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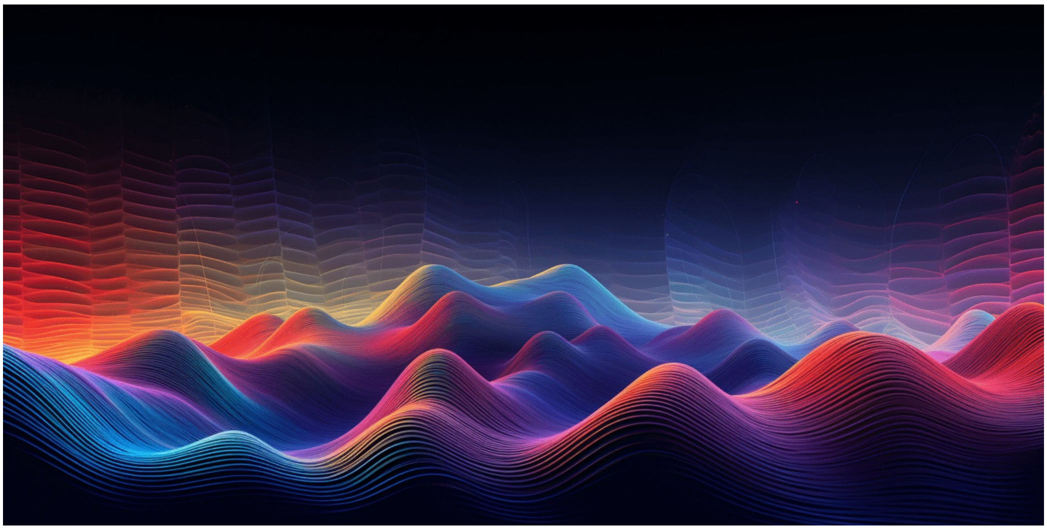

A single hidden variable interpretation of the quantum wave function

David Gentile

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Abstract

An interpretation of quantum mechanics is presented in which there is one hidden variable. While this number of hidden variables is insufficient to explain Bell nonlocality, it can help solve the measurement problem. It also provides an explanation of the delayed choice quantum eraser experiment that is more intuitive than current explanations. In addition, a theory of nonlocality emerges directly from its assumptions. The key idea is that from the perspective of an outside observer, not entangled with an observed system, we treat all interactions within the system as unitary. However, from the perspective of an “observer” inside the system, entangled with the system, we treat all new entanglements as “micro-observations” and as a projection onto some basis of measurement. One particle can “observe” another. Thus, particles will have a defined value on one measurement basis from the inside perspective. This means that the wave function, from the outside view, will at times describe an objective uncertainty, at other times a subjective uncertainty 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, while for an observer inside the system, only the objective part of the uncertainty remains, and this can be described by an inner wave function. The hidden variable is invisible to the outside observer.

David Gentile

Riverside, IL, USA

ORCID: 0000-0001-5777-761X

E-mail: gentile.david31@yahoo.com

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Contents

1. Introduction

We begin in section 2 by defining two types of uncertainty, objective and subjective. We then assert that the standard or outer wave function represents the total uncertainty to an outside observer not entangled 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 "observe" each other and give each other definite values on some (unknown) measurement basis. 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 basis that is unknown. One hidden variable is insufficient to explain Bell nonlocality; however, it is helpful with other problems. We attempt to show, for example, that it offers a solution to the measurement problem. In section 3, after the most basic example, we first discuss a configuration in 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, but another, by Bob, will resolve objective uncertainty. In this configuration, we attempt to show that the results of the delayed choice quantum eraser experiment can be addressed, and that this explanation is more intuitive than existing explanations. Then, in section 4, we 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 explaining nonlocality emerges directly from the assumptions of the interpretation and existing experimental results. Then, in sections 5 and 6, we attempt to tackle the measurement problem. In section 5, we address the questions of "what happens in a micromeasurement?", "what happens in a macroscopic measurement?", and "when do observations become nonerasable?" Then, we take a brief look at the new Wigner's friend experiment. Finally, in section 6, we argue that observations are not truly erased; they are just rehidden.

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. The first represents real uncertainty in the universe, and the other is about what information we have available. In statistics, historically, these conceptions of probability divided mathematicians into two camps, classicists and Bayesians (Jaynes, 2003), although 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 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 sort of behavior, nor does classical physics. The coin flip in classical physics would not be described as intrinsically random, but 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 entangled 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], entangled with the system, we treat all new entanglements as "micro-observations". One particle can "observe" 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, while from an outside perspective, subjective uncertainty regarding that variable's value remains. Objective uncertainty also persists, however. Values for other variables that would have to be measured on an incompatible orthogonal basis 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. The 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 entangled 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 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 delayed choice quantum erasure experiment

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

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

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

$$|\psi\rangle = |U_+\rangle \qquad (2)$$

This indicates a positive value on some unknown basis of measurement. But then, of course, on some orthogonal basis of measurement, say V, we could also write the wave function as a superposition.

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

In equations (2) and (3), we see the minimum possible uncertainty that must exist for any observer, even if they are entangled with the system. There is no uncertainty on some basis and objective uncertainty on some orthogonal basis. If we then consider equation (1), we can see that while it correctly predicts the results we will see if we measure multiple photons – 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 U basis, then our measurement will only resolve our subjective uncertainty as to the preexisting value. However, if we happen to measure on basis V, orthogonal to U, then our result is objectively undetermined until we measure, and a nondeterministic event occurs.

Let us now turn to a more complex example. In (Hobson, 2022), a pair of entangled photons or a biphoton is considered. Suppose 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 via path 1, then Bob will as well and the same for path 2. We can write the wave function from an outside perspective, which represents the minimum uncertainty we must have from that perspective as:

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

Suppose Bob puts a phase shifter on one path and tries to get his photon to interfere with itself. He will not be successful. As (Hobson, 2022) points out, experiments have shown that this does not happen. (Hobson, 2022), citing (Horne, Shimony, & Zeilinger, 1990) and (Horne, Shimony, & Zeilinger, 1989), also says that the theoretical reason why interference does not appear is that the nonlocal photon's contribution needs to be considered. When this is done, the phases always line up so that, as (Hobson, 2022) puts it, "the photons decohere each other", that is, they prevent each other from creating an interference pattern. Thus, all experimental evidence of superposition has been eliminated in this configuration. (Hobson, 2022) contends that this represents a measured state[5]. The experimental setup discussed is diagrammed below (fig. 1):

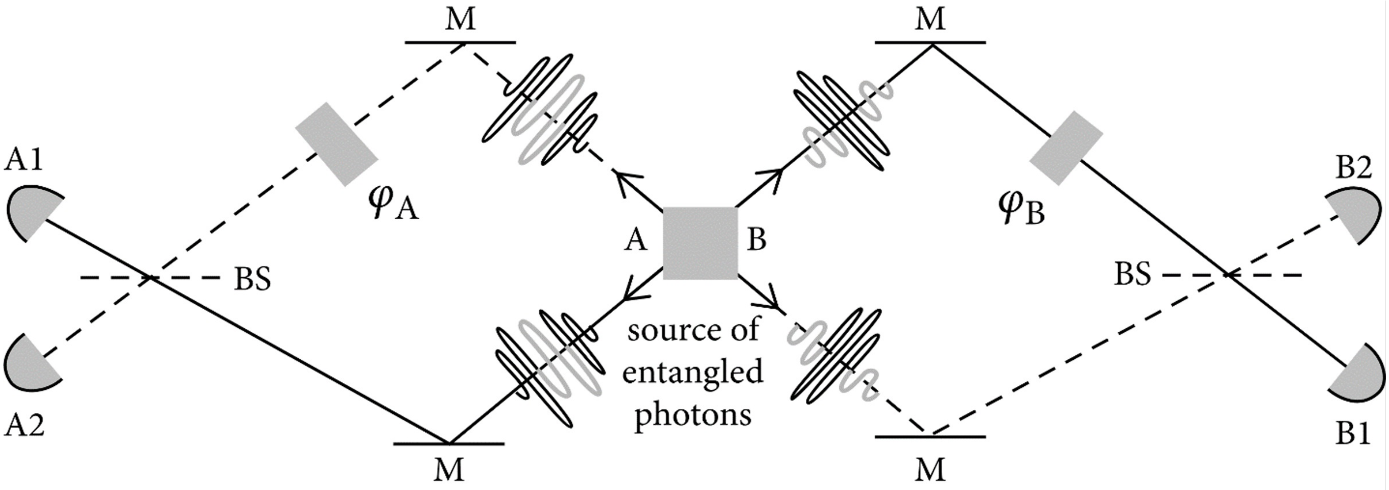

Figure 1. A diagram of the experimental apparatus discussed here and in (Hobson, 2022).

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)[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 basis 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, to an outside observer unentangled 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 give correct statistical predictions. However, for a "micro-observer" entangled with the system, in this specific case, equation (9) is correct.

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

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 "micro-observation". 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 on multiple incompatible orthogonal measurement bases to be preexisting (Napolitano & Sakurai, 2021). It is not possible in this example that a value on some unknown measurement basis, U, is preexisting and then also have preexisting values on an incompatible orthogonal basis such as V or W. Hidden variables sufficient to explain Bell nonlocality have been ruled out experimentally; however, that does not mean there cannot be an ANY hidden variable[7].

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. That 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 like the following, where P_T, P_O, and P_S represent the total probability, the objective probability, and the subjective probability, respectively.

$$P_T(B1) = P_S(A1) * P_O(B1 \mid A1) + P_S(A2) * P_O(B1 \mid A2) \qquad (12)$$

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

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

A well-known result in quantum mechanics is that if we perform a measurement and then measure again on an incompatible orthogonal basis, the information gained from the first measurement is destroyed (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[8], 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.

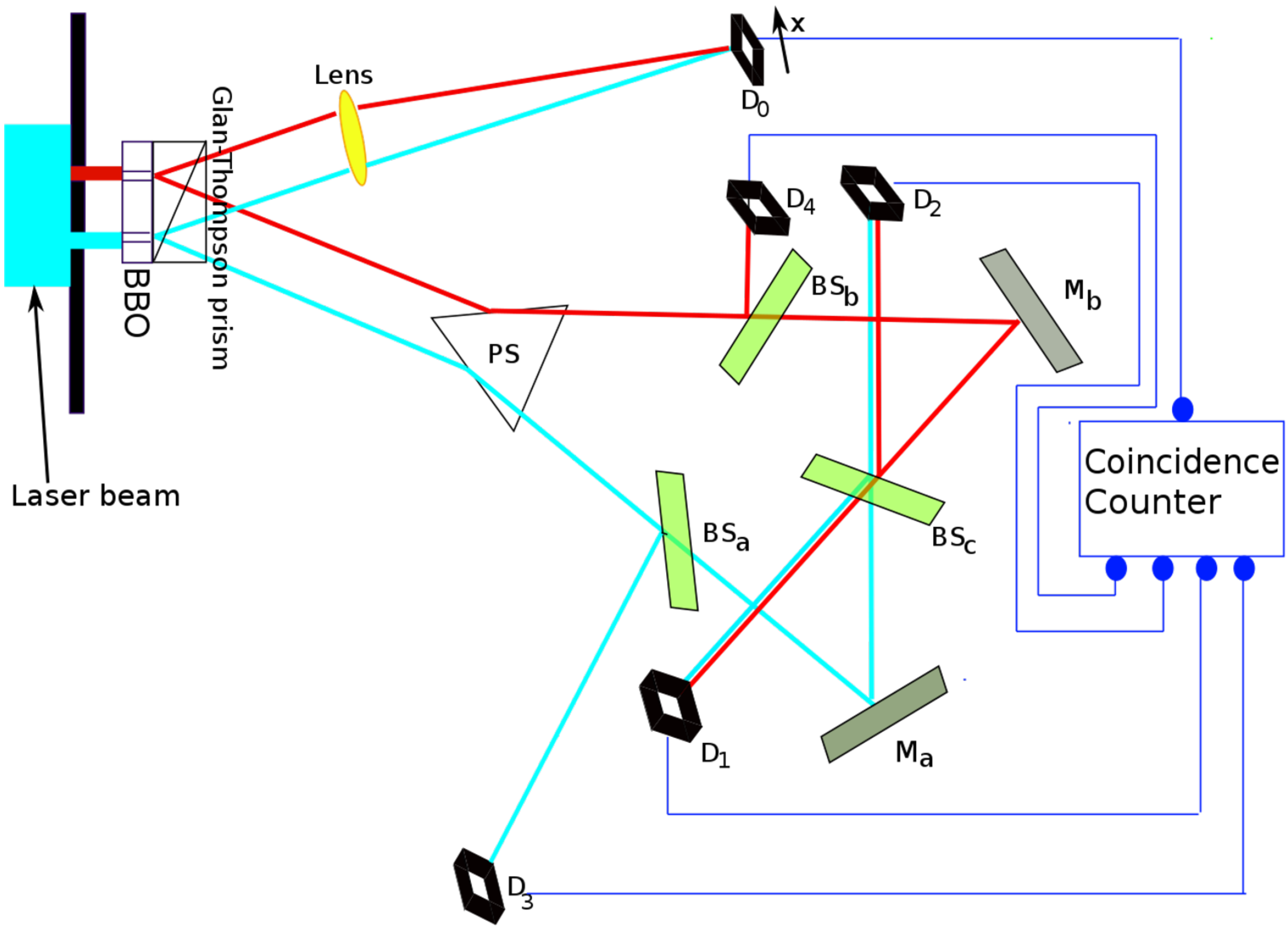

Figure 2. Diagram of the delayed choice quantum eraser experiment. In this diagram, "Alice" would be the detector at D_0, and "Bob", perhaps temporarily renamed "Dan", would be the detectors at D_1 and D_2. We will, however, continue to refer to our hypothetical Alice and Bob experiment.

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. For our simple example here, we will assume they either measure each other's path information or phase information rather than all possible bases on which they could measure each other[9]. There will then be populations of biphotons with preexisting values on some measurement basis. 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 go 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 populations - those biphotons that are 100% determined to be destined for detectors A1, A2, B1, or B2[10]. 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 happened 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.

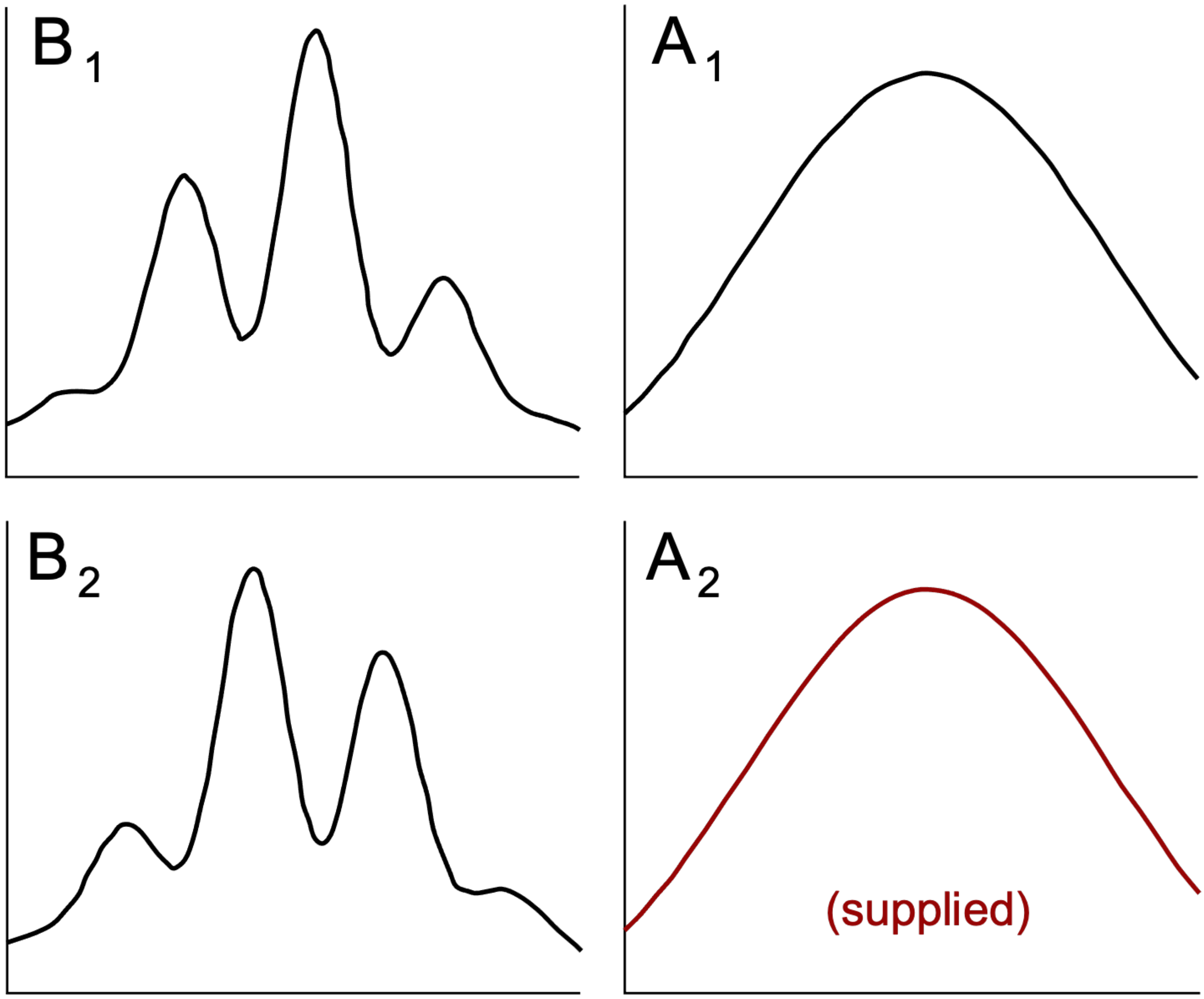

Figure 3. Results of (Kim, Yu, Kulik, Shih, & Marlan, 2000) relabeled for our Alice and Bob thought experiment.

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 on a basis orthogonal to the basis on which the photons measured each other, and both results, taken individually, are objectively undetermined, but they perfectly correlate, even nonlocally, when considered together.

Assuming 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, based on the discussion thus far, only objective uncertainty in this case, as knowledge of the hidden variable adds no useful information.

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

The perfect correlation makes it appear as if Alice and Bob were somehow forced to measure on the preexisting basis, or alternately, the basis altered itself to match their measurement basis. The latter is what we will now assert happens. In order to match all 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 basis of 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 its basis unchanged. Those will have their basis altered to match Bob’s measurement basis, and then Alice’s photon gets dragged along with it to some new basis. She then simply measures relative to the new basis 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 basis all along.

This has a number of benefits. For example, in the quantum eraser experiment, in the nonlocal case, 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[11]. 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,[12] and Bob’s result for that photon is nondeterministic.

Note that assigning half the 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 in experiments such as the quantum eraser. Assuming we exclude superdeterminism and assuming that micromeasurements occur and create a hidden variable as we have asserted, and assuming 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 would 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 -π/3 and Bob sets his to π/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 bring nonlocal effects into the picture.

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 basis. Bob's photon rotates its basis with hers so that Bob is now at 2π/3 relative to the predetermined measurement basis. Alice will find A1 half the time and A2 half the time in these cases, since this outcome is subjectively uncertain on the premeasurement basis. Bob's results can then be calculated to match hers 25% of the time and disagree 75% of the time.

$$P(B1) = (P(A1) = 0.5) * \left(P(B1 \mid A1) = \frac{1 + \cos\left(\phi_B\right)}{2}\right) + (P(A2) = 0.5) * \left(P(B1 \mid A2) = \frac{1 + \cos\left(\phi_B + \pi\right)}{2}\right) \quad (21)$$

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.

Finally, let us look again at the delayed choice quantum eraser experiment. In the delayed choice case, Alice acts first. In the cases where Alice receives the head of the biphoton, she will rotate those biphotons to match her path-information basis of measurement. These will be populations A1 and A2. We then have two options to explain what happens to the tails of the photons on Alice's side. One choice is to suppose that it is no different than the nonlocal case. Bob rotates the head of these biphotons to his basis of measurement, and Alice measures relative to her new predetermined basis. However, this would involve Bob's measurement affecting Alice's measurement in his past light cone. This is the simpler option, but not the better option, in our view.

Alternately, treating the head and tail as CT transformations of each other might just be a useful way of treating the biphoton mathematically, without asserting that retrocausality is what actually happens. In the delayed choice case, it is possible to explain the results without supposing future input dependence. The time-forward alternative is that Alice performs all the basis rotations, although heads and tails are still treated differently. This preserves the standard time order of cause and effect. How would the tails "know" they needed to behave differently than in the nonlocal case? They would not yet have received a signal from the head that entanglement was broken. Similarly, the heads would "know" they had to behave differently once they received a signal from the tail that entanglement was broken.

Alice's unaltered tail photons will pass through both slits in various proportions and have their information determined by the recording screen in nondeterministic events. As the biphotons are measured at the detector, their other half will be rotated so that they continue to have values exactly opposite to each other on some basis. The information recorded on Alice's detection screen will be enough to largely separate the photons into populations B1 and B2 (see equations (17) and (18) and fig. 3).[13] Bob receives population A1 and A2 photons that are objectively undetermined on his basis and then also receives Alice's initially unrotated photons that were largely undetermined before measurement on her end and are now largely predetermined on his end to be either population B1 or population B2.

Note that we are still asserting that head and tail photons behave differently. The heads are rotated to specifically match her "which path" basis of measurement, as if they always had that basis (populations A1 and A2) and the tails (populations B1 and B2) are not. The tails are just measured relative to whatever basis they happen to have, according to the Born rule, and then they drag their counterparts along for the ride so that anticorrelation between the photons is maintained. The tails' information will still be transmitted along the biphoton's entire trajectory, but in this case, the only measurable effect appears as communication into the future light cone at luminal or subluminal speeds between Alice's photon and Bob's photon.

A concrete example of the difference in behavior between head and tail particles seems needed here. Suppose 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 basis. Suppose 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 rotation basis along with them. 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 not choose values on that basis. Nor can Alice know what basis the photons used to measure each other before she imposed her will on the system. 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 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.

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, now we turn to the issue of the measurement problem where we believe the single hidden variable interpretation has a distinct advantage.

5. The measurement problem

In this section, we attempt to answer three questions.

1. What happens in a micro-observation?
2. What happens in a macroscopic observation?
3. When do observations become nonerasable?

We then take a brief look at the Wigner's friend thought experiment, and then in the next section, we will take a different approach and question the importance of the third question in this interpretation. Let us attempt to answer the simplest question first.

5.1. What happens in a micro-observation?

We simply suppose that the particles trade allowed bits of hidden information randomly. Two electrons might, for example, trade hidden spin axes. Particles may also exchange information about position, momentum, or other variables. This is invisible from outside the system, but in effect, the particles have measured each other on some basis. In the case of the electrons trading spin axes, they "know" what the spin axis of the other particle was, and they changed it in the process of measurement. They must obey basic rules such as conservation laws and must not exchange more information than allowed by the uncertainty principle. In addition, the Born rule will play its standard role.

As a simple example, suppose an incoming electron is in a superposition of a$|z_+\rangle$ and a $|z_-\rangle$ spin state in a Stern-Gerlach experiment. An electron in the $|z_+\rangle$ branch is measured by an electron in a target. We would suppose that there would be a 50% chance that the target electron would acquire the $|z_+\rangle$ state, as the Born rule predicts. The incoming electron would then acquire the state of the target electron. This simple trading of spin axes constitutes a measurement. Inner wave function reduction was accomplished.

However, this sems to lead to information loss. Suppose the incoming electron had been in a pure$|x_+\rangle$ state before it acquired the $|z_+\rangle$ state. Was the information regarding the original state erased? Additionally, what happens if the resolution is that the incoming electron is in the $|z_-\rangle$ state, in which case the electron will be determined to not even be on the path where it is interacting? We will return to questions about what happens on the "sterile" path that the electron does not take in the next section. Here, we just note that projection on to a new basis has occurred, from the point of view of the inner wave function, and objective uncertainty has been resolved. From the point of view of the outer wave function, a unitary interaction has taken place, and subjective uncertainty regarding this result will persist.

5.2. What happens in a macroscopic observation?

Let us now turn to macroscopic observations. After the photons in the original Alice and Bob experiment measure each other, we have a couple more steps. First, one of the photons, let us say Bob's, must become entangled with Bob's measuring device and then with Bob. We then have, from the point of view of an outside observer, not entangled with the system:

$$|\psi_B\rangle \otimes |Device\rangle \otimes |Bob\rangle \qquad (22)$$

From Alice's outside perspective, this still describes her probabilities. However, at this point, it represents 100% subjective uncertainty. Decoherence destroyed any possible evidence of superposition long ago. No matter how clever an experiment Alice designs, she will not be able to coax Bob into interfering with himself. And obviously, Bob does not experience himself in a superposition; so what is happening from the inside perspective? From the inside perspective, something important happens in each of the three steps. Objective uncertainty was removed at the particle level. Then, once entanglement with the macroscopic device takes place, the measurement can become thermodynamically irreversible. Whereas we could have erased the "memory" of a single photon, the result has now left an indelible mark on the universe. Finally, Bob looks at the measurement. Let us say that he finds that the photon took path 1. Now, we can finally write:

$$|\psi_B\rangle = |B1\rangle \qquad (23)$$

With no uncertainty. No wave function collapse is needed here. Since Bob is now part of the entanglement, he now knows which path has been taken. The outer wave function persists and describes the subjective uncertainty from the outside perspective for Alice until Bob chooses to inform her of the result. All that has happened is that Bob is now allowed to take the inside perspective, which has existed all along. Bob can now see a value for the formerly hidden variable on some basis he chose to measure.

We now need to distinguish between two different types of bases for measurement. There is an intended basis of measurement by the experimenter, and there are the bases of measurement used by the micro-observers. The experimenter cannot completely control on which bases the micromeasurements are made. However, she can control the experimental design, which will allow her to extract the desired sort of information. In a Stern-Gerlach experiment, for example, magnets separate electron streams according to spin, and then positional detectors are used to record the electrons. Even though Alice cannot control the exact basis of measurement for all the micromeasurements, whatever positional information they do acquire will be enough to give her the desired information about the spin of the electron, since the paths are macroscopically separated. When multiple entanglements take place at her detector, any positional information the micromeasurements acquire will be distinctly different than any positional data that would be acquired at the other detector. Thus, even if an individual micromeasurement does not completely localize the particle, it will definitively identify which detector it has arrived at. The energy absorbed by the detector then sets off a chain of events, which Alice then interprets as a result regarding the electron spin.

She does control something at the micromeasurement level, however. If the electron hitting the detector is in a superposition of spin states, it will have its spin measured on the axis she chose when it interacts with the target, and it will be resolved into one of its two component states. Alice chose that it would be measured on this basis but did not control other information that might have been exchanged.

If the single hidden variable interpretation is correct, then the standard account of what happens in a macroscopic measurement is just shorthand for a more complicated underlying reality that it does not completely capture. In a standard account, Alice measures on some basis. Projection onto this basis occurs, and an eigenvalue is returned to Alice. The wave function is reduced by projection onto the new basis. The actual physical process, in at least one of the actual quantum eraser experiments, involved a silicon avalanche photodiode (Ananthaswamy, 2018). The detected photon is absorbed and causes an electric signal involving billions of electrons. This process is too complex to analyze in detail, so let us turn to another thought experiment and a toy model.

Suppose we have a "detector" consisting of just two particles. Alice is trying to determine the position of an incoming particle, so that is her chosen basis of measurement. However, Alice cannot control the basis on which each micro-observation will be made. Each of the particles will cause their own separate reduction of the interior wave function and project it onto some random basis. Let us suppose that particle 1 measures momentum more precisely and particle 2 measures position more precisely. If we assume for this thought experiment that Alice can somehow directly read these results, she will have two separate positional estimates, and one will have less uncertainty than the other. She can then use some standard statistical procedure, such as the maximum likelihood method, to come up with her best possible estimate of the position. Thus, Alice does not actually obtain an eigenvalue as a result. She gets a messy classical-looking result. If this were a classic two-slit experiment, she obtains a finite-sized dot on her photographic plate, not an eigenvalue. She gets a statistical summary of just the positional portion of whatever information each of the micromeasurements recorded, which she then interprets.

Thus, describing a macroscopic measurement of a macroscopic system as projecting the outer wave function onto some basis is not really a valid move. We can write it as a shorthand for something more complex, but if we actually mean it accomplishes wave function reduction then this is wrong. When Alice looks at the results, all she does is resolve her subjective uncertainty. She can now see the inside description of the wave function rather than the outside description of the wave function. No reduction of the wave function occurs at all in this step. The inner view of the wave function describing the objective uncertainty has existed all along and was reduced with each particle entanglement. And the outer view, by now 100% subjective uncertainty, still describes Bob's perspective until she chooses to inform him of the result. What she discovers once she can take the inside perspective is not an eigenvalue, but a statistical picture built up from many individual micromeasurements, each of which returned an eigenvalue on whatever basis they "chose" to measure. She can then interpret this as a result about the value she intended to measure. For example, if Alice had been interested in the z-axis spin of some electron, the inner wave function describing the objective uncertainty of the spin was reduced when it became entangled with the detector, and multiple position and momentum estimates were also acquired by the detector. Alice does not see any of these individual results. The detector absorbs the incoming energy and sets off a chain of events. Her experimental setup then allows her to infer the spin result from the summary information she does receive.

5.3. When do observations become nonerasable?

Now, we turn to the question of when measurements become nonerasable. In the next section, we argue that in this interpretation, nothing is ever truly erased; instead, the results can be rehidden. However, in this section, we will continue to use the term “erased” in the standard way. The question of when measurements can be effectively erased is still an important one for many purposes even if this interpretation is correct.

The first thing to note is that we cannot even describe what sort of physical process we would use to perform an orthogonal measurement on a macroscopic system. Let us take the famous Schrodinger’s cat thought experiment as an example (Schrodinger, 1937). Let us first assume we can isolate the system from the rest of the universe, including any infrared heat radiation. This alone seems impossible. But then how do we perform a measurement orthogonal to a previous measurement? If the box is spinning on the z-axis, it is not in a superposition of x-axis spin states. The cat is not in superposition. It is nonsensical.

When dealing with subatomic particles, both the outer and inner wave functions are useful. However, for this macroscopic system, the outer wave function is now too far removed from the inner wave function. The inner wave function is 100% objective uncertainty and still describes quantum objects, whereas the outer wave function is by now 100% subjective uncertainty. Trying to project the outer wave function onto some new basis is an invalid move. The math no longer represents a quantum system that can be put in superposition. The outer wave function still represents the subjective uncertainty regarding the fate of the cat, but that is its only useful function now. It has no practical value for predicting new measurements. It’s a matrix of uncountable dimensions that we cannot even fill in values for. However, it will persist as long as we find it useful to keep writing it down, and it will continue to describe the probability for anyone not yet entangled with the system until they open the box and take a look at the cat. Until then, it still describes their epistemological state but no longer describes a potential uninstantiated alternate reality. That path is now permanently closed. (So hopefully the cat is still alive).

Let us now think about the inner wave function describing a carefully controlled state. It will describe objective uncertainty and quantum phenomena such as superposition. Now, if we know what basis a previous measurement used, we will know what on what basis to perform an orthogonal measurement, and we will be able to erase the previous result. Problems will arise as soon as any interactions not fully under our control become involved, however[14]. We will not know the basis of measurement for a random micromeasurement, so we will not know what basis is orthogonal to it. (Think of the position and momentum measurements made by the two-particle detector). And given that each micromeasurement causes its own reduction of the internal wave function, things can get out of control very quickly. We will have “too many witnesses”, each with a slightly different perspective. There will be a myriad of separate, slightly imperfect, records of the event. With a macroscopic number of “witnesses”, even if each of them only has a partial “memory” of the event, when taken together, they represent a permanent record that the event took place. We are now dealing with thermodynamic irreversibility. To erase a macroscopic result, we would have to, in effect, reassemble the dead version of Schrödinger’s cat one subatomic particle at a time.

5.4. The new Wigner's friend thought experiment

Before moving on to the next section, let us take a brief look at 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 a couple of 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 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 a micro-observer, then Bob can erase her result. Or as we clarify in the next section, 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" answer. Does the interpretation allow superluminal causation? Yes, but only hidden variables are affected. Is there a wave function collapse? No, for the standard wave function that describes the outer perspective. Yes, for the inner wave function, which is reduced with every new entanglement. However, we argue that there is no information loss, as nothing is actually erased. Finally, macroscopic observations are absolute and cannot be erased or rehidden in practice. Thermodynamic irreversibility prevents this. Micro-observations are not absolute, as their results can be rehidden, but even they cannot be truly erased, and this is the topic to which we now turn.

6. Not erased, just rehidden

Until this point, we have addressed the question of erasability as a question of being able to measure on an orthogonal basis. 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. Having multiple micromeasurements instead of one macroscopic measurement to erase just makes this task significantly more difficult to accomplish than one might have expected. However, now we ask if we should even talk about "erasure". In the single hidden variable interpretation, all we really 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.

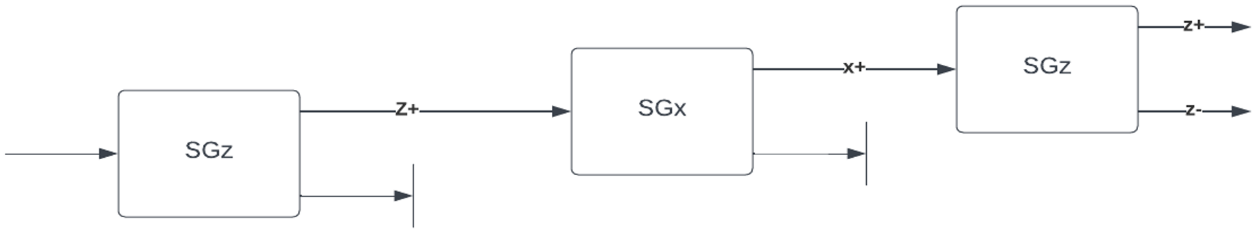

Figure 4. A sequential Stern-Gerlach experiment.

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:

$$|\psi\rangle = |z_+\rangle \qquad (27)$$

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

$$|\psi\rangle = \frac{|x_+\rangle + |x_-\rangle}{\sqrt{2}} \qquad (28)$$

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:

$$|\psi\rangle = |x_+\rangle \qquad (29)$$

Which is then subsequently best written as:

$$|\psi\rangle = \frac{|z_+\rangle + |z_-\rangle}{\sqrt{2}} \qquad (30)$$

What happened between equation (28) and equation (29)? Measurement and projection of course. But where did the information regarding the previous measurement go? It “disappeared” into the wall hit by the $|x_-\rangle$ beam. Similar to 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 suppose 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 truely 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 don't 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 the "particle" does not travel. It should not be surprising then that the system can communicate information to an object on the sterile path as well.

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. The "ideal" target for what we will call this "ghost" electron would be a one where it could exactly cancel out an $|x_-\rangle$ state and leave the target in an $|x_+\rangle$ state. An electron in the state:

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

Would be the ideal target. All the hidden spin values 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, when it eventually does hit a target, leaves an $|x_+\rangle$ state there, while carrying no energy. Of course, it is unlikely to find such an ideal target, so the result would just be a general positive y-axis torque. Just as in the case of the entangled photons, we hypothesize that a basis rotation propagates along the entire length of both potential electron paths. However, with no real electron on the sterile path to receive the torque, the effect would instead be manifested in the target, perhaps in other particle spin states, or perhaps even 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 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 would involve photon spin information. Suppose we split a vertically polarized photon into a LHC polarized beam and a RHC polarized beam. We block the RHC polarized beam and direct the other at a tiny target. If the live photons can be induced to produce a measurable change in angular momentum in the target, then perhaps the ghost photons can as well. The difference would be that the ghost photons, carrying 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, it does not seem impossible that with enough interactions, a macroscopic effect could be produced. This would constitute experimental verification of a unique prediction of this interpretation.

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 (27) to the new value in (29) and deposit information about the original answer in the wall; somewhere we cannot retrieve it. Thus, although the distinction between erasing information and rehiding information does not change the border line between micro-observations and macroscopic observations, it does render that question unimportant, we believe, to the larger question of "What is a measurement?"

If we want our definition of a measurement to stipulate that results cannot be rehidden, then 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. We prefer to simply define micromeasurements as measurements. This interpretation explains how macroscopic observations can be truly nonerasable. One 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.

7. Summary

We treat all new entanglements as micro-observations from an "inside" perspective. These observations transform objective uncertainty into subjective uncertainty on the basis measured but leave values on other potential bases of measurement objectively undetermined. This transformation of uncertainty is invisible from outside the system. If we look again at equation (4):

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

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

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 basis of measurement to match the experimenter's basis of measurement and reorient the tail end of the biparticle along with them, even nonlocally.

Micro-observations are simply particle interactions where the particles exchange allowable bits of random hidden information and obey the Born rule. They might, for example, alter each other's basis of rotation. Macroscopic observations should not be treated as projections onto a basis. Rather, the observer simply gains access to the interior wave function and finds a statistical result built up from many micro-observations.

Micro-observations can be "erased", and macroscopic observations cannot. However, we argue that "erasure" is really the wrong term in this interpretation. Information is instead rehidden and replaced by a new value. Thus, if the definition of 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 cannot then subsequently be truly erased, then micromeasurements are, in fact, just measurements.

This gives us an interpretation of quantum mechanics that avoids difficult ideas such as nonabsolute events, many-world hypotheses, superdeterminism, information loss, (outer) wave function collapse and superluminal causation (affecting nonhidden variables). It intuitively explains the results of the quantum eraser experiment, and it offers a theory of nonlocality. Finally, it offers a proposed solution to the measurement problem.

A challenge for future research would be detailing how this interpretation would deal with observables with continuous eigenvalues, such as momentum. Another challenge would be to attempt to verify it experimentally. Additionally, if this QM interpretation is successful, a larger challenge would be to develop a QFT version of it.

Table of Figures

- Fig. 1 – Diagram of the experimental apparatus discussed here and in (Hobson, 2022). Reprinted from (Hobson,2022). Copyright © 2022 Art Hobson. Open access article distributed under the Creative Commons Attribution License.
- Fig. 2 – Diagram of the delayed choice quantum eraser experiment. Original work by Patrick Edwin Moran – CC BY-SA 4.0, https://commons.wikimedia.org/wiki/File:KimDelayedChoiceQuantumEraserGraphsSVG.svg
- Fig. 3 – Results of (Kim, Yu, Kulik, Shih, & Marlan, 2000) relabeled for our Alice and Bob experiment. Relabeled version of original work by Patrick Edwin Moran - CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=31312077
- Fig. 4 – A sequential Stern-Gerlach experiment. Our own work. Created with Lucidchart.

Statements and Declarations

No competing interests or financial support are declared.

Footnotes

[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 “micro-observations" 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, entangled 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, and in that they can be easily erased. Performing a new observation on an orthogonal basis to an existing micromeasurement will destroy 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.

[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.

[5] This is not the first suggestion that decoherence can solve the measurement problem (Bacciagaluppi, 2020), and while we do not completely agree with the presentation in (Hobson, 2022), it a good jumping off point for our discussion here, since it was while trying to understand the claim in (Hobson, 2022) that we had the idea for this paper.

[6] In effect what we have done is to assume that Alice and Bob are initially measuring on a pure state basis, before any phase shift is introduced by Bob. This will not be the case in general, but it makes the example pedagogically simpler.

[7] 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.

[8] 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.

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

[10] This toy model is also arrived at in (Argaman, 2010).

[11] (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."

[12] 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.

[13] (Fankhauser, 2017) goes into extensive detail here.

[14] Commonly known as decoherence.

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

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