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The Retrocausal Tip of the Quantum Iceberg

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Abstract. We discuss the fundamental role of non-events in quantum mechanics. The (non-)emission of a particle from an isolated atom under the uncertainty principle is studied with the aid of two novel gedankenexperiments, one using projective measurements and the other going deeper with the aid of weak measurements. We describe the basic experimental setups, point out the surprising predictions of quantum theory, analyzed using the Two-State-Vector Formalism, and briefly conclude with some broader implications.

INTRODUCTION

Retrocausality is gradually gaining respect in mainstream physics, not the least thanks to the devotion and inspiration of Daniel Sheehan, who organized some very simulating sessions with this explicit topic within the AAAS meetings. Among many benefits of these sessions, an important dialogue has evolved between the Transactional Interpretation (TI) [1-2] and the Two-state-vector-formalism (TSVF) [3-6], which, despite several differences, share the view that quantum causality is highly time-symmetric, moreover offering a very natural and consistent understanding of quantum mechanics' world of riddles and paradoxes. This dialogue's fruits so far are very promising, as shown below.

In this article we review some published works, followed by more recent, preliminary results, presented somewhat raw, in line with these meetings' tradition of providing a friendly sounding board for novel ideas. They will be shown in greater technical detail in forthcoming papers.

The outline of the paper is as follows. In Sec. 1 we review the Oblivion effect lying at the heart of many quantum phenomena. Secs. 2 and 3 discuss the causal role of nonparticles in light of quantum oblivion. In 4 we present a paradox where two atoms are understood to be both entangled and non-entangled. This paradox and its consequences are then discussed in Sec. 5, before concluding with 6.

1. QUANTUM OBLIVION: THE UNDERLYING MECHANISM OF SEVERAL QUANTUM ODDITIES

Quantum indeterminacy, the wave-particle duality and nonlocality are usually pointed out as quantum mechanics' most unique features. This list may not do full justice to the theory's depth. No less paradoxical is the causal efficacy of *counterfactual* quantum events. Consider, *e.g.*, Interaction-Free Measurement [7]: A particle *may* hit a detector but eventually does *not*, yet just because it *could* have, its momentum *does* change. Other related effects, such as Hardy's paradox [8], intensify this quantum oddity even further.

At first sight, such phenomena lend strong support to the Copenhagen school and related interpretations, which "explain" QM's uniqueness by making it a theory about knowledge, consciousness, *etc.* rather than of objective reality. Strongly opposing this temptation, we aspired for a purely physical account for quantum nonevents. Happily, a simple interaction between two particles (Fig. 1) which we have studied and named Quantum Oblivion [9-11],

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turned out to do just that, namely revealing the basic mechanism underlying all these "could" phenomena. This is an asymmetric interaction, by which one particles undergoes momentum change while the other remains unaffected.

Consider an electron and a positron, both with spin state

$$\left|\sigma_x = +1\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\sigma_z = +1\right\rangle + \left|\sigma_z = -1\right\rangle\right)$$

split by two different Stern–Gerlach magnets positioned at (t_0, x_{e-} , y_0) and (t_0, x_{e+} , y_0), respectively, to enable the asymmetric interaction shown in Fig. 1. The magnets split the particles' paths according to their spins in the x-direction

$$\left|\psi_{e^-}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|1'_{e^-}\right\rangle + \left|1''_{e^-}\right\rangle\right) \text{ and } \left|\psi_{e^+}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|2'_{e^+}\right\rangle + \left|2''_{e^+}\right\rangle\right). \quad (1)$$

Let care be taken to ensure that, should the particles turn out to reside in the intersecting paths, they would mutually annihilate.

The time evolution of these two wave-functions eventually includes also the two nearby detectors $\left|READY\right\rangle_1$, $\left|READY\right\rangle_2$, set to measure the photon emitted upon pair annihilation, which would change their states to $\left|CLICK\right\rangle_1$ or $\left|CLICK\right\rangle_2$.

Initially, the total wave-function is the separable state

$$\left|\psi\right\rangle = \frac{1}{2}\left(\left|1'_{e^-}\right\rangle + \left|1''_{e^-}\right\rangle\right)\left(\left|2'_{e^+}\right\rangle + \left|2''_{e^+}\right\rangle\right)\left|READY\right\rangle_1\left|READY\right\rangle_2 . \quad (2)$$

The particles, depending on their positions at t_1 or t_2, may (not) annihilate and consequently (not) release a pair of photons, which would in turn (not) trigger one of the detectors.
At $t_0 \le t < t_1$, then, the superposition is still as in Eq. 2. But at $t_1 < t < t_2$, either a photon pair is emitted, indicating that the system ended up in

$$\left|1''_{e^-}\right\rangle\left|2'_{e^+}\right\rangle\left|CLICK\right\rangle_1\left|READY\right\rangle_2 ,$$

or not, indicating that the particles did not annihilate, thereby

$$\left|\psi\right\rangle = \frac{1}{\sqrt{3}}\left[\left(\left|1'_{e^-}\right\rangle + \left|1''_{e^-}\right\rangle\right)\left|2''_{e^+}\right\rangle + \left|1'_{e^-}\right\rangle\left|2'_{e^+}\right\rangle\right]\left|READY\right\rangle_1\left|READY\right\rangle_2 , \quad (3)$$

which is a superposition of an interesting type: one component of it is a definite state, as usual, while the other is a superposition in itself.

Similarly at $t > t_2$: If a photon pair is emitted, we know that the particles ended up in paths 1' and 2': $\left|1'_{e^-}\right\rangle\left|2'_{e^+}\right\rangle\left|READY\right\rangle_1\left|CLICK\right\rangle_2$. Otherwise, however, we find the product state

$$\left|\psi\right\rangle = \frac{1}{\sqrt{2}}\left(\left|1'_{e^-}\right\rangle + \left|1''_{e^-}\right\rangle\right)\left|2''_{e^+}\right\rangle\left|READY\right\rangle_1\left|READY\right\rangle_2 , \quad (4)$$

which is even more peculiar. The positron is observably affected: If we time-reverse its splitting, it may fail to return to its source. Its momentum has thus changed. Not so with the electron: It remains superposed, hence its time-reversibility remains intact (Fig. 2). One may deduce now in retrospect that the momentum of the positron's Stern-Gerlach magnet has changed as well. However, it should be remembered that being a massive, macroscopic object, such a momentum transfer to the Stern-Gerlach magnet could hardly be observed – this momentum change is much smaller than the uncertainty in the magnet's momentum.
This is Quantum Oblivion, where one party of the interaction "remembers" it through momentum change, while the other remains unaffected, apparently violating momentum conservation.

This, then, is what happens in IFM: Briefly before macroscopic amplification finalizes the particle-detector (non)interaction, partial entanglement is formed between them, immediately to be dissolved. Consequently, the particle undergoes momentum change while the detector "forgets" the entire interaction.

Under such finer time-resolution, many varieties of quantum measurement similarly turn out to stem from Quantum Oblivion: IFM [7], Quantum Zeno Effect [12-13], Quantum Erasure [14], The AB effect [15] and more. Oblivion was later analyzed in terms of self- cancelling weak values [10-11].

2. THE NEGLECTED ROLE OF NONPARTICLES IN QUANTUM MECHANICS

It is now time to point out the most striking feature of the above experiment, where an electron effects the positron but not *vice versa*. The crucial role be this feat is played by two other, *nonexistent* particles. In Fig. 1c-d, where the interaction ends up with annihilation, the two resulting Gamma photons finalize the outcome upon hitting the detectors, which, significantly, may be *very distant*. Apparently, no such photons seem to be involved in the last case shown in Fig. 1d. This impression, however, is wrong in a most profound way:

Prior to the detector's click or non-click, not only the electron and positron were superposed, in the ordinary spatial uncertainty "left"/"right." There were also two pairs of Gamma photons that could be emitted by these particles' possible annihilation, thereby similarly superposed over "emitted/unemitted."

We wish to stress that these entities, henceforth "nonparticles," rigorously follow from standard quantum theory, despite being rarely if ever discussed. They will play a vital role in the experiments described below.

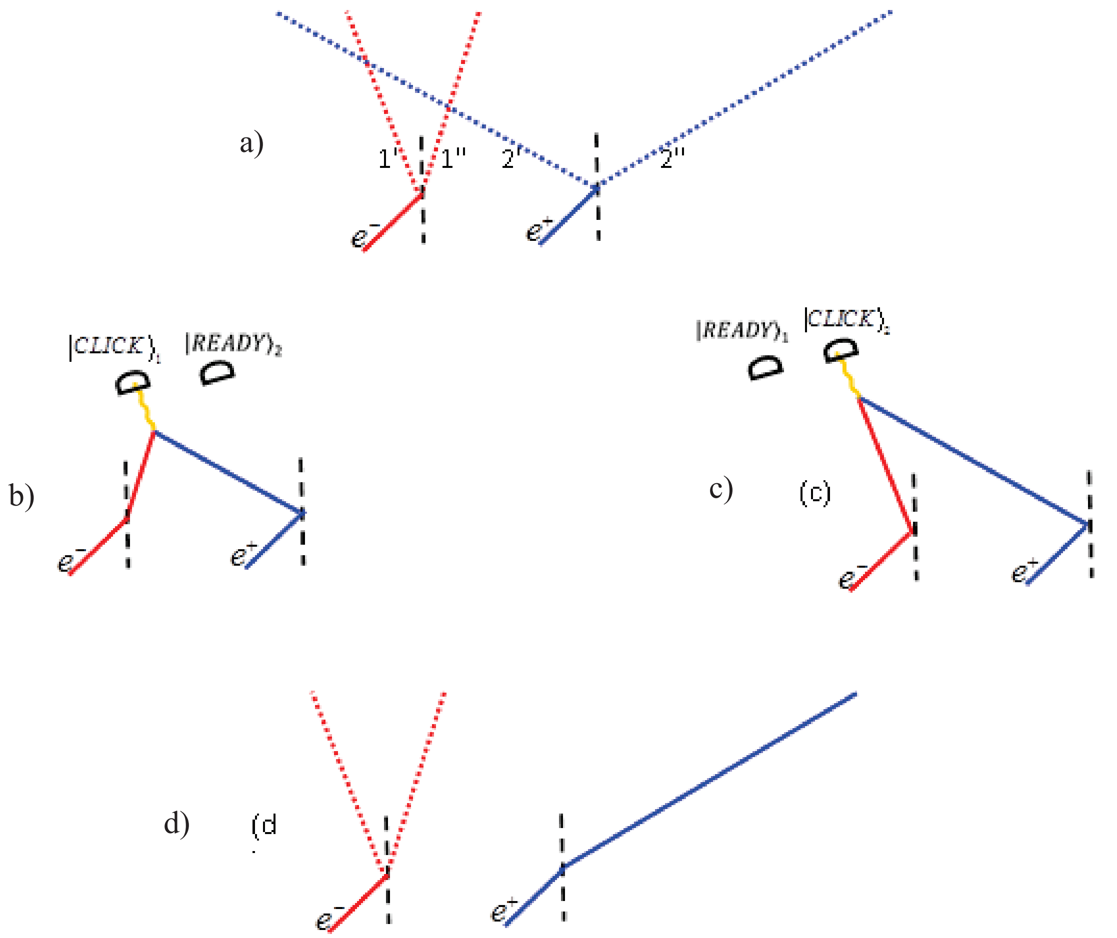

FIGURE 1. Quantum Oblivion. An electron and a positron are split and travel such that one half of the positron's wave crosses the electron's wave-function two halves (a). The interaction may result in either mutual annihilation in one of the two possible meeting points (b-c), or in the positron's "collapse" to the direction opposite to the electron's location as if they never interacted. The electron, however, emerges "oblivious" of the entire evolution. This effect underlies many familiar quantum phenomena.

3. WHAT HAPPENS WHEN AN ATOM DOES NOT EMIT?

Following Mach, consider a single atom, floating in space very far from any other matter. Assume that it is radioactive and also excited. Sooner or later, then, it will emit its α, β and γ particles, as well as a photon. It *will* emit them, but has not yet.

Nothing therefore has happened so far, right? *Wrong*. To reiterate the lesson of Quantum Oblivion, our atom constantly emits non-alpha, non-beta and non-gamma particles as well as a non-photon – all capable of leaving causal marks as in the Oblivion Effect, and all best explained by quantum retrocausality.

Recall first that not only an event's location, but its very occurrence as well, are subject to the uncertainty principle. The uncertainty for the emission of, say, the photon is manifested by its time-dependent state

$$|\psi(t)\rangle_A = 2^{-t/2\tau}|e\rangle + \sqrt{1-2^{-t/\tau}}|g\rangle, \quad \tau\Delta E \geq \frac{\hbar}{2}, \tag{5}$$

where τ is the half-life time of the excited level $|e\rangle$ and ΔE the difference between it and the ground state energy. This puts the potentially-emitted particle in an interesting superposition: like the ordinary spatial uncertainty Δx, superposed over "here" and "there," it is now but Δt, superposing the particle's entire state over a "born" and an "unborn" histories.

Next consider a very distant potential absorber of one of such a particle, say again the photon. By the time it takes for the photon to traverse the distance between the source and absorber atoms, the latter enters into the corresponding superposition of *excited/ground*.

Now we are talking physics – entanglement, nonlocality *etc.,* which, thanks to Einstein, Podolsky, Rosen, Bohm and Bell and their experimental followers, are nowadays practically feasible. The following gedankenexperiment [16] is a simplified, hence sharper version of the Quantum Liar Paradox [17] previously published in this series, and now with many refinements and novel insights.

4. WHEN MOTHER NATURE CONTRADICTS HERSELF: ENTANGLEMENT BETWEEN SOURCE AND FUTURE ABSORBERS

First let us stress again: *Gedanken, gedanken, gedanken* – no concern for technicalities in what follows, confining ourselves to the idealized level.

Our excited atom, *A*, is now placed at *t=0* inside a long reflecting cavity, such that, upon decaying, it emits a photon straight along the cavity's opening direction. Emission will occur under the time-energy uncertainty of (1). Another atom *B*, of the same element but in a ground state, is placed within an identical cavity, located at distance *d* and oppositely facing *A* (Fig. 1). After the excited atom's half-life time $\tau \ll d/c$ (to prevent multiple emissions and absorptions) it has emitted the photon with *P*=50%. Now close A's cavity door and wait until $\tau + d/c$ to close B's cavity door as well. The two atoms' states are now almost maximally entangled

$$|\psi(t)\rangle_{AB} = \sqrt{\frac{1-\varepsilon^2}{2}}\left(2^{-(t-t_i)/2\tau}|e\rangle_A|g\rangle_B + i\sqrt{1-2^{-(t-t_i)/\tau}}|g\rangle_A|e\rangle_B\right) + \varepsilon|g\rangle_A|g\rangle_B|\gamma\rangle, \tag{6}$$

where ε accounts for the chance of finding the two atoms in their ground states and the photon γ still traveling along the route connecting them, which we rather avoid. The proposed paradox would in fact persist in a weaker form even if $\varepsilon > 0$ but for simplicity we shall assume it is strictly zero, by excluding all cases where a photon was caught on its way from A to B. The relative phase of $\pi/2$ is inserted to make the process's unitarity explicit, keeping track which atom was initially excited and which was ground.

FIGURE 2. An excited and a ground-state atoms (a) turn into an entangled excited/ground state (b) after a possible photon exchange, and sealed in their cavities.

Having prepared many such pairs, let atoms *A* and *B* of each pair be given to Alice and Bob, respectively. To prove Bell Inequality violations, each partner randomly chooses one out of three variables to be measured on atom *A*/*B* of the pair. The first variable, naturally, is the atom's energy, namely, whether it is excited/ground. Two other variables, that maintain uncertainty relations with the first, need to be also given to the same choice. Magnetic dipole moment $\vec{\mu}$ is the best for this purpose. A measurement along the $\hat{\xi}$ direction with a suitable magnetic field would give the magnetic moment's outcomes $\mu_\xi \equiv \frac{\vec{\mu}\cdot\hat{\xi}}{|\vec{\mu}|} = \pm 1$, corresponding to linear combinations of the excited/ground states $\cos\alpha|e\rangle + \sin\alpha|g\rangle$. Thus a measurement of μ_z, *i.e.*, along $\alpha = 0$ is essentially an energy measurement resulting in either $|e\rangle$ with eigenvalue $\mu_z = +1$, or $|g\rangle$ with $\mu_z = -1$. In other cases, for instance, a measurement of μ_ζ, where $\hat{\zeta} = \frac{\hat{x}+\hat{y}}{\sqrt{2}}$ corresponds to $\alpha = \pi/4$, discerning between the $\frac{1}{\sqrt{2}}\left(|e\rangle + |g\rangle\right)$ and $\frac{1}{\sqrt{2}}\left(|e\rangle - |g\rangle\right)$ states. Conversely, measurement in the *E or* μ_z basis corresponds to measurement in the $\alpha = 0$ direction. Measurement along other directions refer to rotations of the magnetic field.

This way, precisely like the three customary spin/polarization directions measured in ordinary EPR-Bell experiments, we have the three measurement bases E, μ_{ζ_1} μ_{ζ_2}, with the analogous Bell correlations between them

$$C(\alpha_1,\alpha_2) = -\cos\left(2(\alpha_2 - \alpha_1)\right), \tag{7}$$

where α_1 and α_2 are the angles freely chosen by Alice and Bob in the EPR-Bell version, translated in our version to the above three choices.

Finally, having accumulated many such pairs of outcomes, Alice and Bob compare them for analysis of their EPR effects. Each of them has chosen to measure E, μ_{ζ_1} or μ_{ζ_2} roughly equally in ~1/3 of the cases. For each measurement thus chosen, Alice's outcome provides significant information about Bob's outcomes for each possible choice: 100% correlation if he incidentally chooses the same variable, and 37.5% and 25% for the two others. By Bell's theorem, this combination can arise only nonlocally: *Each measurement's outcome is determined by the other experimenter's deliberate choice of variable plus its random outcome*.

A paradox is now bound to ensue when Alice/Bob/both choose to measure *E*, which determines whether the photon has been emitted/absorbed at all. In half of the cases (total 1/6*), the initially excited/ground atom turns out to be still excited/ground*. And yet, even in such cases the correlations are just as nonlocal. For example, Alice, having obtained $|e\rangle_A$, indicating that her atom has *never* emitted its photon, nevertheless knows that:

1. If Bob measures *E*, he gets $|g\rangle_B$ (affirming that his atom has never absorbed the never-emitted photon) in 100% of the cases.
2. If Bob measures $\alpha_1 = \pi/3$, he gets +1 in 75% of the cases.
3. If Bob measures $\alpha_2 = \pi/6$, he gets +1 in 25% of the cases.

Which, by EPR-Bell, is partially caused/affected by Bob's choice. *The indication of atom A/B that it has never emitted /absorbed a photon, hence could not be untangled with B/A, is the result of this very entanglement*. Epimenides' "all Cretans are liars" is not necessarily absurd when stated by a quantum-mechanical Cretan [18]. The resolution of this paradox [16] can be given in terms of a Cheshire cat behavior [19].

5. WEAK MEASUREMENT MAKES THE "NOTHING" EVEN RICHER

The above experiment has demonstrated an effect exerted on an excited atom by a potential absorber located far away, thereby exerting its influence on the atom from the far future. This has been demonstrated by ordinary quantum measurement. What about more delicate measurements, those that were especially designed for measuring both past and future effects? These are weak measurements [20-24], which, when applied to our lonely atom, reveal a far more intriguing evolution [25-26].

Since our excited atom is also radioactive, it is going to emit charged particles as well. Let us then consider the α particles. "Excited" and "ground," then, denote the state of our atom's nucleus with respect to the α particle's (non-)emission.

Next, let us change our experiment's boundary conditions into a rare case: *i*) There are no potential absorbers within the atom's future causal light-cone extending to the next measurement. *ii*) At both t_1 and t_2, separated by the atom's half-life τ multiplied, say, by 10, *both* the initial and final measurements reveal that the atom has *not* emitted its α particle. This happens with probability $2^{-10} \approx 0.001$. It is such rare cases that enable TSVF to reveal a deeper quantum reality that probably underlies common cases as well.

What can we know about the state – apparently of no interest – extending between this pair of same-outcome measurements? Entanglement verification measurements, like those described above, are strong measurements, hence useless for this case. Perhaps, then, we can concede that, this time, indeed nothing happens? Wrong again: TSVF states that the atom's evolution is the by no means static.

For this purpose, TSVF uses the information coming from both state-vectors, past and future. It also recruits its experimental innovation, namely weak measurement [20-24]. Let us then populate the entire surroundings of our atom with a myriad of appropriately-separated test charges, say, electrons. Due to the precise position with would they were prepared and their resulting momentum uncertainty, their coupling to the possible presence and emission of the positively-charged α particle is obscured by a great deal of noise. Only when all these numerous, individually-unreliable outcomes are appropriately sliced according to both pre- and post-selections (the initial and final measurements (Figs. 2-4), and summed up together, a reliable outcome emerges [23,24].

When the atom is prepared at $t=0$ in an excited state, its forward- evolving wavefunction is given by Eq. (1). The past measurement's contribution is the familiar wave-function, bounded by the future spacetime cone originating from the nucleus forward in time. The latter, in contrast, "spreads" in the opposite time direction, namely *converges* towards the future measurement (Fig. 2). This follows from the mathematical representation of time-dependent weak values

$$A_w(t) = \frac{\langle\Phi|U^\dagger(t-t_f)AU(t-t_i)|\Psi\rangle}{\langle\Phi|U^\dagger(t-t_f)U(t-t_i)|\Psi\rangle}\ , \tag{8}$$

where the pre-selected wave-function $|\Psi\rangle$ and the post-selected wave-function $\langle\Phi|$ evolve unitarily in time through U and $U^\dagger$ respectively, until their meeting point to determine the weak value of an arbitrary operator A. The effective description of the system is now given by the symmetric contributions of future and past. The "collapse" from the combined state

$$|\Psi(t)\rangle = \alpha(t)|e\rangle|0\rangle + \beta(t)|g\rangle|1\rangle \to |e\rangle|0\rangle, \tag{9}$$

is thus unique when incorporating the backwards evolving wavefunction [5].

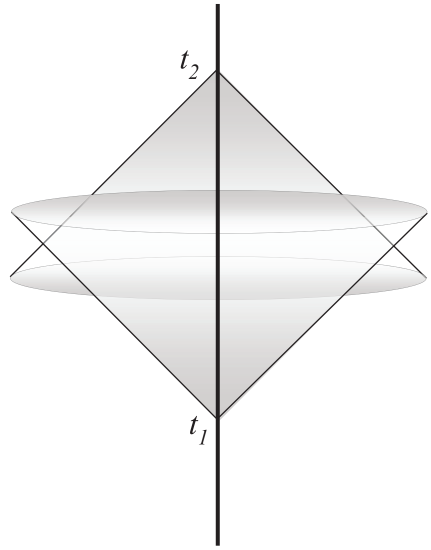

FIGURE 3. The two wave-functions of an atom which has remained excited over a certain time-interval.

Now consider again only the forward (hyper)cone (Fig. 3), more specifically its ever-expanding basis which is actually a three-dimensional sphere. This spacetime sphere represents the α-particle's most extreme momenta: If detected there, its momentum would be maximal. Similarly for the inverted backward cone (Fig. 3): Its spherical perimeter represents high-energy particles on their way *back* to the atom, again with those of highest momenta, going to infinity towards the past.

It is not, however, these infinite cones that concern us but rather their *overlap*. This is the geometrical region where quantum mechanics' "weak reality" is most notably manifested. For simplicity, we shall discuss the 2+1 Minkowski space. When the forward- and backward-evolving states are symmetrically set, our relevant region, then, is a causal diamond with volume $V = \frac{2}{3}\pi c^2 t^3$, delineated by the above two light cones originating from the two measurements (Fig. 3).

Here then is TSVF's account for the still-excited atom's state during this apparent "no emission" period. The possibly-emitted α-particle seems to have been "drawn" back into its origin! This is an example of a more general behavior discussed in [5]. The post-selected state induces an effective dynamics in the intermediate times, and can also provide a collapse mechanism, naturally setting the classical-quantum bound [27].

Along the basis perimeter $P = 2\pi ct$, the two state-vector's effects are the oddest, corresponding to a rare pre- and post-selection. The local vacuum therefore weakly undergoes the most intense perturbations due to these two outgoing and incoming, wave-functions of the α-particle with the highest momenta in the opposite directions: first *away from* the atom and instantly later *back towards* it (Fig. 4).

Let us now take all these weak measurements' outcomes and post-select for all those cases where the its atom was found again in an excited state at $t=t_f$. Its backward-evolving wavefunction is

$$\langle\phi(t)| = \langle e|2^{(t-t_f)/2\tau} + \langle g|\sqrt{1-2^{(t-t_f)/\tau}} \tag{10}$$

The two-state at any intermediate time is therefore

$$\langle\phi(t)|\ |\psi(t)\rangle = \left(\langle e|2^{(t-t_f)/2\tau} + \langle g|\sqrt{1-2^{(t-t_f)/\tau}}\right)\left(2^{-t/2\tau}|e\rangle + \sqrt{1-2^{-t/\tau}}|g\rangle\right) \quad . \tag{11}$$

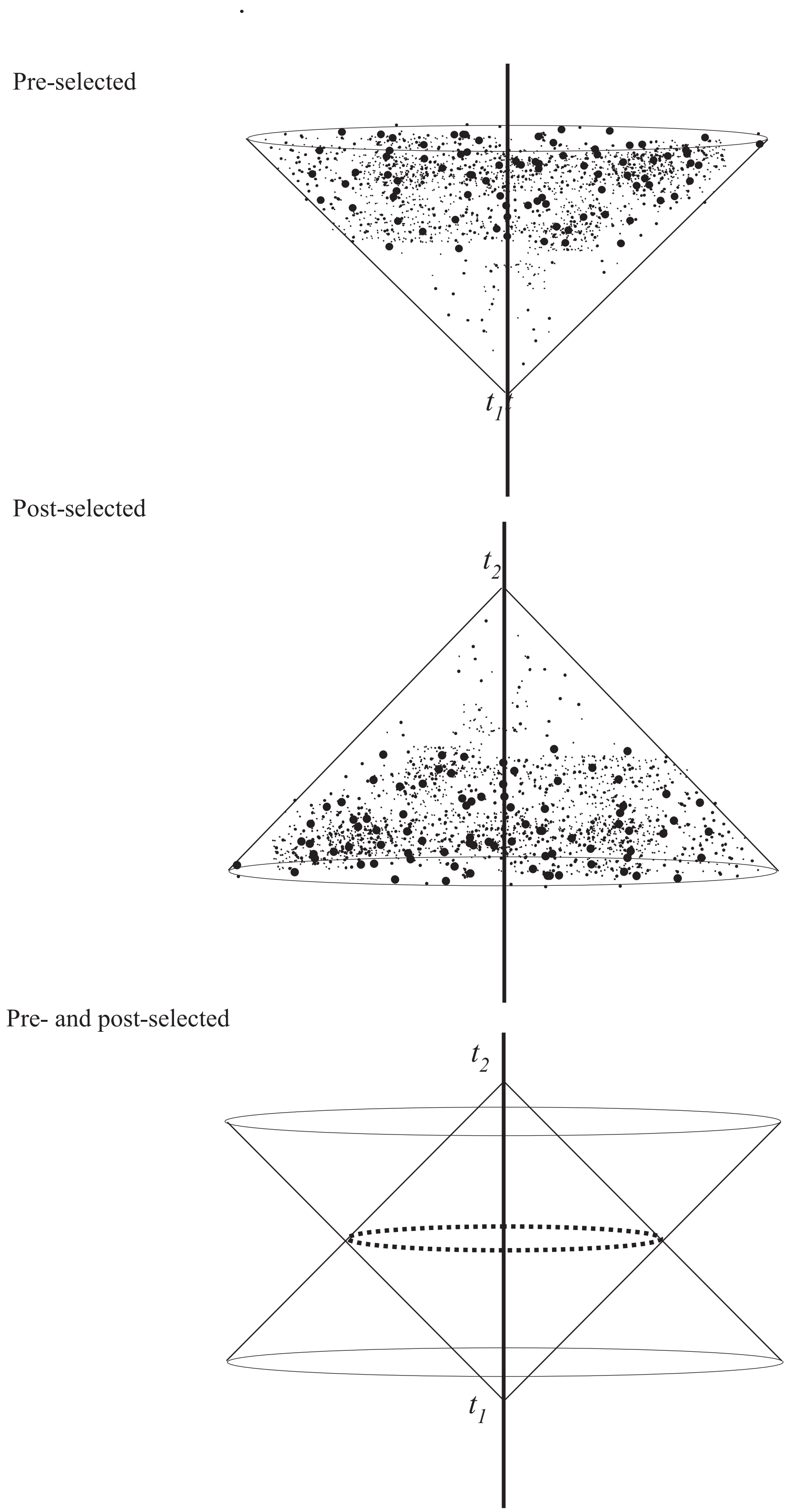

FIGURE 4. Weak measurements' outcomes corresponding to a pre-selected state, a post-selected state and their combination.

Using the two-state we can calculate, for instance, the weak values corresponding to finding the atom excited in any time t:

.

$$\langle \Pi_e \rangle_w = \frac{\langle \phi(t) | \Pi_e | \psi(t) \rangle}{\langle \phi(t) | \psi(t) \rangle} = \frac{2^{-t_f/2\tau}}{2^{-t_f/2\tau} + \sqrt{1 - 2^{(t-t_f)/\tau} - 2^{-t/\tau} + 2^{-t_f/\tau}}}. \tag{12}$$

Two simple limits are:

1. $\lim_{t\to 0} \langle \Pi_e \rangle_w = 1$
2. $\lim_{t_f\to\infty} \langle \Pi_e \rangle_w = 0$, whenever $0 < t < \infty$.

When including the state of the α particle as well, the forward-evolving state is

$$|\Psi(t)\rangle = 2^{-t/2\tau} |e\rangle|0\rangle + \sqrt{1-2^{-t/\tau}}\, |g\rangle|1\rangle \tag{13}$$

and the backward-evolving state is

$$\langle \phi(t)| = \langle 0|\langle e| 2^{(t-t_f)/2\tau} + \langle 1|\langle g| \sqrt{1-2^{(t-t_f)/\tau}} \tag{14}$$

leading to the two-state

$$\langle \phi(t)| \ \ |\psi(t)\rangle = \left(\langle 0|\langle e| 2^{(t-t_f)/2\tau} + \langle 1|\langle g| \sqrt{1-2^{(t-t_f)/\tau}} \right) \left(2^{-t/2\tau} |e\rangle|0\rangle + \sqrt{1-2^{-t/\tau}}\, |g\rangle|1\rangle \right). \tag{15}$$

i.e., an α-particle *weakly emitted and then weakly redrawn by its source atom*.

As insightfully observed in [26]:

> *"The result demonstrates that if an excited atom is found after a period of time to have not decayed, this does not mean the electromagnetic field in the vicinity of the atom is undisturbed. The use of weak measurements can reveal activity in the field. This activity will average to zero, but individual weak values of, say, the energy density of the electromagnetic field, will be non-zero and will in fact grow exponentially large (positive and negative) as the postselection time becomes much longer than the halflife of the excited state."*

In a subsequent paper [28] we elaborate on this weak reality of electromagnetic field.

The emerging account is now clear. For an unstable atom located far away of potential absorbers, its non-emission of a particle obeying the uncertainty principle turns out to be, under the greater resolution of TSVF, the result of a weak emission produced by the initial measurement indicating that the source atom is excited, followed by the time-reversed event: "weak reabsorption" due to the final measurement that finds the atom still excited. This picture may offer some fresh insights into the quantum foundations of electromagnetism.

6. CONCLUSIONS: THE ICEBERG OF NON-EVENTS

A final look at our obstinate lonely atom, still excited, exerting its still-unexplained individual freedom to push the limits of the uncertainty principle, reveals a picture much richer and more intriguing than the classical, static account of "nothing happening." On the contrary, our atom becomes entangled with distant atoms that apparently have no causal connection with it. It is also subject to Zeno effects by these faraway atoms.

Even more unique is this atom's evolution in the *absence* of potential absorbers, in a spacetime region populated with particles that react like *weak* absorbers. Thus, *a wave spreading out and then re-converging back into its atom* would be the underlying scene beneath the classical inactivity.

Turning from this atom to the entire universe, we realize that it is only the tip of an iceberg orders of magnitude larger, comprised of literally countless nonevents in the form of non-particles ceaselessly emitted, reflected and absorbed while leaving only the subtlest causal tracks. The bearings on foundational issues like irreversibility, time's arrow, Mach's principle, separability and nonlocality, to mention only a few, go beyond the present framework but merit intensive study, hopefully to be presented in the following meetings of this series.

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