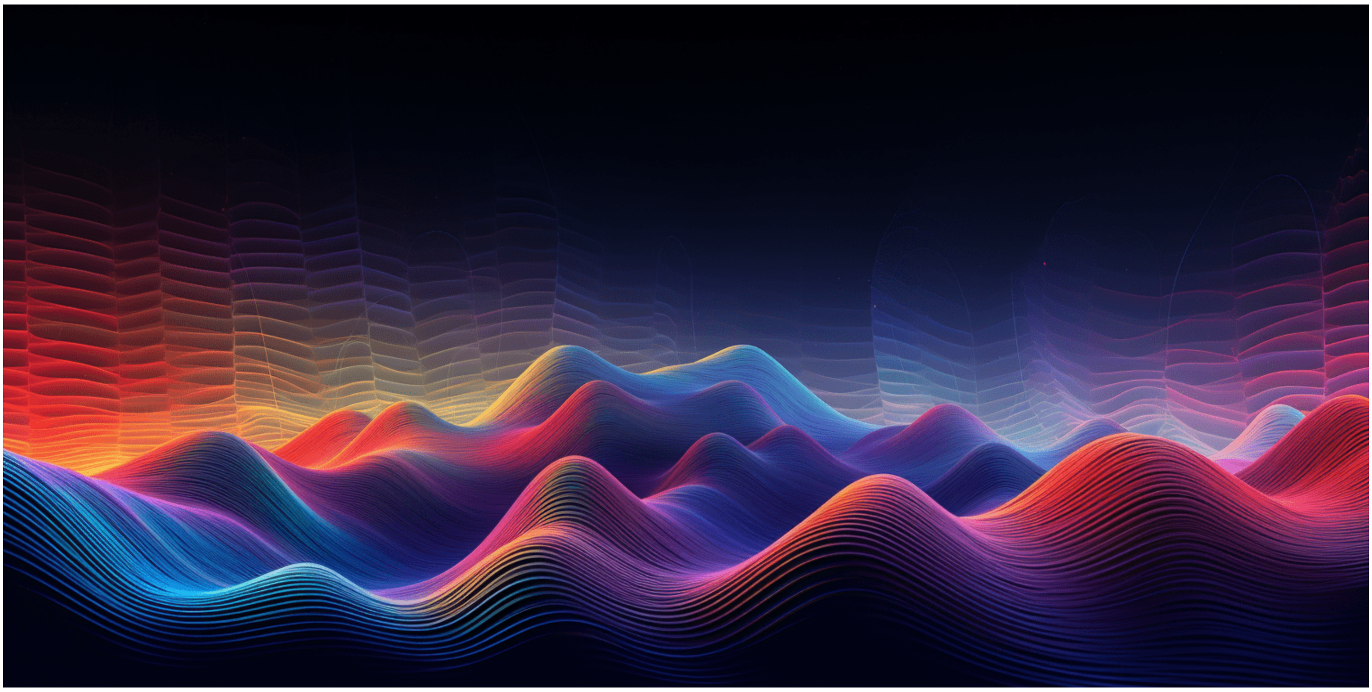
A Single Hidden Variable Interpretation of the Quantum Wave Function

David Gentile



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Abstract

A new interpretation of quantum mechanics is presented in which there is one hidden variable. This could be described as “partial realism” where sometimes quantum variables have real values before we measure and sometimes they don’t. While one hidden variable is insufficient to explain Bell nonlocality, it is allowed by Bell’s inequality. This can help solve the measurement problem and is in principle testable. In addition, a theory of nonlocality emerges directly from this assumption. From the perspective of an outside observer, not correlated with an observed system, we treat all interactions within the system as unitary. However, from the perspective of an “observer” inside the system, we treat all new entanglements as “micromeasurements”, as a projection onto some basis of measurement. One particle can act as a measurement device on another and give the other particle a defined value on one possible measurement axis from an inside perspective. This means that the wave function, from the outside view, will at times describe an objective, fundamentally stochastic uncertainty, at other times a subjective uncertainty that reflects only our lack of knowledge, and at yet other times a combination of both. The standard wave function describes the total uncertainty, the minimal uncertainty that is present for any observer outside of the system, whereas for an “observer” inside the system, only the objective, fundamentally stochastic part of the uncertainty remains, and this can be described by an inner wave function. The hidden variable is invisible to the outside observer.

Contents

1. Introduction.

Bell’s inequality (Bell, 1964), (Maccone, 2013) tells us that hidden variables sufficient to explain quantum phenomena as strictly local and real cannot exist. It does not, however, preclude all hidden variables. Our primary assertion is that there is one such hidden variable. In the argument for Bell’s inequality it is assumed, for example, that values for spin on both an x axis and a z axis are predetermined for a pair of entangled electrons. We then perform the experiments and do the math and arrive at a logical contradiction (Napolitano & Sakurai, 2021). However, nothing says that spin values on the x axis by itself could not have been predetermined; this is just insufficient preexisting information to

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preserve a locally real theory. In this paper, we explore the idea of limited hidden variable information. Our interpretation says that quantities sometimes exist before we measure and sometimes do not. We could call this a partial realism, perhaps. We also argue that measurement alters the wave function. This causes not just decoherence, but also partial wave function collapse and a fundamentally stochastic result.

This does require more fully embracing nonlocality, but given recent experimental results (Hensen, Bernien, & Dréau, et al, 2015), there seems to be little choice in this matter, and we include nonlocality in the interpretation in such a way as to avoid causal loops and signaling.

We begin in section 2 by defining two types of uncertainty, objective and subjective. (Jaynes, 2003). We then assert that a standard or outer wave function represents the total uncertainty to an outside observer not correlated with the system, a combination of objective and subjective uncertainty. From this outside perspective, all interactions are treated as unitary interactions. From a perspective inside the system, all entanglements are treated as projections onto some basis. The particles measure each other and give each other definite real values on some (unknown) measurement axis. The particles act as measurement devices and record information, although this information is hidden from the outside perspective of a human experimenter. From this inside perspective, only objective uncertainty remains, and this perspective can be described by an inner wave function. Thus, from the outside perspective, there is one hidden variable – a definite value on some measurement axis that is unknown.

In section 3, after the most basic example, we first discuss a single photon is a Mach-Zehnder experiment, (Horne, Shimony, & Zeilinger, 1990), (Horne, Shimony, & Zeilinger, 1989), for which, from the outside perspective, only subjective uncertainty remains. We then turn to a situation in which measurement by one observer, Alice, will resolve subjective uncertainty, whereas another, performed by Bob, will resolve objective uncertainty. In this configuration, we attempt to show that the results of the quantum eraser experiment, (Kim, Yu, Kulik, Shih, & Marlan, 2000), (Fankhauser, 2017), (Qureshi, 2020), have an explanation that is more intuitive than existing explanations.

Then, in section 4, we continue to look at the quantum eraser experiment and turn to cases in which there is objective uncertainty for both experimenters. These examples will involve accounting for nonlocal correlations in order to explain their results. Here, a specific theory of how nonlocal correlations occur emerges directly from the assumptions of the interpretation and existing results from the quantum eraser experiment.

Then, in sections 5, 6, and 7, we attempt to address the measurement problem. The new Wigner's friend paradox, (Frauchiger, 2018), (Bong, Utreras-Alarcón, & Ghafari, et al., 2020), (Ormrod, Vilasini, & Barrett, 2023), has brought renewed focus to the question: "What exactly constitutes a measurement?". The thought experiment forces us to choose between various difficult to accept alternatives offered by various QM interpretations. In our interpretation we attempt to "thread the needle" and choose parts of some of the various options while attempting to avoid the worst consequences of each.

We posit a partial wave function collapse with every interaction, although the effect is hidden from us if we are not entangled with the system ourselves. We also allow for nonlocal interactions and along with that comes a form of retrocausality. However, this retrocausality is limited in that events

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cannot affect their own past light cone, and only hidden variables in the otherwhere can be affected. The interpretation also avoids causal loops.

Given the assumptions of our interpretation the measurement problem is not especially challenging to address, whereas it seems interactable given other some other interpretations. In section 5, we look at the phenomenon of decoherence, (Schlosshauer, 2019), (Paz & Zurek, 2000), which we argue can be reinterpreted as a collapse of the inner wave function. Then, in section 6, we introduce nonlocal effects to elucidate the measurement problem. We focus on the Stern-Gerlock experiment in this section, (Napolitano & Sakurai, 2021). We argue that observations are never truly erased; they are just rehidden. Additionally, we address the question of when global entanglements are broken, creating separate subsystems. We assert that zero-energy "interactions" on the sterile path that particles do not follow are critical to this process. We then conclude section 6 with a short discussion of how measurements should be defined.

One might ask if a new interpretation of QM is needed, since many already exist. We show that in addition to being testable in principle, this interpretation has certain benefits, such as rendering the measurement problem fairly easy to solve, whereas it seems intractable, given some other interpretations. In section 7, we compare this interpretation to other prominent interpretations, using the new Wigner's friend paradox as an introduction to these comparisons. Finally, we summarize our work in section 8.

2. Types of uncertainty

Let us define two different types of uncertainty. One we will call intrinsic or objective uncertainty, and the other is epistemic or subjective uncertainty. These types of probability will be familiar to those with a statistical background but may not be familiar to all readers. They do not correspond to the common meanings of the words and should not be confused with "objective" and "subjective" wave functions, which are familiar to those with a background in quantum mechanics. Thus, we spend some time defining the terms here.

Objective uncertainty represents real fundamental stochastic uncertainty in the universe, and the other is about what information we have available. In statistics, these conceptions of probability have historically divided mathematicians into two camps, classicists and Bayesians (Jaynes, 2003); however, today, both are mostly accepted as two valid but different approaches to probability. One simple example of a coin flip is enough to illustrate the difference. Suppose that someone flips a coin and holds the result behind their back. To a classical statistician, the coin is represented as a random number generator. The odds are 50/50 heads/tails before the flip. However, when the coin is flipped but still hidden, the probability is now 1 or 0. We just don't know which. To the Bayesian, the odds are still 50/50 until we learn the result because Bayesian statistics is concerned with the information available to us.

While completely epistemic interpretations of quantum mechanics exist (Barzegar & Oriti, 2022), here, we assume that quantum mechanical systems can and do exhibit real, objective, intrinsic uncertainty. This can be illustrated by many experiments, but the most well-known may be the classic 2-slit experiment (Ananthaswamy, 2018). The photons in this experiment clearly seem to pass through both slits in order to interfere with themselves. Both states exist in superposition with each other. This kind of uncertainty is more than us just not knowing which path the photon took. We might say that the universe does not even "know". Our macroscopic world does not exhibit this type of behavior, nor does

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classical physics. The coin flip in classical physics would not be described as intrinsically random; rather, we simply lack sufficient information to make predictions. Somehow, in moving from the quantum world up to the macroscopic world, intrinsic uncertainty is lost.

Here, we assert that the standard wave function can represent objective uncertainty, subjective uncertainty, or a combination of both, depending on the circumstances, and that the transformation from one type of uncertainty to another is invisible from outside the system. From the perspective of an "outside" observer, not correlated with an observed system, we treat all interactions within the system as unitary. The standard, or outer, wave function then gives a perfect description of the system from this perspective, or at least gives us probabilities that accurately predict all experimental results. But what portion of it represents objective versus subjective uncertainty is unclear.

From the perspective of an "observer" inside the system[1], correlated with the system, we treat all new entanglements as "micromeasurements". One particle can measure another. This transforms some objective uncertainty into subjective uncertainty, at least temporarily[2], with every new entanglement. Assuming a new measurement is not completely compatible with the previous measurement, a "coin is flipped" when this happens. A nondeterministic event takes place. That is, from the perspective inside the system, projection onto some (unknown) basis has occurred, and a variable measured on that basis now has a definite value, whereas from an outside perspective, subjective uncertainty regarding that variable's value remains. However, objective uncertainty also persists. The values for other measurements, orthogonal to the first measurement, remain objectively undetermined. An inner wave function will describe this interior perspective.

The standard wave function describes the total uncertainty, objective and subjective combined. One might ask "Exactly who's subjective uncertainty?" So, to be more precise, the outer wave function describes the minimal uncertainty that is present for ANY observer outside of the system. An individual observer could have greater uncertainty, for some idiosyncratic reason, unrelated to physical laws, but not less uncertainty[3]. We label the subjective part of the wave function "subjective" because the uncertainty is due to a lack of information. This information exists but is unavailable. Similarly, the objective uncertainty, described by the inner wave function, represents the minimal uncertainty that any observer must have, even if correlated with the system. We label it "objective" because the information needed to resolve this sort of uncertainty does not exist. Thus, from an inside perspective, every

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[1] This outside/inside language is borrowed from (Ormrod, Vilasini, & Barrett, 2023) where it is used to describe macroscopic observers with inside and outside perspectives in the new Wigner's friend thought experiment.
[2] We use the term "micromeasurements" to describe entanglements, because like observations in standard interpretations, the claim here is that they transform the wave function by projection onto some basis, from an inside perspective. However, they differ from observations in standard interpretations and also differ from what we here will call macroscopic observations in that they are not performed by a human, but rather by other particles which act as measurement devices, and in that they can be easily erased (or as we argue later in this paper, merely re-hidden). Performing a new measurement orthogonal to an existing micromeasurement will erase the information gathered by the previous measurement and create new objective uncertainty regarding the previously measured values.
[3] (Colbeck & Renner, 2011) show that any extension of QM cannot yield improved predictions. In the interpretation presented here, knowledge of the hidden variable could yield better predictions, if it could be known from outside the system, but it cannot be known.

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entanglement pushes the amount of uncertainty present down toward the minimum allowable limit[4] (Heisenberg, 1925) (Ozawa, 2003) (Bastos, et al, 2015).

3. The basic idea and the quantum erasure experiment.

Perhaps it is best to start with the simplest possible case as an example. Suppose that we have one single random electron that we are not correlated with. From this outside perspective, we might write the wave function as:

$$|\psi\rangle = |\psi_{Initial}\rangle \quad (1)$$

Representing a superposition of all possible states. However, here we assert that there is a hidden variable, which is only visible from an inside view, correlated with the system. The electron already has a determined value on some basis. This value was determined by its most recent interaction. Let's say:

$$|\psi\rangle = |x_+\rangle \quad (2)$$

But then, of course for an orthogonal measurement, we could also write the wave function as a superposition.

$$|\psi\rangle = \frac{|z_+\rangle + |z_-\rangle}{\sqrt{2}} \quad (3)$$

In equations (2) and (3), we see the minimum possible uncertainty that must exist for any observer, even if they are correlated with the system. There is no uncertainty for one measurement and objective uncertainty for a measurement orthogonal to the first measurement. If we then consider equation (1), we can see that while it correctly predicts the results we will see if we measure multiple electrons – namely a random result on any basis on which we measure – it represents a mix of subjective and objective uncertainty. If we happen, by accident, to measure on the x axis, then our measurement will only resolve our subjective uncertainty as to the preexisting value. However, if we happen to measure on the z axis, orthogonal to x, then our result is objectively undetermined until we measure, and a nondeterministic event occurs.

Let us now turn to a more complex example and look at a Mach-Zehnder experiment. A pair of entangled photons or a biphoton is considered. Suppose that two experimenters, Alice and Bob, each receive one of the pair. Each of the photon paths has been split into two paths they can follow with 50% probability. Because the states are correlated, if Alice receives a photon at A1, then Bob will receive a photon at B1, and the same is true for A2 and B2. We can write the wave function from an outside perspective, which represents the minimum uncertainty we must have from that perspective, as follows:

$$|\psi_{AB}\rangle = \frac{|A1\rangle|B1\rangle + |A2\rangle|B2\rangle}{\sqrt{2}} \quad (4)$$

Suppose that Bob puts a phase shifter on one path and tries to obtain a photon to interfere with itself. He will not be successful. Experiments have shown that this does not happen (Horne, Shimony, & Zeilinger, 1990), (Horne, Shimony, & Zeilinger, 1989), (Hobson, 2022). The phases always line up so that

[4] Technically, there could be more than one hidden variable, so long as they were all compatible, since this is allowed by the uncertainty principle.

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the photons decohere each other; that is, they prevent each other from creating an interference pattern. The experimental setup discussed is diagrammed below (fig. 1):

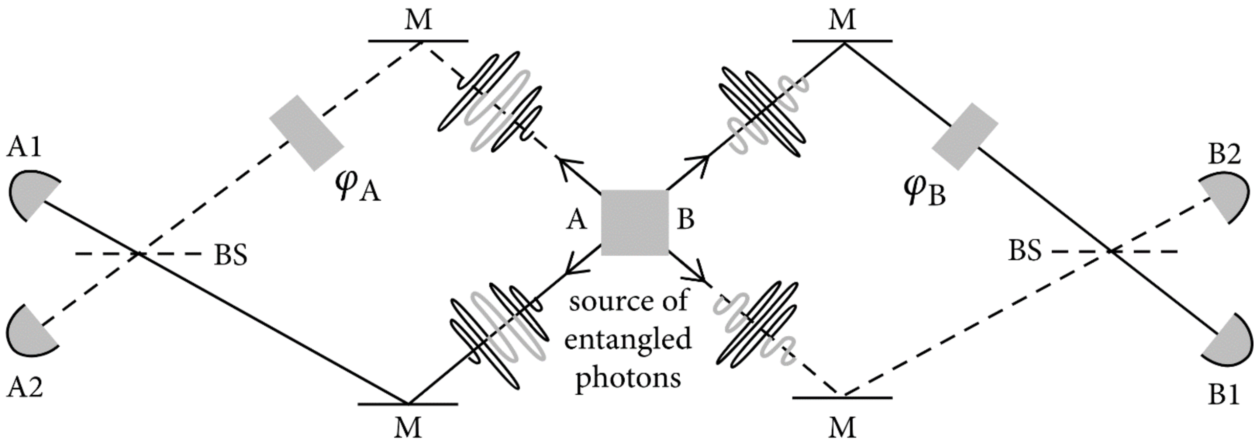

Figure 1 – A diagram of the experimental apparatus discussed (Hobson, 2022).

We can write the two-point nonlocal quantum field amplitudes at the detectors as:

$$\psi_{A1,B1} = \psi_{A2,B2} = \frac{1 + exp(i\,\phi_B)}{2\sqrt{2}} \quad (5)$$

$$\psi_{A1,B2} = \psi_{A2,B1} = \frac{1 + exp(i\,\phi_B + \pi)}{2\sqrt{2}} \quad (6)$$

where ϕ_B is the phase change imposed by Bob, and we have assumed that Alice is not altering her photon and that the various phase changes imposed by the experimental setup have been subsumed into a zero phase shift in eq. (5) and a shift of π in eq. (6).

The joint probabilities are then given by:

$$P(A1, B1) = P(A2, B2) = |\psi_{A2,B2}|^2 = \frac{1 + cos(\phi_B)}{4} \quad (7)$$

and

$$P(A1, B2) = P(A2, B1) = |\psi_{A2,B1}|^2 = \frac{1 + cos(\phi_B + \pi)}{4} \quad (8)$$

Then, we have P(B1) = P(A1,B1) + P(A2,B1) = 0.5 regardless of the phase. And in general, P(A1) = P(A2) = P(B1) = P(B2) = 0.5 regardless of any phase change added by Bob.

In this specific configuration, where Alice happens to measure her photon on the same basis axis that the photons measured each other and Bob has set his phase shift to zero, only subjective uncertainty remains. Let us suppose that the paths to detectors A1 and B1 represent reality. Then, for an outside observer uncorrelated with the system, who has subjective uncertainty, equation (4) still appears to be the correct description of the system and still describes their minimum possible uncertainty. Over many observations of many photons with unknown preestablished values on unknown bases, it will yield correct statistical predictions. However, for a "micro-observer" entangled with the system, in this specific case, equation (9) is correct.

$$|\psi_{AB}\rangle = |A1\rangle|B1\rangle \quad (9)$$

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Let's be clear here that we are not claiming that every photon pair traveling though this system picks a pair of paths in advance. That would be a clear violation of Bell's inequality (Bell, 1964). However, we are arguing that some may, which does not violate the inequality. We still will need a nonlocal theory to explain the totality of the results produced by this system, and we turn to that topic in section 4, but here we are looking at a single photon pair where the measurement they performed on each other lines up exactly, by accident, with the measurements that Alice and Bob are performing. In this very specific case, we are asserting that this particular photon pair picked a pair of paths in advance.

The "coin" has already been flipped in this case. A nondeterministic event occurred as the photons separated. Thus, one crucial component of what we need a measurement to accomplish has already happened: projection onto a basis of measurement. One single entanglement counts as a micromeasurement. We can legitimately speak of Alice's photon as the observed system and Bob's photon as our measuring device, which we have not yet queried. Note that this is not yet a macroscopic measurement; we can still do things such as erase the micromeasurement and reintroduce objective uncertainty. However, for the moment, Bob's photon has measured Alice's photon and vice versa.

One might object that having this information preexisting when the photons are still together constitutes hidden variables. However, Bell's inequality (Bell, 1964), (Maccone, 2013) only tells us that it is not possible for values for multiple incompatible orthogonal measurements to be preexisting (Napolitano & Sakurai, 2021), however that does not mean that there cannot be an ANY hidden variable[5].

Let us now have Bob change the phase by π/2.

$$P(B1) = P(A1, B1) + P(A2, B1) = \frac{1 + cos(\pi/2)}{4} + \frac{1 + cos(\pi/2 + \pi)}{4} = 0.25 + 0.25 = 0.5 \quad (10)$$

$$P(B2) = P(A2, B2) + P(A1, B2) = \frac{1 + cos(\pi/2)}{4} + \frac{1 + cos(\pi/2 + \pi)}{4} = 0.25 + 0.25 = 0.5 \quad (11)$$

We now have introduced new objective uncertainty because Bob's basis of measurement has changed. Bob's measurement is now completely uncorrelated with Alice's, and the result is intrinsically uncertain before measurement. We still have a 50% subjective chance of A1 or A2, and in each case, there is a 50% objective chance of B1 or B2. This objective uncertainty will be resolved when Bob's photon first becomes entangled with his measuring device. This distinction between types of uncertainty is invisible, however, in our equations. We might instead wish to write something such as the following, where P_T, P_O, and P_S represent the total probability, the objective probability, and the subjective probability, respectively.

$$P_T(B1) = P_S(A1) * P_O(B1|A1) + P_S(A2) * P_O(B1|A2) \quad (12)$$

$$P_T(B1) = 0.5 * \frac{1 + \cos(\phi_B)}{2} + 0.5 * \frac{1 + cos(\phi_B + \pi)}{2} \quad (13)$$

$$P_T(B1) = 0.5 * 0.5 + 0.5 * 0.5 = 0.5 \quad (14)$$

[5] This idea takes the middle ground in the historical Einstein, Bohr debate where Einstein thought there must be sufficient hidden variables to avoid any nonlocality (Einstien, Podolsky, & Rosen, 1935), and Bohr believed the wave function was a complete description of the system. Einstein did not yet use the term "hidden variable" but concludes the paper by saying "the wave function does not provide a complete description of physical reality".

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A well-known result in quantum mechanics is that if we perform a measurement and then perform an orthogonal measurement, the information gained from the first measurement is erased (Napolitano & Sakurai, 2021). Alice's photon measured Bob's photon, and Bob's photon was in a definite state where only subjective uncertainty existed until Bob erased this information and reintroduced objective uncertainty.

Some readers may notice that in this configuration, we are very close to the configuration of the delayed choice quantum erasure experiment (Kim, Yu, Kulik, Shih, & Marlan, 2000). We only need to have Alice direct her two beams each into one hole of a two-slit experiment and place Bob significantly farther from the photon source than Alice, and Bob then plays the role of the eraser. Standard interpretations with no hidden variables struggle to explain the results of this experiment without resorting to hypothesizing retroactive erasure of "which way" information[6], and multiple hidden variables are ruled out by Bell's inequality. Our "one hidden variable interpretation", however, has no difficulty explaining the results of the experiment in an intuitively straight-forward way. We also wish to spend some time discussing this experiment, continuing into section 4, because there we show that given our initial assumption of one hidden variable, we are forced into a very specific theory of nonlocality to explain the results of this experiment.

[6] We do not want to imply that in standard interpretations the results of this experiment are entirely inexplicable without retrocausal effects. (Fankhauser, 2017) (Qureshi, 2020). However, we do try to show that the account here is more intuitive.

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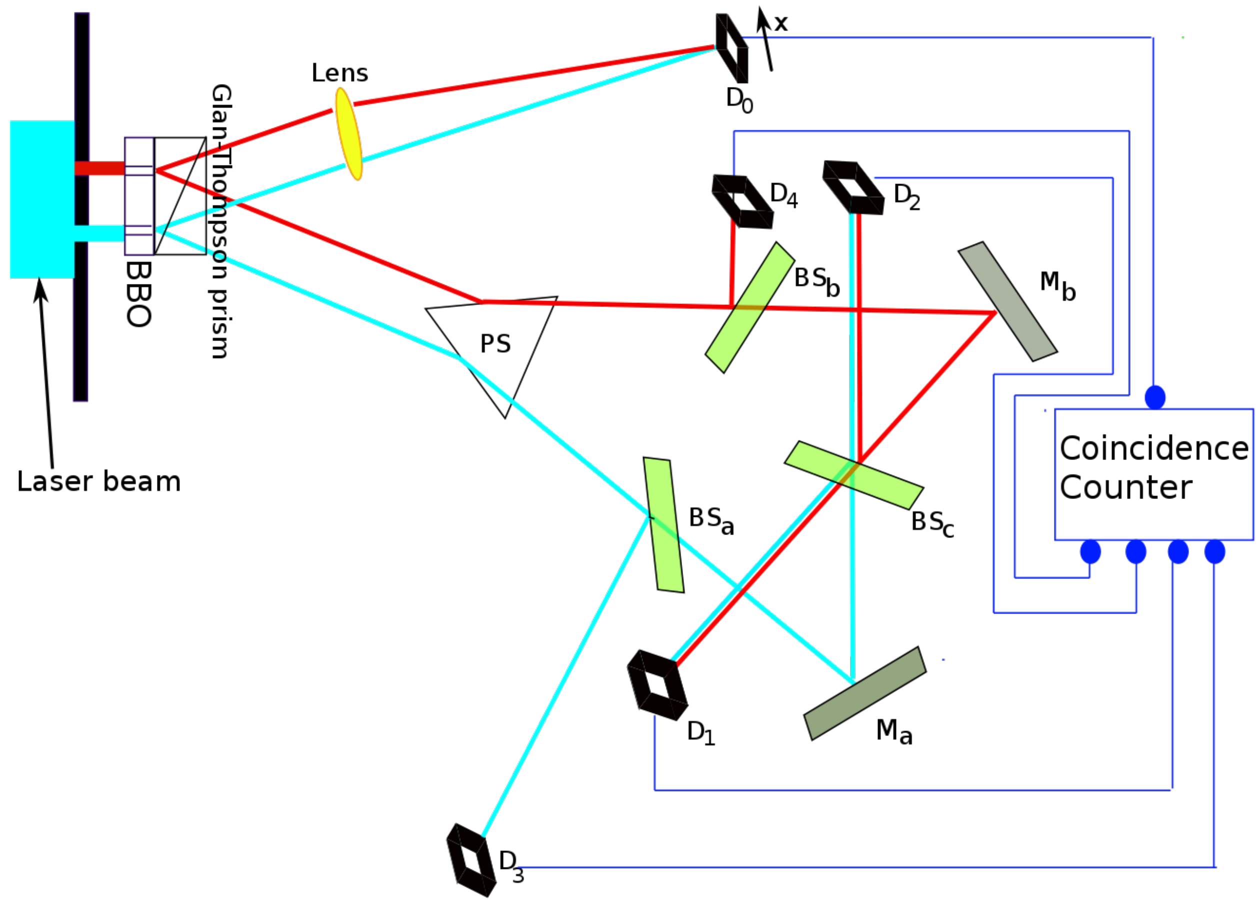

Figure 2 – Diagram of the delayed choice quantum eraser experiment. In this diagram, "Alice" would be the detector at D_0, and "Bob", perhaps temporarily renamed "Dan", would be the detectors at D_1 and D_2. However, we will continue to refer to our hypothetical Alice and Bob experiment.

The experiment will of course involve many pairs of entangled photons, and each photon will measure the other half of its pair on some random basis axis. For our simple example here, we will assume that they measure either each other's path information or phase information rather than all possible ways in which they could measure each other[7]. There will then be populations of biphotons with preexisting values on some measurement axis. Those that happen to be predetermined to be on path A1 we can call "population A1", and they will be objectively undetermined between the B detectors – these will only go through Alice's slit number one. Additionally, those biphotons that happen to have measured each other's phase information rather than path information and are now predetermined to arrive at detector B1 will be objectively undetermined on the A paths. Those photons will pass through both of Alice's slits and interfere with each other. This means that if we only look at the results on Alice's detection screen that correspond to photons that were measured at detector B1, we will see an interference pattern. Suppose for simplicity, rather than every possible population, we have only four

[7] Section 4 takes up the issue of what happens when the preexisting measurement does not match at least one of the experimenters' measurements.

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populations - those biphotons that are 100% determined to be destined for detectors A1, A2, B1, or B2. From the inside perspective, we can write:

$$|\psi_A\rangle = |A1\rangle, |\psi_B\rangle = \frac{|B_1\rangle + |B_2\rangle}{\sqrt{2}} \quad (15)$$

$$|\psi_A\rangle = |A2\rangle, |\psi_B\rangle = \frac{|B_1\rangle - |B_2\rangle}{\sqrt{2}} \quad (16)$$

$$|\psi_B\rangle = |B2\rangle, |\psi_A\rangle = \frac{|A_1\rangle - |A_2\rangle}{\sqrt{2}} \quad (17)$$

$$|\psi_B\rangle = |B1\rangle, |\psi_A\rangle = \frac{|A_1\rangle + |A_2\rangle}{\sqrt{2}} \quad (18)$$

From an outside perspective, the system is still described as a superposition of all the possible states, and the wave function describes the minimum uncertainty that must be present from that outside perspective and still makes correct statistical predictions from that perspective. However, from the inside perspective, these different predetermined populations exist.

Detector B1 will pick up all the population B1 biphotons, of course, and then also half of each of the A1 and A2 populations. The A1 and A2 populations in the mix will smear the pattern out slightly on Alice's detection screen, but an interference pattern will remain. This is a heuristic argument, but it shows that one hidden variable is all we need to explain the results of this experiment intuitively. One "coin flip" already occurred as the photons were created, so it does not matter how delayed Bob's measurement choice is. The population B1 biphotons were always going to be objectively undetermined on the A paths and interfere with themselves at Alice's detector. Population B2 biphotons interfere with themselves as well; however, the pattern is 180 degrees out of phase with the pattern produced by the B1 population. If viewed together, the patterns wash each other out. All Bob does, after Alice's results have been recorded, choose to look at some of the existing populations and not others. He does not retroactively erase "which way" information.

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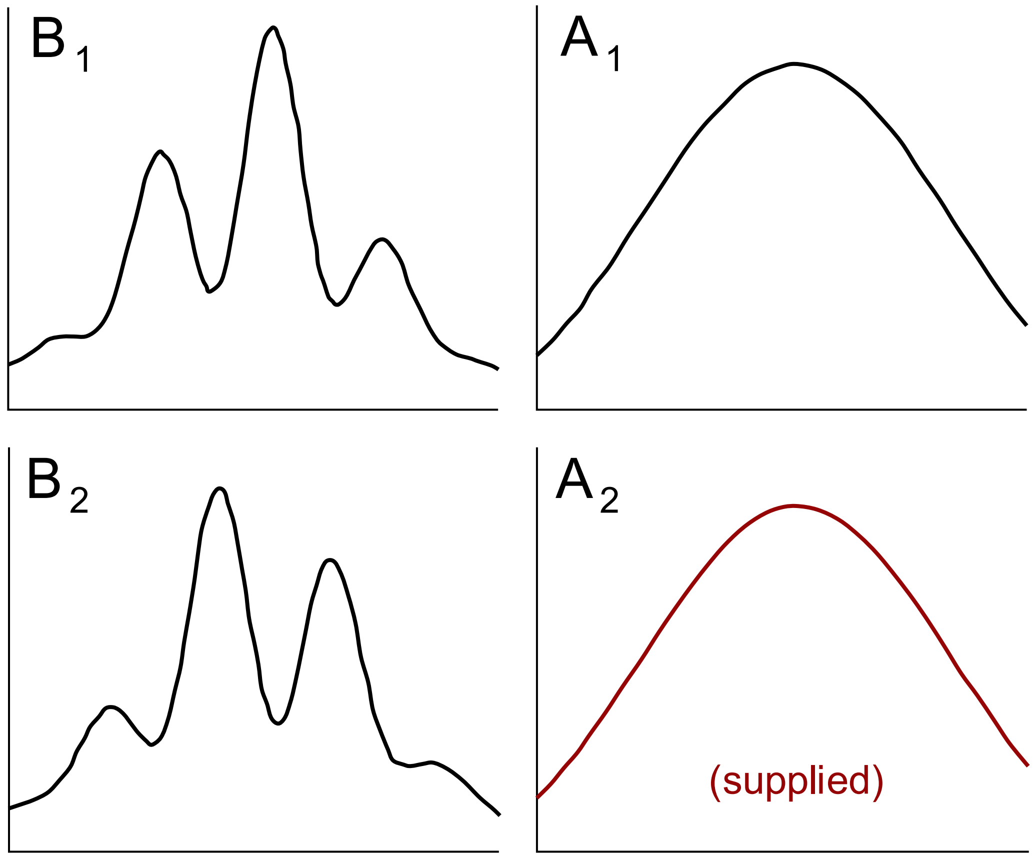

Figure 3 – Results of (Kim, Yu, Kulik, Shih, & Marlan, 2000) relabeled for our Alice and Bob thought experiment.

4. Nonlocality addressed

Now, let us suppose that both Alice and Bob alter their basis of measurement by π/2.

$$P(B1) = P(A1, B1) + P(A2, B1) = \frac{1 + cos(\phi_B - \phi_A)}{4} + \frac{1 + cos(\phi_B - \phi_A + \pi)}{4} = 0.5 \quad (19)$$

$$P(B2) = P(A2, B2) + P(A1, B2) = \frac{1 + cos(\phi_B - \phi_A)}{4} + \frac{1 + cos(\phi_B - \phi_A + \pi)}{4} = 0.5 \quad (20)$$

Both have now measured orthogonally to the measurement with which the photons measured each other, and both results, taken individually, are objectively undetermined, but they perfectly correlate, even nonlocally, when considered together. Assuming that we do not allow superdeterminism, this nonlocal correlation has been conclusively experimentally demonstrated (Hensen, Bernien, & Dréau, et al, 2015), (Storz, Schär, & Kulikov, et al., 2023). The description of the system in this case would be no different than in standard interpretations. From both the inside and outside perspectives, equation (4) describes the state of the system. There is, on the basis of the discussion thus far, only objective uncertainty in this case, as knowledge of the hidden variable adds no useful information.

$$|\psi_{AB}\rangle = \frac{|A1\rangle|B1\rangle + |A2\rangle|B2\rangle}{\sqrt{2}} \quad (4)$$

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The perfect correlation makes it appear as if Alice and Bob were somehow forced to measure on the preexisting measurement axis, or alternately, the axis altered itself to match their measurement. The latter is what we now assert happens. In order to match all the experimental results, we propose the following: The biphoton has a "head" and a "tail". One of the two photons, randomly, is the head or "control photon". If Alice receives the control photon, she rotates the biphoton to match her basis of measurement. Bob's half gets "dragged along for the ride" even nonlocally. If the photon is not a control photon, Alice leaves it unchanged. Those will be altered to match Bob's measurement basis, and then Alice's photon gets dragged along with it. She then simply measures relative to Bob's measurement according to the Born rule. The analysis then proceeds just as in the previous section but on the new bases as if at least one of them had been the preexisting measurement axis all along.

This has a number of benefits. For example, in the quantum eraser experiment, there will ONLY be the 4 populations shown. Alice will reorient half of all biphotons to be populations A1 and A2, and Bob will reorient the other half to be populations B1 and B2. Additionally, a distinct benefit is that nonlocality becomes slightly less mysterious. One difficulty with instant correlation at a distance is that SR tells us that either Bob or Alice could be regarded as having acted first, so who influenced whom is a difficult question[8]. Our answer is that 50% of the time Alice influences Bob nonlocally, and 50% of the time it is the other way around. Either way, we have only one nondeterministic event. If Alice reorients the basis of her photon, her result is predetermined,[9] and Bob's result for that photon is nondeterministic.

Note that assigning half the head, or control photons to Alice and half to Bob is not arbitrary or done merely to attempt to demystify nonlocality a little bit. The even division is needed in order to reproduce the results of experiments, such as the quantum eraser. Assuming that we exclude superdeterminism and assuming that micromeasurements occur and create a hidden variable as we have asserted, and that the hidden polarization affects the next measurement in a standard way, according to the Born rule, then the rotations to the new basis of measurement we've proposed must take place, and they must be distributed half to each observer, and there must be a predetermined head and tail. Without the rotations, we obtain incorrect probabilistic predictions. And, if Alice rotated all of the biphotons, we would only have populations A1 and A2, and if there were no predetermined head and tail and random "decisions" to rotate were made on each end, then some photons might be missed completely.

Let us suppose, as an example, that Alice sets her phase adjustment to $-\pi/3$ and that Bob sets his to $\pi/3$. Without nonlocal effects, the single hidden variable interpretation would yield incorrect predictions in this case. It would say that Alice and Bob should agree with the value on the hidden measurement basis 75% of the time. They could then disagree no more than 50% of the time. However, standard theory predicts, and experiments show, they will disagree 75% or the time in this configuration. Thus, we need to include nonlocal effects in the picture.

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[8] (Gillis, 2019) writes, "In general, it is very difficult to construct a coherent account of effects that are both nonlocal and nondeterministic without assuming some underlying sequence."

[9] To be more precise, it is predetermined following the rotation. We assume that the choice of which direction to rotate is partly nondeterministic and follows the standard Born rule.

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Let us say that Alice receives the control photon. She reorients it to her basis of measurement. It is now as if, all along, she was measuring on the predetermined axis. Bob's photon rotates with hers so that Bob is now at 2π/3 relative to the predetermined measurement axis. Alice will find A1 half the time and A2 half the time in these cases, since this outcome is subjectively uncertain on the premeasurement axis. Bob's results can then be calculated to match hers 25% of the time and disagree 75% of the time.

$$P(\mathrm{B1}|\mathrm{A1}) = \frac{1+\cos(\phi_B)}{2} = 0.25,\ P(B1|A2) = \frac{1+\cos(\phi_B+\pi)}{2} = 0.75 \quad (21)$$

The fact that only the heads of the biphotons cause nonlocal correlations leads to an obvious suggestion. Rather than treating the head and tail as Parity transformations of each other, we could treat them as CT transformations of each other. This would yield a future input-dependent interpretation (Warton & Argaman, 2020) where the head of each biphoton actually originates at its respective detector. That is, population A1 photons originate at detector A1 and travel backward in time, etc. This would also yield a continual action interpretation, (Warton & Argaman, 2020). Communication between the photons is mediated by a chain of events. Basis rotation takes place over the entire trajectory of the biphoton. At least in the nonlocal case, treating the head of the biphoton as a CT transformation of the tail is certainly an attractive idea. At the very least, the biphoton behaves as if this were true. And while theoretically this involves particles traveling into the past, the measurable effects are only manifested nonlocally, not in the past light cone.

A concrete example of the difference in behavior between head and tail particles seems needed here. Suppose that we have one half of a stream of entangled electrons, and we put them into a magnetic field on the z-axis, as in the Stern-Gerlach experiment. Each of the electrons will already have a definite spin on some random axis. Suppose that one particular electron has a spin angle of 60 degrees from the z+ axis. If it is a tail electron, it will behave just like an unentangled electron in the magnetic field. It will split itself into two streams: 75% into the spin-up stream and 25% into the spin-down stream. The two parts will have the same net z-axis spin as the original electron. When the tail electron hits a detector, if it is still part of an entangled pair, it will rotate its counterpart, at that point in time, to maintain perfect anticorrelation.

The head electrons will behave differently. When they enter the magnetic field, they will not split into two beams. They will take one path or the other with 100% probability, destroying coherence, (Thiago De Oliveira & Caldeira, 2006), as in the photon experiments. To maintain the anticorrelation and the same net z-axis spin, they will drag their distant partner along to a new axis of rotation. They respond to the experimenter's preparation to measure on some basis. In the time reverse picture, then, they will appear to have originated 100% at one detector or the other.

One might be concerned that this would allow signaling. However, the experimenter can only control the hidden basis (in a random half of all cases) and cannot choose values on that basis. Bob's outer wave function and his probabilities are unchanged by Alice changing the basis of the hidden variable. If he could see the basis of the hidden variable, signaling would be trivial to accomplish. However, any attempt that Bob might make to see it will just cause projection onto some new basis. The basis Bob finds will always be the one he chooses to find.

In theory, this is something a very sensitive experiment could test. Half of the electrons should cause a torque, in the apparatus, in a random direction, large enough to rotate the biparticle. The net average torque would be zero. Interestingly, if this torque could be measured exactly and added to the

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information acquired at the final detector, it would allow Alice to identify the value of the hidden variable on the basis on which the entangled electrons measured each other. This would not be possible with the tail electrons or with unentangled electrons.

Let us take stock of what we claim to have accomplished thus far. If this analysis is correct, the single hidden variable interpretation will replicate all the predictions of any standard quantum mechanical interpretation regarding the results of QM experiments. This would make choosing between interpretations mostly a philosophical matter. However, we now turn to the issue of the measurement problem where we believe that the single hidden variable interpretation has a distinct advantage.

5. The measurement problem

Specifying where exactly a measurement takes place is challenging for many QM interpretation. On our interpretation it is a much simpler problem. Every interaction is what we have called a "micromeasurement". The only challenges left, at that point, are to specify how these micromeasurements can become non-erasable and as we discuss in section 6, this step also involves the destruction of global entanglements. Here is section 5, we begin with a reinterpretation of what is going on in decoherence.

(Schlosshauer, 2019) extensively discusses the well-studied phenomenon of decoherence. He writes "effectively, the environment is performing nondemolition measurements on the system" and "This suggests that decoherence can indeed be understood as an indirect measurement—a monitoring—of the system by its environment". (Schlosshauer, 2019) also notes that decoherence alone cannot solve the measurement problem, in part because decoherence theory is based on the unitary development of the wave function. These comments fit very well with our interpretation, since we assert that the outer, or standard, wave function never collapses but also that "under the hood", the environment can perform uncontrolled micromeasurements, collapsing the inner wave function and transforming the outer wave function into pure subjective uncertainty.[10]

A disagreement we have is that (Schlosshauer, 2019) states that after local coherence is destroyed, only a global measurement of the system that includes the environment can reveal it. We do not believe that such a global measurement, showing superposition, would be possible.[11] The roots of this disagreement can be found in the simplest example in (Paz & Zurek, 2000). Here, three one-bit systems are used to represent a measured system, an apparatus, and the environment. The system and

[10] Our assertion that a collapse is taking place might raise concerns about conservation of energy. However, collapse models that conserve energy exist. (Gao, 2013) is an example. A key feature of this model is that it does not assume that collapse to a positional eigenstate occurs, and neither do we. Rather than a "collapse" of the inner wave function, a "localization" of the inner wave function is perhaps a better term, particularly in the case of continuous observables. However, when we are dealing with observables with discrete eigenstates, then collapse of the inner wave function to a single eigenstate is a valid description of the process.

[11] (Nielsen & Chuang, 2016) points out that the state of a system with only 500 qbits would take 2^{500} amplitudes to specify. This number is larger than the number of atoms in the known universe. It seems unreasonable that nature would be keeping track of that quantity of information in such a small system. It seems more reasonable to suppose nature continually simplifies the wave function. This is accomplished by the destruction of global entanglements, as we discuss in section 6, and by the collapse/localization of the inner wave function.

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the apparatus are first entangled, and it is stated that this cannot constitute a measurement, just an entanglement.

$$(\alpha \mid \uparrow\rangle + (\beta \mid \downarrow\rangle)|A_0 \rightarrow \alpha \mid \uparrow\rangle|A_1\rangle + \beta \mid \downarrow\rangle|A_0\rangle = \Phi \text{ (24)}$$

Then, bringing in the third system, an environment bit that has premeasured the apparatus, allows us to look at a reduced density matrix representing the first two systems. This is accomplished by tracing over the environment.

$$\rho_{AS} = Tr_\epsilon|\Psi\rangle\langle\Psi| = \alpha^2|\uparrow\rangle\langle\uparrow||A_1\rangle\langle A_1| + \beta^2|\downarrow\rangle\langle\downarrow||A_0\rangle\langle A_0| \text{ (25)}$$

This allows us to see a classical "OR" instead of a quantum "AND" in this specific case. (Paz & Zurek, 2000) conclude section (2.4) by writing, "*Disappearance of quantum coherence because of a 'one–bit' measurement has been verified experimentally… A single act of quantum measurement we have discussed here should be regarded as an elementary discrete instance of continuous monitoring, which is required to bring about the appearance of classicality."*

We agree that it looks like a measurement has taken place, but that is, we argue, because a micromeasurement actually has taken place, causing a collapse of the inner wave function to a single eigenstate. We also agree, however, that no collapse of the outer wave function takes place. It just represents subjective uncertainty at this point. If this was only a micro-observation, then the outer wave function could be converted back into objective uncertainty. However, if a macroscopic apparatus was involved, then no global process, including bringing the environment into the picture, would allow superposition to be recreated. This destruction of the global entanglement is discussed in section 6.2.

We suggest a different interpretation of the same three bit experiment. Suppose that the environment bit that is "monitoring" the system instead represents a micro-observer. The observer is pre-entangled with the apparatus. This allows the observer to take the view of the inner wave function, where in this case objective uncertainty has been resolved[12]. Equation (25) then reflects our subjective uncertainty about a result that already exists. With that one minor reinterpretation of the role of the environment/micro-observer bit, the reduced density matrix in decoherence theory can be reunderstood to describe the probable results of micromeasurements, the actual results of which can be described by the inner wave function. We want to emphasize this stunning conclusion. All the work that has been done studying the phenomenon of decoherence can be easily reinterpreted to be about the collapse or localization of the inner wave function.

The difference in interpretation is that we assert that "coin flips" have taken place "under the hood" where we cannot see them, leaving us with only epistemological uncertainty about their results. A key insight in this interpretation is that the wave function can both collapse and persist. The outer wave function describing total uncertainty persists, whereas inner wave function collapse takes place, and projection occurs. However, the standard interpretation of decoherence theory says that we only have the "*appearance"* of classicality, with no collapse taking place. This does not lead to any differences in predictions, as far as we can tell at this point, except that we do not predict that half alive, half dead cats can be created by any sort of global procedure. That is, as long as we focus on only the reduced matrix,

[12] In (Paz & Zurek, 2000) "if the states of the environment are correlated with the simple products of the states of the apparatus–system combination" then the result is that the reduced density matrix appears classical. We would say that only subjective uncertainty remains.

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there will be no disagreement. The disagreement occurs only when we consider the global matrix, which includes the environment. We assert that measurements destroy the hypothetical global entanglement, creating separate subsystems. Again, we return to the topic of entanglement destruction in section 6.

However, even when we look at a global system that is still entangled, before separate subsystems are formed, there are no differences in predictions. Let us look at an example involving continuous observables[13]. In section 7.6.2, “Decoherence and the destruction of cat states”, (Benenti, Casati, Rossini, & Strini, 2019) gives a standard example of two Gaussian wave packets moving along the x-axis in superposition.

$$\psi_{cat}(x) \equiv \frac{1}{\sqrt{2}}[\, \psi_+(x) + \psi_-(x)] \quad (26)$$

$$\langle x|\rho_{cat}|x'\rangle = ½\, [\, \psi_+(x)\psi_+(x') + \psi_-(x)\psi_-(x') + \psi_+(x)\psi_-(x') + \psi_-(x)\psi_+(x')] \quad (27)$$

A photon that is much lighter than the system is scattered off the system. This destroys the visible signs of superposition. The diagonal terms of the density matrix for the original cat states are almost unaffected, but the off-diagonal terms are eliminated. Standard interpretations would assert that the global system, including the photon, could still be described as a superposition. We assert that a micromeasurement has taken place, and there is currently only subjective uncertainty as to the result. However, as in our original Alice and Bob example, this distinction does not offer any differences in predictions. The difference is invisible. If we take X to represent the position of the large system and x to represent the photon state correlated with the position of the measured system, then we assert that the current state, from the inner perspective, is as follows:

$$|\psi_{Xx}\rangle = |X_-\rangle|x_-\rangle \; or \; |X_+\rangle|x_+\rangle \quad (28)$$

Rather than:

$$|\psi_{Xx}\rangle = \frac{|X_-\rangle|x_-\rangle + |X_+\rangle|x_+\rangle}{\sqrt{2}} \quad (29)$$

This is essentially the same state as the original state in our Alice and Bob experiment. Only subjective uncertainty exists, but objective uncertainty could theoretically be restored by orthogonal measurement. Entanglement prevents evidence of superposition from appearing in this configuration, according to standard interpretations. There is no observable difference between the interpretations.

Given that for experiments we can actually do, there is no difference in observable predictions between the standard interpretation of decoherence and our interpretation, all we can do to illustrate our perspective is compare the differences in interpretation step by step. In the three bit experiment, in the two particle case, (Paz & Zurek, 2000) state that no measurement has taken place and that ambiguity regarding bases is present. We assert that a micromeasurement has taken place but that we have subjective uncertainty as to what basis was used. When the third particle becomes involved, (Paz & Zurek, 2000) state that the basis uncertainty has been resolved. The environment bit determines what

[13] A detailed version of this interpretation that applies to continuous observables is another topic for future research. However, a point to note is that for continuous observables, micromeasurements only reduce objective uncertainty by converting it to subjective uncertainty. They do not eliminate all objective uncertainty regarding continuous observables. We would also assert that the photon is this example measures a combination of position and momentum. (Gampel & Gajda, 2023) offers current insight into such simultaneous measurements.

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basis will be used for the apparent measurement or environmental monitoring. We would say that because the third bit is pre-entangled with the system, we now have access to the inner wave function and can see what measurement basis was used. And, if we could directly query our one bit apparatus, we would see that its hidden variable contains information about what value was discovered. Measurement has taken place, and if we are correlated with our measurement apparatus, we will have access to the result of the measurement.

6. Nonlocal effects and the measurement problem.

In this section, we introduce nonlocal effects, similar to those discussed in section 4, to explain some key features of the measurement process. Unlike the assertions in section 4, there is no one clear chain of deductive reasoning from our original hidden variable assumption to the assertions made in this section that motivates these assertions. However, we hypothesize that similar nonlocal effects might be involved in both entanglement and wave function collapse.

6.1 Not erased, just rehidden.

A standard way to think about the question of erasability is to think of it as a question of being able to perform an orthogonal measurement. That is, if the experimenter can manage a real-life orthogonal measurement of the system, then it is erasable; if she cannot, then it is nonerasable. Although this task may significantly be more difficult to accomplish than one might have expected[14]. However, we now ask if we should even talk about "erasure". In the single hidden variable interpretation, all we truly do is rehide information. We make the information unavailable in the description given by the outer wave function, but from an inner perspective, the information never truly goes away.

Let us look at a prototypical example of erasure and see what this interpretation says is going on. Figure 4 shows a sequential Stern-Gerlach experiment.

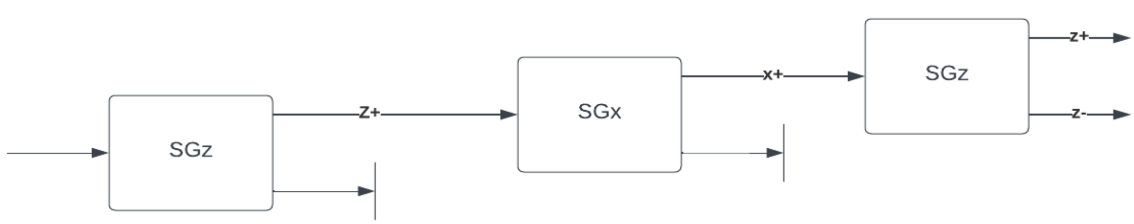

Figure 4 – A sequential Stern-Gerlach experiment.

We initially prepare a steam of electrons (actually silver atoms, in practice) with a z+ spin. In this case, the inner and outer wave functions are now identical. We have:

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[14] (Schlosshauer, 2019) writes "Decoherence is a genuinely quantum-mechanical effect, to be carefully distinguished from classical dissipation and stochastic fluctuations. One of the most surprising aspects of the decoherence process is its extreme efficiency…".

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$|\psi\rangle = |z_+\rangle$ (30)

We then put it through the SGx apparatus. Now, it is best described as:

$|\psi\rangle = \frac{|x_+\rangle + |x_-\rangle}{\sqrt{2}}$ (31)

This is both the exterior and interior wave function. Objective uncertainty exists on the x-axis. The input into the next step, however, is best written as:

$|\psi\rangle = |x_+\rangle$ (32)

which is subsequently best written as:

$|\psi\rangle = \frac{|z_+\rangle + |z_-\rangle}{\sqrt{2}}$ (33)

What happened between equation (31) and equation (32)? Measurement and projection of course. But where did the information regarding the previous measurement go? We assert that it "disappeared" into the wall hit by the $|x_-\rangle$ beam. Like entanglement, wave function collapse is also a nonlocal process. In fact, this is what Einstein originally meant by "spooky action at a distance" (Ananthaswamy, 2018). As in the case of entanglement, we assert that information is transmitted along both paths of the electron. When the $|x_-\rangle$ beam hits the wall, it changes from 50% $|x_-\rangle$ to 0% $|x_-\rangle$. It leaves hidden basis information with the particles in the wall. It then communicates this information back along its path to the moment it split from the $|x_+\rangle$ beam, and then the information propagates forward along the $|x_+\rangle$ path. Thus, the electron in the $|x_+\rangle$ beam "knows" it is now 100% $|x_+\rangle$.

So did the $|z_+\rangle$ spin information truly disappear? No, it just became unretrievable in the wall. To retrieve that information, we would have to have known the exact state of the hidden variables of the particles in the wall before they interacted with the electron. From an outer perspective, we do not have access to that information. Thus, we might wish to change terminology.[15] Rather than asking if the experimenter can erase the information via orthogonal measurement, we might ask instead if the experimenter can reconceal the discovered information via orthogonal measurement.

Our assertion that information is deposited in the wall by the $|x_-\rangle$ beam on a path where there is no energy exchange might be easier to accept if we consider the quantum bomb experiment (Elitzur & Vaidman , 1993). From that experiment, we know that quantum systems can discover information about a path that the "particle" does not travel. It should not be surprising then that the system can also communicate information to an object on the sterile path.

But what if the electron hits the wall and is resolved into an $|x_-\rangle$ state? It had been in a $|z_+\rangle$ state. Where does this information go if the $|x_+\rangle$ beam does not hit a wall anytime soon? We must suppose that the sterile beam continues to carry this information. Sometime in the future, it will deposit this information into a target that can accommodate it. The target would receive zero energy transfer, but a torque would be applied to it. To picture the situation, imagine that the real particle has a missing "ghost" particle that it would have if it were part of an entangled pair. The ghost electron would have, effectively, been in a $|z_-\rangle$ state:

[15] Although, ironically, the term "erasure" is likely permanent.

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$$|\psi\rangle = |z_-\rangle = \frac{|x_+\rangle - |x_-\rangle}{\sqrt{2}} \quad (34)$$

And would be rotated to an $|x_+\rangle$ state. All the hidden spin values would balance in this case. The incoming $|z_+\rangle$ and this $|z_-\rangle$ are both gone. The "live" branch created an $|x_-\rangle$ state in the wall it hit, where it also transferred energy and linear momentum when it traded states with an electron in the wall. The sterile branch would now be in an $|x_+\rangle$ state. There is no real electron on the sterile path, however. But we hypothesize that the torque to rotate the live branch will still come from this branch. The ghost electron would need to receive a positive y-axis torque; and therefore, a negative y-axis torque should appear in the target. As in the case of entangled photons, we hypothesize that a basis rotation then propagates along the entire length of both potential electron paths. The effect in the target would likely be manifested in other hidden particle spin states but also, perhaps, in a macroscopic object's angular momentum.

This might be something a cleverly designed experiment could detect. A difficult aspect of this would be that there would be no other sign that a zero energy "particle" hit a target, other than a tiny torque. A negative result might mean that it missed the target or "declined" to interact. In addition, the acquired angular momentum would likely only be found in a hidden variable in the target, making it undetectable. On the other hand, it does not seem impossible that a tiny target could show a measurable effect, particularly if it could be hit many times. (Galvez & Zhelev, 2007) describe an experiment involving photons imparting angular momentum to a latex sphere 5 µm in diameter trapped in an optical tweezer and suspended in oil. Something like this is what we have in mind since photons would be easier to work with than electrons. A difference is that their experiment involved photon orbital angular momentum, and this experiment would involve photon spin information. Suppose we split a vertically polarized photon into an LHC polarized beam and an RHC polarized beam. We block the RHC polarized beam and direct the other beam at a tiny target. If live photons can be induced to produce a measurable change in angular momentum in the target, then perhaps ghost photons can as well. The difference would be that the ghost photons, which carry no energy, could only alter the orientation of the angular momentum in the target, not increase the total angular momentum. For the most part, at least, we would expect that only hidden information would be affected. However, with enough interactions, a macroscopic effect might be produced. This would constitute experimental verification of a unique prediction of this interpretation.

6.2 Destruction of entanglements.

One final assertion we make here regards the question of exactly when old entanglements are broken. We assert that interactions on the sterile branches that particles do not follow are critical to breaking old entanglements without forming new ones. For example, between eqs. (31) and (32) the most obvious thing that happens is that the $|x_-\rangle$ beam interacts with a target. Given the other assertions of this interpretation, particularly the assertion that live branch interactions that form entanglements are the loci for micromeasurements, sterile branch interactions are nearly the only place where entanglements could be broken, thus this is what we propose takes place. To the best of our knowledge there is no experimental data that would contradict this assertion.

Breaking of entanglements is the final important piece of the measurement puzzle. Although breaking entanglements will not by itself guarantee that values discovered in a micromeasurement of a system cannot be erased/rehidden, it will just create separate subsystems, guaranteeing that no global

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process can accomplish “erasure” and/or recreation of superposition. It will prevent us from creating a Schrödinger’s cat via some hypothetical global manipulation, and thermodynamic irreversibility will prevent us from creating a superimposed cat via a process that involves addressing one subsystem at a time.

While interactions on both the live and sterile branches can affect the values of hidden variables, this is the only proposal we have made here that would affect the outer or standard wave function in any way. All real particle interactions are still treated as unitary interactions, but we assert that sterile branch “interactions” should be treated as events that separate the system that the wave function describes into separate subsystems. For example, in the diagram below, the indicated source is a source of entangled particles in singlet states. Then, looking only at the particles that are received at Bob’s x-axis detectors:

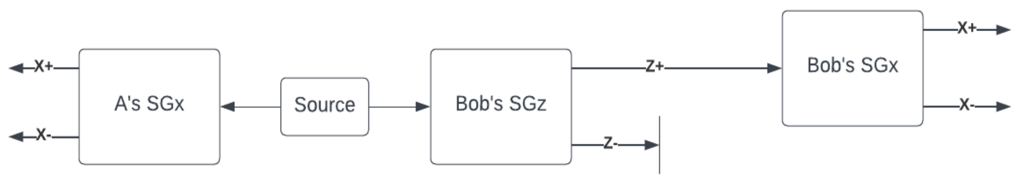

Figure 5 – A diagram of an experiment used to show when entanglement is broken.

$$|\psi_{AB}\rangle = \frac{|Ax+\rangle|Bx-\rangle+|Ax-\rangle|Bx+\rangle}{\sqrt{2}} \quad (35)$$

Becomes:

$$|\psi_A\rangle = \frac{|x_+\rangle + |x_-\rangle}{\sqrt{2}} \text{ and } |\psi_B\rangle = \frac{|x_+\rangle + |x_-\rangle}{\sqrt{2}} \quad (36)$$

A and B are now independent, and we assert that the transition happened when an information transfer event occurred during the sterile branch’s interaction with the target. From the moment entanglement ends, the outer wave function will continue to yield correct subjective probabilities regarding previous results. However, if it is used to describe any new manipulations of the system, it will be incorrect.

6.3 How should we define a measurement?

Finally, we can turn to the general question of “What constitutes a measurement?” If what we mean by a measurement is that it causes projection onto some basis and causes some objective uncertainty to be resolved in a nondeterministic event and that the information acquired cannot then subsequently be truly erased, then micromeasurements are measurements, period. If we “erase” a measurement, that does not change the fact that it happened, and the information gathered is not truly destroyed. We transform the system, and this hides the result from us. We change the old value in (30) to the new value in (32) and soon or later deposit information about the original answer somewhere we likely cannot retrieve it. This explains how macroscopic observations can be truly nonerasable. One

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might ask how even a myriad of erasable micromeasurements could add up to a nonerasable macroscopic measurement. The answer is that the micromeasurements are not truly erasable either.

However, if we want our definition of a measurement to also include the destruction of existing entanglements, then we must be sure to include sterile branch information transfer events as part of our definition of a measurement. Adding this component to the definition would yield a definition that says that measurement results cannot be rehidden via any global process.

Or if we want our definition of a measurement to stipulate that results cannot be rehidden via any process, including processes that address individual subsystems separately, then in practice, the question of what exactly constitutes a measurement will come down to a question of exactly how clever experimenters can be in concealing information from themselves in erasure experiments that do not, in general, replicate natural processes. In theory, nothing other than thermodynamic irreversibility prevents arbitrarily large systems from being treated in this manner.

Our preference is to use the term “measurement”, without qualification, to refer to events that include the destruction of global entanglements. Including this feature in the definition gives measurements an important form of irreversibility. We prefer to continue to use the term "micromeasurement” to refer to any new entanglement. The key feature here is that a nondeterministic event occurs, removing at least some objective uncertainty. Finally, we prefer to use the term “macroscopic measurement” once thermodynamic irreversibility has become a factor. In our view, the involvement of a human mind, when an observer becomes correlated with an observed system and can take the inside perspective, is not a critical part of the measurement process.

7. Comparing this interpretation to other interpretations

One way to start a comparison to other interpretations is with the new Wigner’s friend thought experiment (Frauchiger, 2018), (Bong, Utreras-Alarcón, & Ghafari, et al., 2020), (Ormrod, Vilasini, & Barrett, 2023). It treats a macroscopic observer as a quantum system in a larger experiment and arrives at a contradiction. The contradiction can be resolved but only at a cost. Different authors have published proofs that enumerate all the logical possibilities. This provides several different taxonomical systems with which to classify interpretations. One issue with this thought exercise is that what constitutes a measurement is not defined. We will provide our definitions. It is then an interesting exercise to see where this interpretation falls in the taxonomies.

In short, in the thought experiment (Ormrod, Vilasini, & Barrett, 2023), Alice and Charlie have a spacelike separation from Daniella and Bob. All perform measurements. Daniella has an inside perspective and precedes Bob, who has an outside perspective. If Daniella is a macroscopic observer, then we would claim that in practice, Bob cannot perform an orthogonal measurement. It is possible in theory, but only if he has perfect knowledge and control of every subatomic particle and erases all the previous results, one by one. He has a myriad of orthogonal measurements to perform. Alternately, if Daniella is just a particle that acts as a measurement device and performs a micromeasurement, then Bob can erase her result. Or as we have asserted, his measurement, in effect, changes the answer, erases her “memory”, and hides her original answer away where no one can see it.

So, where does this interpretation fall on the taxonomies? We clearly avoid some difficult ideas, such as superdeterminism and many-world hypotheses. In other cases, it is more of a “yes and no”

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answer. Does the interpretation allow superluminal causation? Yes, but only hidden variables in the otherwhere are affected, and there can be no signaling. Is there a wave function collapse? This is a complex question. No, for the standard wave function that describes the outer perspective, although we have argued that when entanglements are broken, it is divided into separate descriptions of separate subsystems. However, it still persists and correctly describes subjective probabilities for external observers not correlated with the observed system, and it never collapses to a single eigenstate. The inner wave function collapses to a single eigenstate in the case of discrete observables, although it never collapses to a single positional eigenstate, so it might be better to say that it is just “localized” in the case of continuous observables. We have argued that there is no information loss in this process, as nothing is actually erased.

Finally, are observations absolute? Yes, macroscopic observations are absolute and cannot be erased/rehidden in practice. Destruction of global entanglements and thermodynamic irreversibility prevent this. No, micro-observations are not absolute, as their results can be rehidden, but even they cannot be truly erased.

In addition to checking these various taxonomical boxes, a few interpretations need to be mentioned for specific comparison. We address the ideas of Bohmian mechanics, relational quantum mechanics, the transactional interpretation, many-worlds and the Copenhagen interpretation, all of which have certain similarities to our interpretation that stand out but all of which are also significantly different in some way.

Bohmian mechanics (Bohm, 1952), also known as the de Broglie–Bohm interpretation, has some clear similarities to our idea. It can also be described as a hidden variable theory; it can also explain the measurement problem, and it is also nonlocal. However, it also differs significantly from our idea. In Bohmian mechanics, a particle always has a specific position. This is not the case in our interpretation. For example, in the two-slit experiment, we contend that the “particle” passes through both slits when an interference pattern is created. The “particle” is never more localized than a Gaussian wave packet in our interpretation. It never has an exact position. We do, however, assert that real values always exist for discrete observables such as spin and polarization. In Bohmian mechanics, the wave function is objective and persists forever. In the single hidden variable interpretation, the outer wave function persists but simply describes subjective probabilities after a time. And the inner wave function, which describes objective uncertainties, collapses. Bohmian mechanics is also more “intensely” nonlocal than our interpretation. Bohmian mechanics allows for a complex universal web of entanglement to potentially affect each individual particle. However, while we allow nonlocal effects between entangled particles, we assert that entanglement is a limited phenomenon that can be broken. Thus, the number of particles that can have nonlocal influences on another particle is generally quite limited, often to only one other particle, and we propose a specific theory for this nonlocal influence. Another difference is that Bohemian mechanics is deterministic, whereas our interpretation allows for nondeterministic events.

Another interpretation we need to mention is relational quantum mechanics (Rovelli, 1996). This interpretation has one very important feature in common with our idea. It asserts that variables acquire values with every interaction. Thus, as in our idea, all particles function as measurement devices. Any physical system can play the role of the Copenhagen interpretation’s observer, and any interaction counts as a measurement (Laudisa, 2021). A key difference, however, is that in RQM, values are only ever relative to each other and have no absolute values apart from an observer. Thus, two different

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macroscopic observers can come to different equally valid conclusions about the value of a quantum variable. Our interpretation is more relist. Real, observer-independent values for discrete variables, such as spin, always exist, and our interpretation does not allow differences in observed quantities for macroscopic observers. In one sense, the two interpretations could be seen as having opposite philosophies. RQM asserts that there is no separate classical world, and that everything is quantum. Whereas our interpretation asserts that the quantum world is somewhat more real and classical in nature than is generally assumed.

The Copenhagen interpretation is a historically important interpretation, of course. We have contrasted our ideas with this interpretation throughout the paper. Our references to "standard interpretations" primarily refer to this idea as the "default" interpretation. As in Copenhagen, we assert that measurement causes wave function collapse. However, in the Copenhagen interpretation, the locus of measurement is ill defined. Depending on the version, it may be located in human consciousness, or in a macroscopic measurement device, or it may just lack specificity. Our interpretation could be viewed as a version of Copenhagen where it is specifically asserted that every interaction constitutes a measurement, as in RQM, and then that what we have presented here is the logical consequence of following that idea to its conclusion. The wave function collapse in our interpretation is hidden from the perspective of an observer not correlated with the system. This creates a hidden variable which is not part of the standard Copenhagen interpretation.

All interpretations give up something to achieve something else. In our interpretation, perhaps the most difficult idea to accept is the idea of a limited form of retro-causality, which allows nonlocal causation to occur. Hidden variables in the past can be altered in the present. Evidence of these changes can be observed statistically and non-locally. However, our idea does not allow non-hidden effects to appear in past light cones of causes, and causal loops and signaling are impossible. An analogy that we would like to use in order to think about this issue is an analogy to the conservation of energy. We know conservation of energy applies in the long run, but quantum phenomena can briefly "borrow" energy before returning it to the vacuum. As a loose analogy, we assert that time has a definite forward arrow, defined by the resolution of nondeterministic events. However, minor temporary exceptions to this overall direction of forward time flow can exist but never in such a way that they violate the basic principle that time flows in the forward direction.

Other retro-causal models have been proposed, of course. The transactional interpretation (Cramer, 1986) is a well-known example. Our proposal differs in a number of ways. The transactional interpretation features advanced and retarded waves, which are not features of our interpretation. It treats time as symmetric, whereas our proposal contains a distinct arrow to time based on the resolution of non-deterministic events. It is also more intensely non-local as the entire future light cone of the universe could be involved in the resolution of an event. Additionally, our proposal that biparticles have "heads" and "tails" is unique to our knowledge.

One more point to consider is what happens to this theory if we make one small adjustment. We are proposing that if a torque is applied to the head of a biparticle in the present, this effect is transmitted to the past and to the point where the halves of the biparticles separate, and this effect can be measured in the tails of the biparticles. While the event order may "bounce around" in spacetime, there is a linear casual order of events.

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Now, suppose instead that when the signal from the head of the biparticle alters the past, it also alters *its own past*. That is, it changes the past it “perceives” not just the past as perceived by the tail. Now once the past is altered there is no need for any torque to be applied to the head of the biparticle since it is already in that orientation and always has been. This is a circular causality loop. But we have now recreated the many worlds interpretation, stated differently. Measurements select the universe in which they will exist and an endless past history consistent with the result. There is no longer any measurable distinction between the head and the tail and thus no need to speak of them. The many worlds interpretation is, however, circularly causal in a way. The result of the measurement event causes the past history to be chosen that creates the result of the measurement event.

We believe our proposal is philosophically simpler. It avoids universal global entanglement and offers a solution to the measurement problem. However, this thought exercise illustrates that this theory is only subtly removed from popular interpretations such as the many worlds interpretation.

8. Summary

Bell’s inequality (Bell, 1964) tells us that hidden variables sufficient to explain quantum phenomena as strictly local and real cannot exist. It does not, however, preclude any hidden variable. Our primary assertion is that there is one such hidden variable. This could be describes as “partial realism” in that sometimes quantum variables have definite values before we measure them and sometimes they do not, and from our perspective we can’t tell which is which.

We treat all new entanglements as micromeasurements from an inside perspective. These observations transform objective uncertainty into subjective uncertainty on the basis axis measured but leave values on other potential measurements objectively undetermined. If we look again at equation (4):

$$|\psi_{AB}\rangle = \frac{|A1\rangle|B1\rangle + |A2\rangle|B2\rangle}{\sqrt{2}} \quad (4)$$

Depending on the axis on which Alice and Bob choose to measure, it may represent completely subjective uncertainty in the case where they both measure on the same axis on which the photons measured each other. Alternately, it may represent completely objective uncertainty for an experimenter measuring orthogonally to the premeasurement axis. Alternatively, it may represent a combination of both if they measure on some other axis.

The standard or outer wave function represents the total probability, objective plus subjective, and the minimal uncertainty that any outside observer must have. The objective probability is what is uncertain to an observer that is part of the system, the minimal uncertainty that any observer must have. It is represented by an inner wave function. The difference between them is that from the inner perspective, one can see the value of hidden variables.

We have provided a theory of nonlocality that is a direct consequence of our hidden variable assumption and a desire to match all experimental data. In this theory, biparticles have heads and tails, and the heads behave differently than unentangled particles. They orient their preexisting axis of measurement to match the experimenter’s axis of measurement and reorient the tail end of the biparticle along with them, even nonlocally. A very sensitive experiment might be able to test for this effect.

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Micromeasurements are simply particle interactions where the particles exchange allowable bits of hidden information. They might, for example, alter each other's basis of rotation. Nondeterministic events obeying the Born rule occur, which resolve at least some objective uncertainty. Macroscopic observations should not be treated as projections on to a basis. Rather, the observer simply gains access to the interior wave function and finds a statistical result built up from many micromeasurements. Micromeasurements can be "erased", and macroscopic observations cannot. However, we argue that "erasure" is truly the wrong term in this interpretation. Information is instead rehidden and replaced by a new value.

We also argue that the reduced density matrix in decoherence theory can be reunderstood to describe the probable results of micromeasurements, the actual results of which would be described by the inner wave function. We also argue that interactions on sterile paths that particles do not follow are critical to destroying previous entanglements without creating new entanglements, thus creating separate subsystems rather than a continuing global entanglement. We also argue that the definition of a measurement, unqualified by "micro" or "macroscopic", should be that a measurement happens when global entanglement ends, and thus, no global procedure can then cause "erasure" of existing results.

This gives us an interpretation of quantum mechanics that avoids difficult ideas such as nonabsolute macroscopic events, many-world hypotheses, superdeterminism, information loss, and superluminal causation (affecting nonhidden variables). It intuitively explains the results of the quantum eraser experiment, and it offers a theory of nonlocality. It offers a proposed solution to the measurement problem and a reinterpretation of decoherence. It restores a degree of realism to the quantum world. It provides an arrow to time. Finally, it proposes an explanation for how entanglements are destroyed, and it banishes cats in superposition from QM.

A challenge for future research would be to attempt to verify this interpretation experimentally. Additionally, if this QM interpretation is successful, another challenge would be to develop a QFT version of it. We also note that this interpretation may be compatible with the recently published idea of postquantum classical gravity (Oppenheim, 2023), which also requires nature to be fundamentally stochastic. Additional projects for future research have also been described in the text.

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