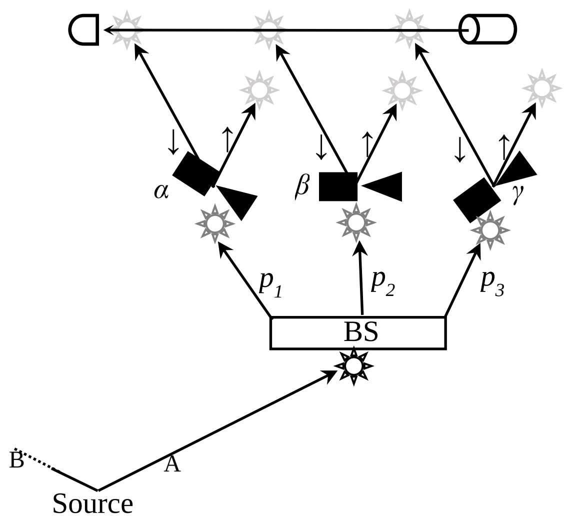

Fig. 3. Obtaining a spin value before orientation is determined. A photon is emitted by the source at the right of the three "down" exits. Should it arrive to the left detector, the atom's spin would be certainly "up." Otherwise, the spin is "down" and the atom is also excited.

6. The Too-Late Entanglement

The above procedure has given rise to a new entanglement. Unlike the superposition of spin *value* in the standard EPR-Bell, here the spin *orientation* remains superposed and then subjected to measurement. So, for spin "up,"

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

and for "down"

$$|\psi\rangle_{\downarrow} = \frac{1}{\sqrt{3}}\left(|\alpha\rangle_{\downarrow} + |\beta\rangle_{\downarrow} + |\gamma\rangle_{\downarrow}\right), \qquad (2)$$

modifying the EPR state into

$$\left|\text{TooLate}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\psi^{A}\right\rangle_{\uparrow}\left|\psi^{B}\right\rangle_{\downarrow} - \left|\psi^{A}\right\rangle_{\downarrow}\left|\psi^{B}\right\rangle_{\uparrow}\right), \tag{3}$$

where the familiar cosine-like correlations are expected. Now, however, it is the measurement of one particle's spin orientation that nonlocally affects the orientation of the other, as the spin values is already fixed. But then, again, by the experiment's time evolution, the spin orientations have been determined prior to the spin values (Fig. 4).

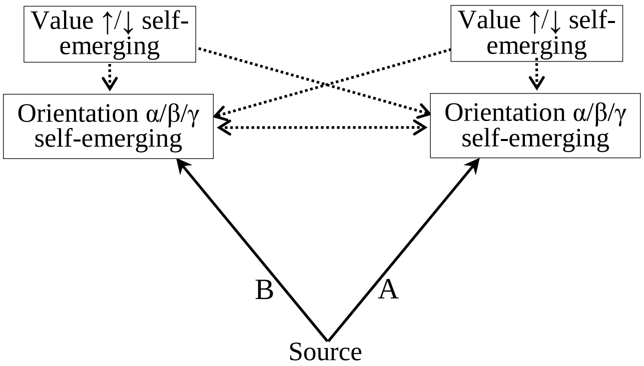

Fig. 4. The local and nonlocal correlations' web of Fig. 1 inverted by the Too-Late version. The nonlocal correlation between spin orientations can be inferred only after spin-values measurements were completed.

7. How Rigorous is the Argument? A Bohmian Alternative and an Auxiliary Counter-Argument

Our above argument relies on Bell's proof. The latter, however, originally devised for non-locality, cannot be extended to retrocausality. The reason is simple: In the EPR setting, spin orientations *e.g.*, α and β, are deliberately *imposed* by an external agent, forcing the spin values to behave nonlocally so as to comply with spin conservation. Our setting, in contrast, cannot do so with spin values, *e.g.*, impose two ↑'s, so as to force nonlocality on the orientations. Consequently, even Bell's banishment of local hidden variables does not rule out nonlocal but orthocausal hidden variables.

Fortunately, another control employed by our setting enables challenging this last resort. We can show that the most notable realistic alternative to retrocausality, namely that of Bohmian mechanics, is challenged.

In the Too-Late Choice experiment, so the Bohmian account would go, each EPR atom (*i.e.*, the corpuscular part of the wave-function) enters, in reality, only one SGM, and then one of that SGM's arms, while its accompanying guide wave goes through all six paths. The two atoms, therefore, inform one another about their spin orientations, as well as spin values long before the final detections merely *post-select* these histories. This enables explaining even interference effects of the atom, should one try to prove that the atom has gone through all three SGMs. While this Bohmian account runs contrary to the quantum formalism's depiction of spin orientation and value as being still superposed, the former predicts the same results as the latter.

This account is indeed reasonable, as long as it deals with a single particle. With more than one, it resorts to a multidimensional configuration space, apparently with much less realistic content. In our setting, this change becomes acute in those cases where the spin value measurement (Sec. 5) ends up with the photon absorbed by the superposed atom (Fig. 3).

Having absorbed the photon, our superposed atom is excited. Hence, if sufficiently delayed within the three SGMs, it will reemit the photon. Now, should we place three photon detectors next to the three magnets, one of them will absorb the photon upon reemission, thereby indicating the atom's position. We can, however, place a single detector far enough and at equal distance from all three magnets, such that the photon's detection would leave its origin superposed. This is an interference effect, leaving the photon's origin superposed as well.[2] Let this procedure be performed also with respect to the second atom. Consequently, the entanglement between the atoms swaps to entanglement between the emitted photons. Hence, nonlocal correlations between the photons' polarizations are expected.

Obviously the guide-wave model is somewhat strained at this point. *How can an empty wave absorb a photon (or worse, the photon's guide wave) in full accordance with the atom's internal structure (electron shells, etc.) and then emit it back, just like a corpuscular atom*?

In reply, Bohmian mechanics would argue that, when dealing with entangled particles, it no longer ascribes them well-defined positions in ordinary space. Rather, both the atom and its photon have definite and correlated coordinates in *configuration space*. This resort to a space which is purely mathematical, seems to rob Bohmian mechanics of much of its realistic aspirations. So much so, to the extent of resembling

[2] It also resembles the Hong–Ou–Mandel effect [23], which can be seen as the quantum version of the Hanbury-Brown-Twiss experiment

its Copenhagen archrival, that one may wonder whether the medicine is not worse than the disease itself.

This gedanken experiment's outcome, echoing similar sentiments in recent reviews, is part of a more detailed critique of Bohmian mechanics [24].

8. Summary: Why Go Time-Symmetric?

As pointed out earlier (Sec. 1), the merits of time-symmetric interpretations have long ago been illustrated on the ordinary EPR experiment. The latter famously intrigues us by Alice's choice of spin orientation somehow affecting Bob's outcome and *vice versa*. This feat seems to be best elucidated if each measurement determines not only the particle's present state but its *earlier history* as well. Via the resulting spacetime zigzag, "nonlocal" turns out to be local in four dimensions (see also [7]).

But this account does more than mitigate the conflict between QM and special relativity. It also rids the poor particle from several other daunting tasks imposed by hidden-variables models. How, for example, can the presumed effect travel from one particle to the other without being attenuated by distance? And how does it precisely locate the particle's twin, no matter where it went, how far, and among how many zillions of identical particles? The mathematical abstraction of Hilbert spaces answers these questions, but they remain conceptually disturbing.

Moreover, the time-symmetric formalism was also shown to account for the apparent collapse we see in nature and the measurement problem [8]. It also gave rise to various surprising predictions (see e.g. [25]).

Other reasons for opting for the time-symmetric interpretations are also discussed in our critical examination [24] of the prevailing interpretations of QM, which we classify into two major groups: *i*) abandonment of ontology *vs*. *ii*) excessive ontology. In the first group, there are the Copenhagen school [26], QBism [27] and their like, which eschew the very notion of objective reality. Only data, information, "knowledge," *etc.*, are admitted as essential ingredients of the quantum formalism. Consequently, no matter how unique and surprising can be a new effect predicted by QM, under this "shut up and calculate" spirit they are stripped of any mystery. Physics is thus denied the motivation to account for apparent anomalies, resolve paradoxes and search for better models.

In the second group (*ii*), schools like Many Worlds [28] and Bohmian Mechanics [29] 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 hidden variables: They must remain undetectable, otherwise violations of the uncertainty principle and SR would inevitably ensue ("hidden variables must be hidden forever" [30]). Above (Sec. 7), however, we gave an example where, when faced with more than one particle, Bohmian mechanics assumes such an abstract form that amounts to "defection" to group (*i*).

Where do the time-symmetric interpretations belong according to this classification? They are certainly ontological, as they argue that spacetime objectively possesses some unfamiliar properties. Yet this ontology is by no means excessive, neither untestable. If, at the quantum realm, causal effects proceed on both time directions, then sufficiently delicate experiments should be able to reveal this dual nature. 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. If Retrocausality underlies quantum phenomena, something very profound about time is still unknown, 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 retrocausality, is it not time to admit this lacuna and, moreover, begin addressing it?

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