Published in *Contemporary Physics* on 28 November 2017.
Link to this article: https://doi.org/10.1080/00107514.2017.1401368

Review and suggested resolution of the problem of Schrodinger's cat

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Abstract

This paper reviews and suggests a resolution of the problem of definite outcomes of measurement. This problem, also known as "Schrodinger's cat," has long posed an apparent paradox because the state resulting from a measurement appears to be a quantum superposition in which the detector is in two macroscopically distinct states (alive and dead in the case of the cat) simultaneously. Many alternative interpretations of the quantum mathematical formalism, and several alternative modifications of the theory, have been proposed to resolve this problem, but no consensus has formed supporting any one of them. Applying standard quantum theory to the measurement state, together with the analysis and results of decades of nonlocality experiments with pairs of entangled systems, this paper shows the entangled measurement state is not a paradoxical macroscopic superposition of *states*. It is instead a phase-dependent superposition of *correlations between states* of the subsystems. Thus Schrodinger's cat is a non-paradoxical "macroscopic correlation" in which one of the two correlated systems happens to be a detector. This insight resolves the problem of definite outcomes but it does not entirely resolve the measurement problem because the entangled state is still reversible.

Keywords: quantum measurement, problem of definite outcomes, Schrodinger's cat, quantum entanglement, quantum nonlocality, quantum correlations.

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1. The measurement problem

Quantum state collapse is a standard principle of quantum physics. Given a quantum (e.g. a quantum object such as a photon, electron or atom) described by a superposition of eigenstates of some observable operator **O**, the principle asserts that a "measurement" of **O** must yield an eigenvalue of **O** and that the measurement causes the state of the quantum to collapse, or jump, into the corresponding eigenstate. This raises a host of questions: What exactly do we mean, physically and mathematically, by a "measurement" of a quantum? Does the collapse occur all at one instant? Wouldn't an instantaneous collapse contradict special relativity? If the collapse occurs during a time interval, then what equation describes this time-evolution? Quantum states are presumed to follow the Schrodinger equation, which prescribes a continuous time evolution; how can instantaneous state collapse be reconciled with this smooth evolution? And how can we resolve the "problem of outcomes" that appears to arise when a superposed quantum's (e.g. a photon or electron or atom) state is measured by a "which-state" detector, creating a so-called entangled state of the quantum and detector that appears to be an indefinite superposition of two macroscopically distinct states of the composite system?

Such questions comprise the quantum measurement problem, surely quantum physics' most enduring puzzle and, according to some, an unsolvable logical paradox. Many alternative interpretations of the quantum physics mathematical formalism, and several alternative modifications of the theory, have been proposed to resolve this problem, with no consensus on a solution. It is remarkable that, despite the unparalleled experimental success of quantum theory across a vast range of experiments, most of these suggested solutions differ from standard quantum physics in one or more significant respects. Most of them involve new interpretations of the standard mathematical formalism, interpretations such as "human minds collapse the quantum state" or "all the possible collapses occur but only one of them occurs in our particular universe" or even a rejection of the physical reality of the quantum world and the assumption that quantum probabilities (and hence changes in those probabilities, such as quantum state collapse) are mere measures of personal degrees of belief. Other suggestions assume modifications of the standard mathematical formalism, such as an additional mechanism that causes quantum states to spontaneously collapse from time to time, or new "hidden" and hence uncontrollable variables that create the illusion of quantum randomness. This paper describes the measurement problem and suggests a resolution of the problem of definite outcomes that lies entirely within standard quantum physics.

This paper does not entirely resolve the measurement problem. The measurement problem comprises two more-or-less independent conundrums: the problem of definite outcomes and the problem of irreversibility, i.e. the problem of making a macroscopic record of one outcome. This paper suggests a resolution of the former but not the latter.

Let's begin with the question of definitions. What do we mean, physically, by a quantum measurement? The great John Bell railed against the very use of this term. He was the theorist who first gave us, in 1964, a practical mathematical condition ("Bell's inequality") that a probabilistic theory must satisfy if it is to be considered "local," meaning that the theory allows no unmediated or instantaneous physical action at a distance. Furthermore, he showed that standard quantum physics fails this test [1]. This validated the much earlier conclusion of Einstein and others that standard quantum physics makes nonlocal predictions in certain specific physical situations [2]. Bell's last publication prior to his untimely death in 1990 [3], provocatively titled "Against Measurement," urged that this term "should now be banned altogether in quantum mechanics." Bell complained that quantum physics concerns itself exclusively with "measurements" made in laboratories, and that "to restrict quantum mechanics to be exclusively about piddling laboratory operations is to betray the great enterprise. A serious formulation will not exclude the big world outside the laboratory" [3].

I agree that we need a non-anthropomorphic definition of the concept known as "measurement," but rather than ban this widely-used term, let's just broaden its physical definition to include Bell's "big world" as follows: A "quantum measurement" means any quantum process that results in a macroscopic effect, regardless of whether humans or laboratories are involved. Thus not only is an electron striking a laboratory viewing screen and creating a visible flash a measurement, a cosmic-ray muon striking and macroscopically moving a sand grain on a planet in some other galaxy is also a measurement.

To analyze measurement, let's look at a specific experiment: An electron beam passes through a pair of double slits (two narrow closely-spaced parallel slits cut into a partition) and then impacts a viewing screen. This might be physicists' most popular experiment; it was described by Richard Feynman as "a phenomenon which is impossible ... to explain in any classical way, and which has in it the heart of quantum mechanics" [4]. Just as in Thomas Young's similar double-slit experiment using light, performed in 1801, the pattern formed on the viewing screen shows interference between the two portions of the electron beam coming through the two slits: A broad dark-and-bright striped pattern diffracts (spreads out) widely on the screen, much wider than the slits, indicating regions of destructive (dark) and constructive (bright) interference [5]. On closer inspection, the bright lines are formed by zillions (my word for a really large number) of tiny individual electron impacts, each one making a small flash on the screen [6]. According to our above definition, each flash is a measurement of the position of an electron as it hits the screen.

Experiments like this make us wonder whether electrons are tiny particles or waves in a continuous spatially-extended field: We see particle-like behavior in the individual flashes, and wave-like behavior in the interference pattern made by zillions of flashes. As I have argued elsewhere [7], this and many other experiments are impossible to explain by assuming electrons are small particles. Instead, *each electron* is a spatially extended bundle of energy that comes through both slits and interferes with itself at the viewing screen. Slowed-down experiments in which electrons come through the slits one at a time demonstrate this [6]. Just prior to impact, each electron is extended over the entire extent of the interference pattern. The interaction between each electron and the atoms of the screen then collapses each electron to atomic dimensions. Although each individual electron must ultimately be conceptualized as a wave in a universal "matter field" or "psi field" (the official term is "electron-positron field"), the experiment displays both wave and particle aspects (Chapter 5 of [8]). Similar effects occur in Young's interference experiment with light, but with non-material photons replacing the material electrons.

Each electron's flash on the screen is a measurement. But for purposes of analysis, it's better to consider a related example of a measurement, still based on the double-slit experiment. Suppose an electron detector is installed at the slits, a detector that can detect the electron's position as it passes through the slits while disturbing each electron only minimally (in the precise sense described below).

Measurement, even by a minimally-disturbing "which-path detector," changes everything. Exactly when the detector turns on, the pattern on the screen changes from the striped interference pattern to a smoothly-spread-out sum of two single-slit patterns, each showing diffraction but no interference. The interference pattern abruptly vanishes. So far as I know, this experiment showing the jump from interference to non-interference has not been performed with electrons but there is little doubt how it would turn out. The analogous experiment has been done using light (photons) instead of electrons, and using an interferometer rather than a double-slit interference setup. A which-path detector was randomly switched on or off as each photon passed through this experiment; the photons for which the detector was "off" formed an interference pattern while the photons for which the detector was "on" formed the expected non-interference pattern [9]. In this so-called "delayed-choice experiment," the collapses were instantaneous to within the accuracy of the fast switching between the two states; each collapse was executed entirely while the photon was inside the interferometer.

We can gain considerable insight by studying how quantum theory describes this which-path measurement (pp. 63-5 of [10]). Note that this is in fact a measurement as defined earlier, because the detector registers "slit 1" or "slit 2" macroscopically for each electron. Using the formulation of quantum physics that describes states as vectors in a mathematical Hilbert space, let's denote the state of one electron passing through slit 1 as $|\psi_1\rangle$ and the state of one electron passing through slit 2 as $|\psi_2\rangle$. John von Neumann, the first to carefully analyze measurement in purely quantum-theoretical terms [11], insisted on treating not only the measured quantum but also the macroscopic detector as a quantum system because, after all, detectors are made of atoms and they perform a quantum function by detecting individual quanta.

Accordingly, let's represent the "ready to detect" quantum state of the detector by $|\text{ready}\rangle$, and the state of the detector after detecting an electron by $|1\rangle$ if $|\psi_1\rangle$ was detected, and by $|2\rangle$ if $|\psi_2\rangle$ was detected. A properly operating detector will surely transition from $|\text{ready}\rangle$ to $|1\rangle$ upon measurement of an electron that has been prepared (perhaps by simply shutting slit 2) in state $|\psi_1\rangle$. As a limiting idealization, let's assume, with von Neumann, that measurement of an electron prepared in state $|\psi_1\rangle$ leaves the electron still in state $|\psi_1\rangle$ after detection. Such a minimally-disturbing measurement would cause the electron-plus-detector composite system, initially in the composite state $|\psi_1\rangle|\text{ready}\rangle$, to transition into the final state $|\psi_1\rangle|1\rangle$. We can summarize this process as

$$|\psi_1\rangle|\text{ready}\rangle \Rightarrow |\psi_1\rangle|1\rangle. \qquad (1)$$

Similarly, the minimally-disturbing measurement of an electron initially prepared in $|\psi_2\rangle$ is described mathematically by

$$|\psi_2\rangle|\text{ready}\rangle \Rightarrow |\psi_2\rangle|2\rangle. \qquad (2)$$

Now suppose both slits are open so each electron can pass through either slit, and suppose the preparation and the experiment (e.g. the slit widths) is symmetric with respect to the two slits. Then the state of each electron as it approaches the slits prior to detection must be described by the symmetric superposition

$$|\psi\rangle = (|\psi_1\rangle + |\psi_2\rangle)/\sqrt{2} \qquad (3)$$

where the $1/\sqrt{2}$ factor is required for normalization. But quantum physics, including its time dependence, is linear. Thus (1) and (2) imply that $|\psi\rangle|\text{ready}\rangle$ evolves according to

$$|\psi\rangle\,|\text{ready}\rangle \Rightarrow (|\psi_1\rangle|1\rangle + |\psi_2\rangle|2\rangle)/\sqrt{2}, \qquad (4)$$

The final state

$$|\Psi\rangle = (|\psi_1\rangle|1\rangle + |\psi_2\rangle|2\rangle)/\sqrt{2} \qquad (5)$$

following the detection is said to be "entangled" because it cannot be factored into a simple product of states of the two sub-systems. Quantum entanglement is a large complex topic (Chapter 9 of [8]). As indicated schematically in Figure 1, when two independent quanta pass near each other, interact, and subsequently separate, the interaction generally entangles the two quanta and the entanglement then persists after the interaction regardless of how far apart the two quanta might eventually travel, provided only that the two quanta experience no further interactions. Despite their possibly wide spatial separation, entangled quanta have a unity not possessed by non-entangled quanta. This unity is the source of quantum non-locality, as I'll discuss later. Entanglement is ubiquitous in nature; for example, the electrons in any many-electron atom or molecule are entangled with each other [12]. Erwin Schrodinger has said that quantum entanglement is "*the* characteristic trait of quantum mechanics" (the emphasis is Schrodinger's) [13].

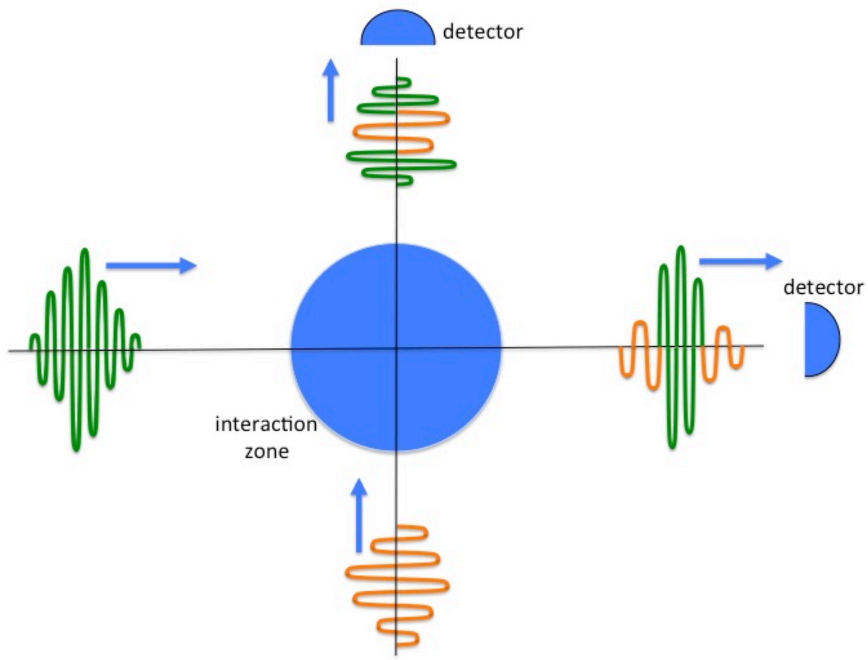

Figure 1. When the green quantum on the left interacts with the orange quantum at the bottom, their two spatially-extended quantum states entangle with each other to form a single "bi-quantum" (the two green-and-orange quanta form a bi-quantum). This highly unified composite state has non-local characteristics.

The entangled "measurement state" (5) at the heart of quantum measurement is remarkably subtle. To grasp it, we first need to understand quantum superpositions. A key quantum principle says that any linear combination of possible quantum states of a system, as in (3) and (5) for example, is also a possible quantum state of that system. Figure 2 pictures an experiment that demonstrates such a superposition of states. It shows a layout of optical paths called a "Mach-Zehnder interferometer." A light beam enters at the lower left by passing through a "beam splitter" BS1; this is a small plate of glass (shown edge-on in Figure 2) angled at 45 degrees so that the reflected beam makes a right angle with the incoming direction while the transmitted beam passes straight through (with refraction at the two surfaces). It's designed to reflect 50% and transmit 50% of the incident light. So the beam splits and each half traverses one of the two paths; mirrors M bring the paths back to a crossing point as shown. Devices called "phase shifters," denoted by φ_1 and φ_2, are placed into each path. A phase shifter can add a short variable length to a path, perhaps by using mirrors. A second beam splitter BS2 can be placed at the crossing point. Without BS2, each half-beam moves straight ahead along one path to the detector on that path.

Things get more interesting with BS2 in place. Because 50% of each of the two beams then goes to each detector, BS2 mixes the two beams together so they can show interference. The interferometer is constructed so that, when the phase shifters are set to zero, the two "optical paths" (the number of wavelengths, after accounting for phase changes upon reflection and refraction) from the entry point to D1 are equal while the two optical paths to D2 differ by half a wavelength. It is then found that the light interferes constructively at D1 and destructively at D2, so all the light goes to D1. If we then use φ_1 or φ_2 to add half a wavelength to either path, light then interferes constructively at D2 and destructively at D1 so all the light goes to D2. And as we continuously vary the length of one or the other path by varying one or the other phase shifter, we find the amount of light arriving at D1 varies continuously from 100% down to 0%, while the amount arriving at D2 varies from 0% to 100%. The two paths are clearly interfering. This experiment is the interferometer-based analog of Young's double-slit interference experiment demonstrating the wave nature of light.

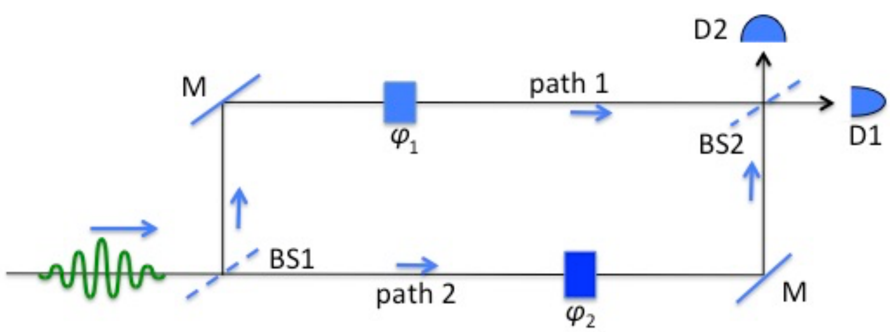

Figure 2. A Mach-Zehnder interferometer can demonstrate the interference of light when both beam splitters are present and the phase shifters alter the length of either path. But light is made of indivisible photons. What happens when only one photon is present?

But light is made of photons, and photons are indivisible. So how does nature solve this problem when we dim the light to the point where only one photon at a time traverses the interferometer? After all, the photon still traverses BS1, yet it cannot split in two because a quantum is unified and can't be split. With BS2 removed, we find either D1 or D2 registers a single entire photon, *randomly,* i.e. with 50-50 probabilities, regardless of how the phase shifters are set. Careful tests verify this randomness as absolute, i.e. more random then any human macroscopic game, such as coin flips, that mimics randomness. Nature invents quantum randomness in order to deal with obstacles such as beam splitters while preserving the unity of the quantum (Chapter 6 of [8]). Detectors never register half a photon. You get either a whole photon or no photon.

What happens in the single-photon experiment with BS2 present? Beginning from path lengths yielding constructive interference at D1 and destructive interference at D2, as the phase shifters vary *the probabilities of detecting the photon at D1 and D2 vary* as in

Figure 3, which shows the percentage of photons impacting D1. Importantly, these results don't depend on which phase shifter the experimenter chooses to vary. Since each photon responds to changes in either path length, each photon must follow both paths! This verifies the superposition principle and shows that quanta can be in two places at the same time. This is paradoxical if you assume photons are tiny particles, but if you assume photons are waves in a universal field it's not paradoxical: Each photon simply spreads along both paths, interfering with itself at D1 and D2 [7].

The interferometer experiment of Figure 2 can be performed with atoms and even molecules, with the same results: Atoms and molecules can be superposed along two paths, and can interfere with themselves just as photons can. So these objects are also waves in fields, not tiny particles. Search on "atom interferometry" for more information.

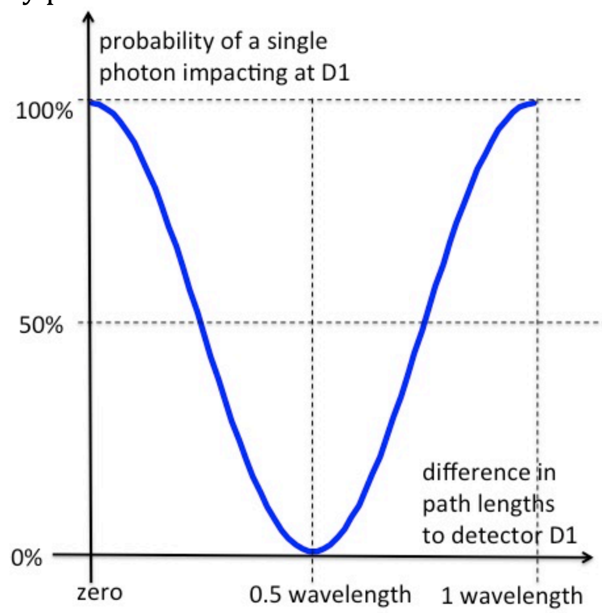

Figure 3. Evidence of quantum superposition in the experiment of Figure 2 with BS2 inserted. Each photon must follow both path 1 and path 2 because these probabilities vary no matter which phase shifter is varied.

Furthermore, we must conclude that each photon travels both paths even when BS2 is not present to directly verify this, because once a photon enters the interferometer it must behave in the same manner regardless of whether BS2 is placed or not placed at the far end. Jacque et al's delayed-choice experiment [9] referred to above provides further evidence for this conclusion: Since these photons "do not know" whether BS2 will be inserted, they must travel both paths on all the trials including those for which BS2 is not inserted.

This is connected with entanglement. With BS2 removed, the situation is like the double-slit experiment with a which-slit detector present: Each photon is entangled with macroscopic detectors D1 or D2 as in the right side of (5). With BS2 present, the two paths mix and the situation is like the double-slit experiment with no which-slit detector: each photon follows two paths to each detector where it interferes with itself, and we detect the interference state (3).

All of this suggests that *measurements collapse superposed quantum states via entanglement of the superposed quantum with a detector*.

2. The apparent paradox of Schrodinger's cat

It's physicists' favorite tale. As Schrodinger told it [14]:

> One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following device (which must be secured against direct interference by the cat): In a Geiger counter there is a tiny bit of radioactive substance, so small, that *perhaps* in the course of the hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives *if* meanwhile no atom has decayed. The psi-function of the entire system would express this by having in it the living and dead cat (pardon the expression) mixed or smeared out in equal parts.
>
> It is typical of these cases that an indeterminacy originally restricted to the atomic domain becomes transformed into macroscopic indeterminacy, which can then be *resolved* by direct observation. That prevents us from so naively accepting as valid a "blurred model" for representing reality.

Mathematically, the nucleus and cat have become entangled in the measurement state (5), with $|\psi_1\rangle$ and $|\psi_2\rangle$ representing the undecayed and decayed states of the nucleus and $|1\rangle$ and $|2\rangle$ representing the alive and dead cat. According to Schrodinger's understanding of the situation, the indeterminacy of the nuclear state "becomes transformed into macroscopic indeterminacy" of the cat, and we cannot comfortably accept this as a "blurred" state--a cat that is in a superposition of being both alive and dead. This paper will show that, according to standard quantum physics, Schrodinger's 1937 understanding was incorrect: The composite system (cat-plus-nucleus) is not predicted to be in a superposition of two *states* of the cat, or nucleus, or composite system. Instead, the composite system is predicted to be in a superposition of two *correlations between* the cat and nucleus, one in which a live cat is 100% correlated with an undecayed nucleus, and the second in which a dead cat is 100% correlated with a decayed nucleus. Entanglement has transformed a pure state superposition of nuclear *states* to a pure state superposition of *correlations between* subsystem states. We will see that this is precisely what one expects, and is not paradoxical.

The problem of definite outcomes applies of course to more than Schrodinger's dramatized example. Regardless of whether the measuring instrument is a which-slit detector, a Geiger counter, or a cat, the entangled state (5) applies. This state appears at first glance to represent a quantum superposition in which the detector is in two macroscopically different states simultaneously. If so, then there is an inconsistency within quantum physics, because it obviously cannot be this easy to create a macroscopic superposition.

Is it true that (5) really represents a macroscopic superposition? There is more to this entangled state than meets the eye. If you assume the detector to be in a superposed state $a|1\rangle + b|2\rangle$ where a and b are complex constants, you soon find that (5) necessitates either a=0 or b=0 [15], implying that the detector is not in an individually superposed state within its own Hilbert space. The same applies to the detected quantum: It is not in a superposed state $a|\psi_1\rangle + b|\psi_2\rangle$ with both $a\neq 0$ and $b\neq 0$. The entanglement process leaves neither sub-system superposed! So far as I know, this simple fact has long been ignored by analysts of the measurement problem.

The density operator formalism for quantum physics provides a stronger version of this conclusion. If you aren't familiar with density operators, you can find a straightforward presentation in Section 2.4 of [10]. The density operator for a quantum system whose state is $|\psi\rangle$ is simply the projection operator

$$\boldsymbol{\rho} = |\psi\rangle \langle\psi|. \tag{6}$$

If a system is in a state whose density operator is $\boldsymbol{\rho}$, then the standard quantum expectation value $\langle\mathbf{O}\rangle$ of an arbitrary observable $\mathbf{O}$ is found from

$$\langle\mathbf{O}\rangle = \mathrm{Tr}\,(\boldsymbol{\rho}\mathbf{O}) \tag{7}$$

where "Tr" represents the trace operation (the sum of the diagonal elements). This approach is especially useful if the quantum system is a composite of two subsystems A and B. Define the density operator $\boldsymbol{\rho}_\mathbf{A}$ for subsystem A alone by

$$\boldsymbol{\rho}_A = \mathrm{Tr}_B\, \boldsymbol{\rho} \tag{8}$$

where " Tr_B" means that the trace is taken only over the states of subsystem B. It is then easy to show [10] that the standard quantum expectation values for subsystem A alone (the values obtained by an observer of A) are

$$\langle\mathbf{O_A}\rangle = \mathrm{Tr}\,(\boldsymbol{\rho}_\mathbf{A}\mathbf{O_A}) \tag{9}$$

where $\mathbf{O_A}$ means any observable operating on system A alone (i.e. operating within A's Hilbert space).

Applying this formulation to the measurement state (5), the reduced density operators for the quantum system (call it A) and its detector (call it B), respectively, are

$$\boldsymbol{\rho}_\mathbf{A} = (|\psi_1\rangle \langle\psi_1| + |\psi_2\rangle \langle\psi_2|)/2, \tag{10}$$

$$\boldsymbol{\rho}_\mathbf{B} = (|1\rangle \langle 1| + |2\rangle \langle 2|)/2. \tag{11}$$

The plus signs in (10) and (11) make one think of superpositions such as (3), but these are not superpositions. The density operator for (3) has cross-terms:

$$\boldsymbol{\rho} = |\psi\rangle \langle\psi| = (|\psi_1\rangle \langle\psi_1| + |\psi_1\rangle \langle\psi_2| + |\psi_2\rangle \langle\psi_1| + |\psi_2\rangle \langle\psi_2|)/2. \tag{12}$$

The two cross-terms, involving both $|\psi_1>$ and $|\psi_2>$, are missing from (10). So (10) does not describe a system in a superposition of two quantum states. However, (10) is precisely the density operator you should use if you know the quantum system is either in state $|\psi_1>$ or in state $|\psi_2>$ but you didn't know which and so, due your own to lack of information, you simply assign a probability of 1/2 to each of these two possibilities (Section 2.4 of [10]). The same goes for (11). (10) and (11) are "classical" probabilistic states--analogous to the "states of knowledge" you would assign to a coin flip when you know the outcome to be either heads or tails with equal probability but you don't know which. The situation described by a density operator such as (10) is known as a "mixture" of the states $|\psi_1>$ and $|\psi_2>$, as distinct from the "superposition" of states observed in the experiment of Figure 2 and represented by (3).

Equation (9) tells us that all the correct statistics for subsystem A alone can be found from the standard formula (7) applied to subsystem A alone. But we have just seen that (10) is the density operator one should use if one knows A to be in either $|\psi_1>$ or $|\psi_2>$ without knowing which. The same goes for subsystem B and (11). In the case of Schrodinger's cat, it follows that *an observer of the cat alone sees outcomes appropriate to a cat that is either alive or dead,* not both. For subsystems, the interference terms are missing, and an "ensemble" of repeated trials must exhibit a nonsuperposed mixture rather than a superposion. This is the clear prediction of quantum physics for the entangled state (5). Others have long come to the same conclusion (see pp. 183-185 of [16], also [17]).

But we must be careful, because (10) and (11) are not complete descriptions of the quantum states of the nucleus or the cat. In fact, (10) and (11) are not quantum *states* at all but merely "reduced states" arising from the actual state (5) of the composite system. In the case of Schrodinger's cat, (10) and (11) give the correct *predictions* for observations of either the nucleus alone or the cat alone, but they do not represent the *state* of either subsystem because this is given by (5). In fact, when two quanta are entangled, neither one *has* a quantum state of its own (Figure 1)!

Physicists, philosophers and mathematicians who specialize in quantum foundations have in the past objected to the argument that reduced density operators can be adduced in this manner to clarify the measurement problem. They offer two key objections (Section 2.4 of [10]): The first, "basis ambiguity," charges that the "basis set" (the set of orthogonal eigenvectors) for the operator (11) (for example) is entirely ambiguous, so (11) cannot represent a true quantum state. It's true that (11) doesn't represent the true state of a subsystem, because (11) is actually just the identity operator $|1> <1| + |2> <2|$ in B's subspace, divided by 2, so that any other orthogonal basis set could be used instead. For example, given only the description (11), subsystem B could just as well be described by any other pair of orthonormal vectors in B's subspace, for example $(|1> \pm |2>)/\sqrt{2}$. But B's state of affairs is certainly *not* entirely described by (11). Rather, it is described by the composite state (5). Equation (11) merely tells us the following: If the cat and nucleus are in the state (5) then, when one looks at the cat, one is going to see a cat that is either alive or dead. There is no claim that (11) represents the complete quantum state of the cat. That is, there is no claim that the cat is really in either the state $|1>$ or the state $|2>$, because the state it's really in is admittedly (5). Thus the basis ambiguity objection to our conclusion (namely, that Schrodinger's cat is either alive or dead, not both) fails.

The second key objection is that (10) and (11) are "improper density operators" because they arise not from insufficient knowledge (as classical probabilities arise) but from reductions of the full density operator (5) to the Hilbert subspaces of each subsystem. It's true that these reduced density operators do not arise from insufficient knowledge about the actual state. In fact we have complete knowledge of the state of both A and B, namely the measurement state (5). So the objection fails not because it is false but because it is irrelevant: The reduced operators admittedly do not represent the state of the composite system. They tell us what we will observe at the nucleus and at the cat, but they tell us nothing about the correlations between these observations, so these density operators do not tell us the real state of the system.

3. The unity of the quantum

And so the plot thickens. The entangled state (5) properly describes both individual subsystems. However, the plus sign in (5) signifies a superposition of the two terms, yet we know that neither subsystem A nor subsystem B is superposed. What is the meaning of this plus sign? This superposition arose from the superposition represented by (3). We cannot logically ignore it--a strategy known as the "shut up and calculate" approach to quantum measurement. Instead, we must ask: Exactly what is superposed when two subsystems are in this entangled state?

Superpositions preserve the all-important unity of the quantum. When Max Planck proposed in 1900 that electromagnetic radiation occurs in energy steps of magnitude E = hf, he tacitly implied the central quantum principle: The unity of an individual quantum. Energy (electromagnetic energy in the case of radiation) comes in spatially extended bundles, each having a definite and identical quantity of energy. You can't have half a quantum, or 2.7 quanta. You must have either 0 or 1 or 2 etc. quanta. In its own way, this is a fairly natural notion--apparently nature prefers to sub-divide the universe into a countable or even a finite set of entities as opposed to an uncountable continuum. The spatial extension of these bundles then entails nonlocality: If you have one quantum and you destroy it (by transforming it to something else), you must destroy all of it everywhere simultaneously, because you can't at any time have just part of a quantum. Louis de Broglie put it perfectly in 1924, regarding another kind of quantum namely the electron:

> The energy of an electron is spread over all space with a strong concentration in a very small region. ...That which makes an electron an atom of energy is not its small volume that it occupies in space--I repeat it occupies all space--but the fact that it is undividable, that it constitutes a unit. [18]

When you transform the state of a quantum, you've got to transform the entire extended quantum all at once. Hence there are quantum jumps. Furthermore, composite entangled systems such as atoms also behave in a unified fashion. This unity is also the source of the nonlocality seen in experiments involving entangled pairs of photons. Nonlocality is exactly what one would expect, given the unity and spatial extension of the quantum and the unitary (i.e. unity-preserving) nature of the entanglement process.

Standard nonrelativistic quantum theory prescribes two kinds of time evolution: collapse upon measurement, and the Schrodinger equation between measurements. A key feature of the Schrodinger equation is that it prescribes a so-called "unitary" time evolution, meaning time evolution that preserves pure states, i.e. transforms unit Hilbert space vectors into other unit vectors. Again, this is required physically by the unity of the quantum: If a quantum is described by a pure quantum state at t=0, it should remain pure at later times. This notion prompts us to ask whether the measurement process also preserves pure states. At least in the case of the idealized process described in (4), the answer is "yes" because both the "before" and "after" states are pure.

The measurement state (5), since it is pure, represents a highly unified state of affairs, even though one of its subsystems is a macroscopic detector. Thus we suspect that this state, like its progenitor (3), is truly a superposition in which the superposed terms represent two situations or states of the same object. But precisely what is that object, i.e. what is superposed? We have seen that states of subsystem A are not superposed, nor are states of subsystem B. The conventional interpretation (which, as we will see, is subtly incorrect) of a product state such as $|\psi_1>|1>$ is that it represents a state of a composite system AB in which subsystem A is in state $|\psi_1>$ while B is in state $|1>$. In this case, (5) would represent a superposition in which AB is simultaneously in the state $|\psi_1>|1>$ and also in the state $|\psi_2>|2>$. The situation of Schrodinger's cat would be: a live cat and undecayed nucleus superposed with a dead cat and decayed nucleus. This is at least as physically outrageous as a live cat superposed with a dead cat, and it contradicts the physical implications (a cat that is either alive or dead) of the reduced states (10) and (11) as described in Section 2. Something is wrong.

The remainder of this paper will demonstrate that, according to standard quantum theory (and of course according to experiment), the measurement state (5) represents none of these paradoxical situations.

4. Experimental nonlocality and entanglement

The unity of the quantum suggests that the measurement state (5) represents a unified, hence superposed and pure, quantum state of the composite system. But precisely what is superposed? We studied the simple (i.e. non-composite) superposition (3) via the interference exhibited in the experiment of Figure 2. Varying the length of either path 1 or path 2 created varying interference effects in the detectors, demonstrating each photon really must travel both paths to its detector. Quantum theory agrees entirely with these conclusions, as can be shown by using photon wavelengths to show that the path differences correctly predict the interferences observed at each detector.

This suggests that, to understand the measurement state, we need to find and analyze entanglement experiments that demonstrate interference. As it happens, this has been done for several decades in connection with quantum nonlocality. The key theoretical analysis was done by John Bell [1]. Many nonlocal interference experiments have been done beginning with Clauser and Freedman [19], continuing with the definitive experiment of Aspect et al [20] and other experiments such as the two described below, culminating in experiments demonstrating nonlocality across great distances [21] and that simultaneously closed all possible loopholes in all the previous experiments [22] [23] [24]. By now, it is well known that the entangled state (5) predicts nonlocal effects between its two subsystems, and that phase variations of either subsystem cause instantaneous, i.e. non-local, readjustments of the possibly-distant other subsystem.

But it's not easy to vary the phase of a cat, and as we saw in the experiment of Figure 2, one cannot understand a superposition without varying the phases of its superposed parts. These nonlocality experiments are carried out with pairs of simpler quanta such as photons. The nonlocal entanglement experiments most appropriate for investigating measurement were conducted nearly simultaneously by Rarity and Tapster [25] and Ou, Zou, Wang, and Mandel [26]. Figure 4 shows the layout for these "RTO" (for Rarity, Tapster, and Ou) experiments. The "source" in Figure 4 creates entangled photon pairs by "parametric down- conversion," a process which needn't concern us here.

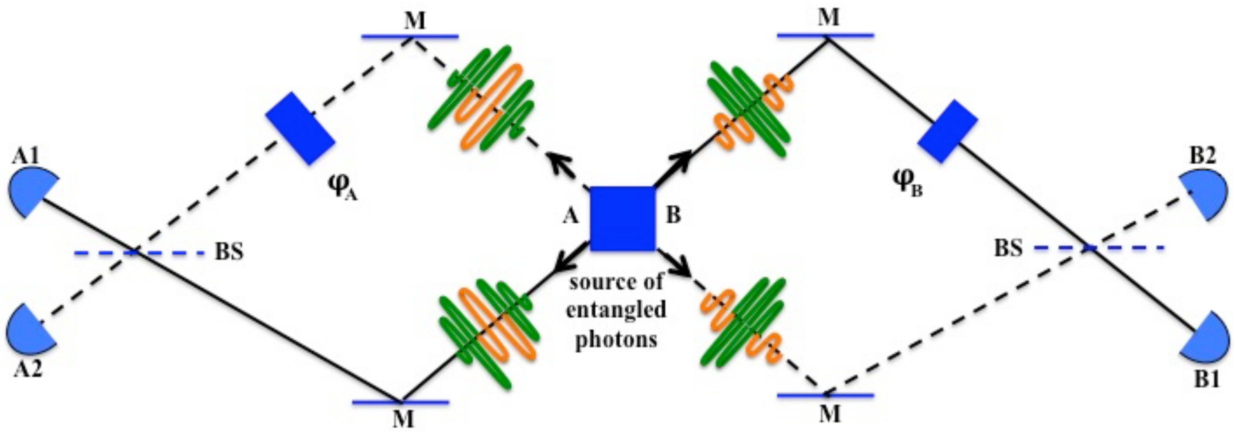

Figure 4. The RTO experiments provide an ideal portrait of entanglement. In each trial, the source emits two entangled photons A and B into a superposition of the solid and dashed paths to create an entangled state.

Compare this layout with Figure 2. The RTO experiment is two back-to-back interferometer experiments but with the first beam splitter for each photon located inside the source of entangled photons. Without entanglement, each single photon (either A or B) would interfere with itself at its own detectors according to its own phase shift φ_A or φ_B. The two entangled photons are emitted into a superposition of the solid path connecting detectors A1 and B1, and the dashed path connecting detectors A2 and B2. Note that the two photons are already entangled when they are emitted.

The entanglement changes everything. No longer does either photon interfere with itself at its own detectors. Instead, the photons are entangled in the measurement state (5) with $|\psi_1\rangle$ and $|\psi_2\rangle$ representing (say) the solid-line and dashed-line states of A and $|1\rangle$ and $|2\rangle$ representing the solid-line and dashed-line states of B, although in the RTO experiments neither subsystem is macroscopic. Each photon now acts like a which-path detector for the other photon. Recall the double-slit experiment: When a which-slit detector is switched on, the pattern on the screen switches abruptly from the striped interference pattern indicating the pure state nature of each electron across both slits, to a phase-independent sum of two non-interfering single-slit patterns. The entanglement between the electron and the which-slit detector breaks the pure state into two single-slit parts, so that the measured electron comes through either slit 1 or slit 2. This suggests that in the RTO experiment, the entanglement should break the pure-state superposition (3) into two non-interfering parts.

This is exactly what is observed. Both photons impact their detectors as random 50-50 mixtures, just like a flipped coin. The entanglement breaks the single-photon pure state (3) observed in the experiment of Figure 2, causing each photon to behave "incoherently" with no dependence on its phase setting.

But (5) is a pure state. Where has the phase dependence gone? The answer lies in the phase-dependent *but nonlocal* relationship observed between Figure 4's solid and dashed branches. This phase dependence is observed experimentally in coincidence (or correlation) measurements comparing detections of entangled pairs. The flipped coins mentioned above turn out to be correlated with each other. This phase dependence across the two separated subsystems is essential to preserve the unity of the (now entangled) quantum.

This is not an easy experiment to perform: The source creates a stream of photon pairs, and one must compare the impact of a single photon A at detectors A1, A2 with the impact *of its corresponding entangled photon B at detectors B1, B2.* RTO figured out how to do this, with the result shown in Figure 5.

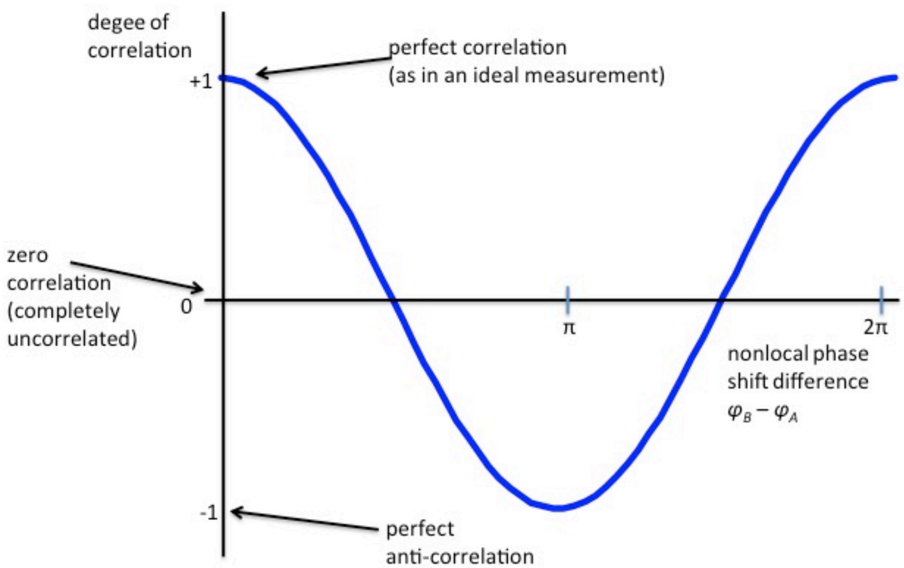

Figure 5. Nonlocal interference in the RTO experiments. As the nonlocal phase difference φ_B - φ_A varies, the "degree of correlation" (see text for precise definition) between A and B shows phase-dependent interference.

Figure 5 graphs the *degree of correlation* between A and B. This is a measure of the agreement between the outcomes at A's detectors and B's detectors. A correlation of +1 means perfect, or 100%, agreement: Either both sets of detectors register outcome 1 (i.e. A1 and B1 click) or both register outcome 2, as in a measurement: You want the which-slit detector to register "slit 1" if the electron is in state $|\psi_1>$, you want it to register "slit 2" if the electron is in state $|\psi_2>$, and you want this agreement on every trial. The opposite extreme is a correlation of -1, meaning 100% disagreement: If one detector registers 1, the other registers 2. Either correlation, +1 or -1, implies that either photon's outcome is predictable from the other photon's outcome. A correlation of zero means one photon's outcome does not at all determine the other's outcome: Each photon has a random 50-50 chance of either outcome regardless of the other photon. Correlations between 0 and +1 mean the outcomes are more likely to agree than to disagree, with larger correlations denoting a higher probability of agreement; for example, a correlation of +0.5 means a 75% probability of agreement. Similarly, correlations between 0 and -1 mean the outcomes are more likely to disagree than to agree; a correlation of -0.5 means a 75% probability of disagreement.

The RTO experiment agrees entirely with the predictions of standard quantum physics. When an accounting is made of the optical paths for both photons, we obtain the following result [27]:

$$P(correlated) = P(A1 \text{ and } B1) + P(A2 \text{ and } B2) = 1/2[1 + \cos(\varphi_B - \varphi_A)] \quad (13)$$

$$P(anticorrelated) = P(A1 \text{ and } B2) + P(A2 \text{ and } B1) = 1/2[1 - \cos(\varphi_B - \varphi_A)] \quad (14)$$

where *P(correlated)* is the single-trial probability that A's and B's detectors will agree, and *P(anticorrelated)* is the single-trial probability that A's and B's detectors will disagree. The degree of correlation, defined as *P(correlated) - P(anticorrelated)*, is then simply $\cos(\varphi_B - \varphi_A)$, as graphed in Figure 5.

In 1964, John Bell published a ground-breaking article stating a sufficient condition for a statistical theory such as quantum physics to meet the condition known as "locality." He defined locality to mean "that the result of a measurement on one system be unaffected by operations on a distant system with which it has interacted in the past" [1]. Bell expressed this sufficient condition in the form of an inequality (Eq. (15) of [1]) that any local theory must obey. He also demonstrated that certain statistical predictions of quantum physics violate Bell's inequality, i.e. quantum physics makes nonlocal predictions. The results in Figure 5 turn out to be a case in point: Figure 5 violates Bell's inequality at all phase differences $\varphi_B - \varphi_A$ other than 0, π, and 2π. Let me underline the meaning of this: The violation of Bell's inequality means that the statistics of measurements on photon A--photon A's "statistical behavior"--is necessarily affected by the setting of photon B's phase shifter.

In fact, even without Bell's condition, the nonlocality of this experiment is intuitively obvious. Here's why: Suppose we set the phase shifters to zero and that all four optical paths (two solid, two dashed) in Figure 4 are then equal; thus $\varphi_B - \varphi_A$ is zero. *Without* the two beam splitters BS, the two photons emitted into the solid pair and dashed pairs of paths would impact either detectors A1 and B1 or A2 and B2 because of the symmetry of the experiment and conservation of momentum. This is neither surprising nor nonlocal, and would happen even if the photons were not entangled. But a beam splitter is a randomizing device that mixes the solid and dashed paths; any photon passing through it has a 50-50 chance of reflection or transmission. With non-entangled photons and both beams splitters in place, there would then be no correlation between photon A's outcome and B's outcome because the two photons are independent of each other. With entanglement, the correlation is perfect. How does one photon know which path the other photon took at the other photon's beam splitter? Each photon is now "detecting" the quantum state of the other photon, from a distance that could be large. The perfect correlation certainly "feels" nonlocal even though (as mentioned above) this perfect correlation at $\varphi_B - \varphi_A = 0$ does not violate Bell's inequality. Note that such a violation is a sufficient but not necessary condition for nonlocality.

Non-locality is written all over the RTO experiment. Each photon "knows" which direction the other photon takes at its beam splitter and adjusts its selection accordingly.

The key nonlocal feature of Figure 5 is that the graph, which is simply a cosine function, has $(\varphi_B - \varphi_A)$ as its independent variable. Thus any desired shift in correlations can be made by an observer at either of the possibly-widely-separated phase shifters. Bell suspected that this situation meant that observer A (call her Alice) could use her phase shifter to alter the outcomes that would have occurred *at both her own and observer B's* (call him Bob) *detector* and, following up on this hypothesis, derived his inequality involving the probabilities at both Alice's and Bob's detectors which, if violated, implied that *both* photons must have readjusted their states. Such readjustment is just what we expect, given the unity of the quantum and thus the unity of atoms and other entangled systems such as our two photons. The two photons form a single "bi-quantum," an "atom of light," in the pure state (5). When Alice varies her phase shifter, both photons "know" both path lengths and readjust their behavior accordingly to produce the proper correlations. Analogously, a single photon "knows" both path lengths in the single-photon interferometer experiment of Figure 2.

Finally, the central question of this paper: What is actually superposed in the entangled superposition (5)? The experiment of Figure 2 tests the simple superposition (3), while the RTO experiment tests the entangled superposition (5). We know what is superposed in Figure 2, namely the quantum states $|\psi_1>$ (path 1) and $|\psi_2>$ (path 2). This is deduced from the effect that either phase shifter has on both states. Now consider the RTO experiment. What is the effect of shifting either phase shifter? One thing that does *not* change is the state ("local state" would be a better term, as discussed in Section 5) of either photon A or photon B: As we know, both photons remain in 50-50 mixtures regardless of either phase setting. *What does change with variations in either phase shifter is the correlations between A and B.* With $\varphi_A = \varphi_B = 0$ we have perfect correlation: Either A1 and B1 (which we will denote (11)) or A2 and B2 (denoted (22)). As we vary either φ_A or φ_B we obtain non-zero probabilities of anti-correlated individual trials, denoted (12) (outcomes A1 and B2) and (21) (A2 and B1). When the non-local phase angle difference $(\varphi_B - \varphi_A)$ reaches $\pi/2$, we have zero correlation, and when it reaches π we have perfect anti-correlation.

Table 1 summarizes this crucial point in more detail. The column titled "simple superposition" shows how the superposition state of a single photon (Figure 2) varies from "100% state 1" to "100% state 2" as the phase angle between the two states varies. The column titled "entangled superposition of two sub-systems" shows that the *state* of each photon remains unchanged throughout the entire range of both phase settings, while the nonlocal *correlation between the states of the two photons* varies from "100% correlated" to "zero correlation" and then to "100% anticorrelated" as either of the two local phase angles varies.

What is superposed in the RTO experiment? The hallmark of a superposition is its dependence on the phase difference between the objects that are superposed. But Table 1 exhibits no such phase dependence of the states of the two photons. Each photon remains in an unchanging 50-50 mixture of its own "path 1" and "path 2" states, a situation that is radically at odds with the true superposition of path 1 and path 2 exhibited by the experiment of Figure 2. Thus in the entangled RTO state, neither photon is superposed. We see here the source of the "classical" or non-superposed nature of the reduced density operators (Eqs. (10) and (11)), not to mention the non-superposed and hence non-paradoxical nature of Schrodinger's cat. Our examination of the phase-dependence of the measurement state (5), as demonstrated by nonlocality experiments such as the RTO experiment, reveals the true nature of Schrodinger's cat. The last column of Table 1 shows us what actually is superposed when two subsystems are entangled in the measurement state (5). Since the correlations between the two photons vary sinusoidally as the non-local phase angle between the two photons varies, it is clearly these correlations between the states of the two photons, and not the states themselves, that are interfering. The entanglement has shifted the superposition, from the states of one photon A (Eq. (3), Figure 2) to the correlations between photon A and photon B (Eq. (5), Figure 4).

Simple superposition:		**Entangled superposition of two sub-systems:**		
φ	State of photon	$\varphi_B - \varphi_A$	State of each photon	Correlation between the two photons
0	100% “1”, 0% “2”	0	50-50 “1” or “2”	100% corr, 0% anti
$\pi/4$	71% “1”, 29% “2”	$\pi/4$	50-50 “1” or “2”	71% corr, 29% anti
$\pi/2$	50% “1”, 50% “2”	$\pi/2$	50-50 “1” or “2”	50% corr, 50% anti
$3\pi/4$	29% “1”, 71% “2”	$3\pi/4$	50-50 “1” or “2”	29% corr, 71% anti
π	0% “1”, 100% “2”	π	50-50 “1” or “2”	0% corr, 100% anti

Table 1. In a simple superposition, the photon's state varies with phase angle. In an entangled superposition, the relationship between states of the two photons varies, while individual states of both photons are phase-independent (or "mixed").

5. Summary and discussion

In order to resolve the problem of definite outcomes of measurements, aka Schrodinger's cat, this paper analyzes the entangled state (5) of a microscopic quantum and its macroscopic measuring apparatus. This state is a superposition of the two composite entities $|\psi_1\rangle|1\rangle$ and $|\psi_2\rangle|2\rangle$, with a phase angle between these entities that can range over 2π radians. In a measurement, this phase angle is fixed at zero because we design the detector so that the two basis states of the measured quantum are 100% positively correlated with the basis states of the measurement apparatus.

To resolve the problem of definite outcomes we must ask: Precisely what does the composite superposition (5) actually superpose, physically? In order to understand the simple non-composite superposition (3), we looked at the effect of varying the phase angle between the superposed entities $|\psi_1\rangle$ and $|\psi_2\rangle$ in an experimental setting such as the interferometer of Figure 2. The theoretically predicted and experimentally observed results then made it obvious that the quantum whose state is (3) flows simultaneously along two separate paths described by $|\psi_1\rangle$ and $|\psi_2\rangle$.

To understand the superposition (5), we should proceed similarly by studying situations in which the phase angle between the superposed entities $|\psi_1\rangle|1\rangle$ and $|\psi_2\rangle|2\rangle$

varies. As it happens, theorists and experimentalists studying the phenomenon of nonlocality have been doing this for decades, but quantum foundations specialists have not particularly noticed this work in connection with the measurement problem. In fact, nonlocal aspects of the state (5) have been studied since Bell's 1964 theoretical paper [1] and Clauser and Freedman's 1972 experiment [19]. The 1990 experiments of Rarity and Tapster [25], and of Ou, Zou, Wang, and Mandel [26], furnish the ideal vehicle for such an analysis and are the central feature of this paper.

One lesson of this analysis is that, in order to understand the measurement problem, one must understand the significance of nonlocality. This is because the key measurement state (5) that caused Schrodinger and decades of experts so much concern has nonlocal characteristics. It must be understood as a superposition of correlations, rather than a superposition of states, but this cannot become apparent until one considers the effect of variations in the phase angle between its superposed terms. Such variations are not part of the measurement process itself because measurements are designed to take place at zero phase angle. Experimental or theoretical studies of such phase variations will have nonlocal ramifications, because such variations are inherently nonlocal. This situation would have prevented Schrodinger in 1935, or indeed anyone prior to Bell's 1964 paper and the experimental confirmations of the reality of nonlocality beginning in 1972, from understanding the entangled superposition (5).

It's worth emphasizing that, when two subsystems are entangled in the measurement state (5), neither subsystem is superposed. Only correlations between the subsystems are superposed. In the RTO experiments, the two correlations in question are represented by the solid and dashed paths connecting pairs of outcomes. A pair of photons entangled in the state (5) follows both of these paths simultaneously. The subsystems themselves, however, are not in superpositions but are instead in indeterminate mixtures of definite states. Thus observers of either subsystem will observe only definite outcomes, as predicted by the local mixtures (10) and (11).

The RTO experiments are the entangled analog of the interferometer experiment of Figure 2: a pair of back-to-back interferometer experiments, with an entangled pair of quanta of which one quantum passes through each interferometer. The experiment and its theoretical analysis shows that, when a superposed photon A becomes entangled with a second photon B to form the state (5), the nonlocal aspect of A's superposition (Figure 2) is transferred to the correlations between A and B (Figure 4). Thus an entangled state such as (5) is neither a superposition of states of A nor of states of B, but instead a superposition of the correlations between the states of A and the states of B.

To see this most clearly, let's compare the simple superposition (3) with the entangled superposition (5). In the simple superposition, the state observed by a "which-state" detector varies smoothly from 100% $|\psi_1\rangle$, through 50% $|\psi_1\rangle$ and 50% $|\psi_2\rangle$, and finally to 100% $|\psi_2\rangle$ as the phase angle φ between $|\psi_1\rangle$ and $|\psi_2\rangle$ varies from 0 to π. In the entangled superposition, neither the state of A nor the state of B varies as φ_A or φ_B varies; both A and B remain in 50-50 mixtures throughout. What does vary is the correlation between A and B. A non-local "correlation detector" (i.e. an RTO-type of experiment!) would find the relation between the two subsystems varies from 100% positively correlated (either the pair state 11 or 22, pictured by the solid and dashed paths in Figure 4), to 50% positively correlated and 50% anti-correlated, and finally to 100% anticorrelated (12 or 21), as the nonlocal phase difference $\varphi_B - \varphi_A$ varies from 0 to π. This is a superposition of correlations, not a superposition of composite states or of non-composite (single-system) states.

This conclusion implies that our standard physical description of a composite non-entangled (i.e. factorable) product state such as $|\psi_1>|1>$ has been long mistaken. We usually regard $|\psi_1>|1>$ as a *state* of the composite system AB, one in which subsystem A is in state $|\psi_1>$ and subsystem B is in state $|1>$. But this leads us into the paradox of Schrodinger's cat, where $(|\psi_1>|1> + |\psi_2>|2>)/\sqrt{2}$ represents a state in which two macroscopically different composite states exist simultaneously as a superposition. According to the present study, quantum theory and quantum experiments imply this entangled state to be a superposition of correlations between states rather than a superposition of composite states. Thus $|\psi_1>|1>$ is not a *state* of the composite system, but instead a *correlation between* the two subsystems. That is, $|\psi_1>|1>$ means "subsystem A is in the state $|\psi_1>$ if and only if subsystem B is in the state $|1>$," an important departure from the usual description.

Even if one of the two subsystems happens to be a macroscopic detector, the entangled state (5) is simply a non-paradoxical superposition of correlations. It says merely that the state $|\psi_1>$ of A is correlated with the state $|1>$ of B, and the state $|\psi_2>$ of A is correlated with the state $|2>$ of B, with the non-local phase angle $\varphi_B - \varphi_A$ determining the degree of each correlation. In the case of measurement, this phase angle is fixed at zero. Regardless of phase angle, neither subsystem is in a superposition. The entangled measurement state (5) is best described as a "macroscopic correlation": a pair of superposed (i.e. phase-dependent) quantum correlations in which one subsystem happens to be macroscopic. It is technically very difficult to create a macroscopic superposition, but macroscopic which-path detectors routinely achieve the state (5). It's not paradoxical, even though many analyses have puzzled over it.

At least in our idealized case of a minimally-disturbing von Neumann measurement, the initial stage of the measurement process (through the formation of the measurement state (5)) can be described as follows: A quantum in a simple superposition such as (3) entangles with a macroscopic which-path detector. At the instant of entanglement, the local states of the both the quantum and the detector undergo a radical change, a quantum jump. Locally, the detector and the quantum jump into mixtures (10) and (11). Simultaneously, the global state (5) continues evolving smoothly according to the Schrodinger equation. Entanglement causes the superposed single quantum to be instantly transformed into superposed correlations between the quantum and the detector.

This stage of the measurement process is entirely describable in terms of pure global states following the Schrodinger equation. The collapse from a local superposition to local mixtures occurs because of the formation of the entangled state (5) and the resulting formation of subsystems whose local states (Eqs. (10) and (11)) have definite outcomes. Note that the phenomenon of nonlocality is essential to preserving the pure-state nature (the unity) of the composite system. To put this more intuitively, a re-organization throughout the entire extent of the composite entangled system is required in order to preserve the unity of the (now entangled) quantum.

According to Table 1, when two systems entangle to form the state (5), both collapse into phase-independent local mixtures. Relativity requires this phase independence: If any phase-dependent aspect of the entangled state were locally observable, instant information-containing messages could be sent, violating special relativity. *Local states of entangled subsystems must be invariant to phase changes*. Thus, only the relationship--the correlations--between A and B, but not A or B themselves, can vary with phase angle. Since local observers cannot detect these correlations, the entangled state cannot be used to send superluminal signals. This is, ultimately, the reason Schrodinger's cat must be either alive or dead rather than a superposition of both. A phase-dependent superposition involving both local states would permit nonlocal signaling, violating relativity.

In entanglement, nature employs an ingenious tactic. She must not violate relativistic causality, yet she must be nonlocal in order to maintain the pure-state nature of the original single-quantum superposition over composite objects such as bi-photons. Thus she accomplishes nonlocality entirely via the superposition of correlations, because correlations cannot be locally detected and thus their superposition cannot violate relativity. This tactic lies behind the nonlocal spread of phase-dependence over large spatial distances. By means of the superposition of correlations--entanglement-- nature creates a phase-dependent pure-state quantum structure across extended quantum systems such as bi-photons.

I've frequently used the term "local" as contrasted with "global." For composite systems, and especially the entangled measurement state, it's a crucial distinction. Entangled states such as (5) have distinct local and global (nonlocal) aspects. The local description means the situation observed by two (or N for an entangled N-body system) observers, each observing only one subsystem. In the case of (5), this "local description" is fully captured by the reduced density operators (10) and (11)--each local observer detects a mixture, not a superposition, of one subsystem. The "global description" means the evolving pure state of the entire composite system, in our case Eq. (5). It is a superposition of nonlocal correlations that can only be detected by observing both subsystems and, via an ensemble of trials that individually record corresponding outcomes at both subsystems, determining the state of the correlations between them. Although the global state implies the local description, the local description cannot hint at the global correlations because any such hint would violate Einstein causality. Thus, when an electron shows up in your lab, neither an examination of the electron nor an examination of an ensemble of identically-created electrons can give you the least hint of whether or how this electron is entangled with other quanta elsewhere in the universe.

This clarification of entanglement resolves the problem of definite outcomes, aka Schrodinger's cat. An ideal measurement of a superposed microscopic system A by a macroscopic detector B establishes the measurement state (5) at 100% positive correlation. This state is equivalent to the logical conjunction "A is in local state $|\psi_1\rangle$ if and only if B is in local state $|1\rangle$, AND A is in local state $|\psi_2\rangle$ if and only if B is in local state $|2\rangle$," where AND indicates the superposition. This conjunction is precisely what we want following a measurement. Schrodinger's cat is not in the least paradoxical.

This analysis does not entirely resolve the quantum measurement problem. It resolves the problem of definite outcomes associated with the measurement state (5), but this state continues to obey Schrodinger's equation and is hence reversible. In fact, the entangled state between a quantum and its which-path detector can actually be reversed in the Stern-Gerlach experiment (Figure 11.1 of [8]). A quantum measurement must result in a macroscopic indication such as a recorded mark, and a mark is irreversible. The above analysis shows the entangled state (5) describes a mixture of definite, not superposed, outcomes of measurements, but these outcomes remain indeterminate and the global state remains reversible.

The irreversibility problem is the question of how this nonlocal superposition of correlations then further collapses irreversibly to just one of its possible outcomes, a collapse that occurs in the RTO experiment only when one photon impacts a detector. The present analysis does not claim to resolve this problem. In the case of the RTO experiment, however, it seems fairly clear that the nonlocal superposition described by Eq. (5) must irreversibly decohere [10] when either of its subsystems A or B interacts with a detector. The RTO experiment furnishes a particularly good setting for this question, because the two photons remain in the reversible entangled state (5) throughout their flights from the source to detectors, and thus the two key questions of the measurement problem (the problem of definite outcomes and the problem of irreversibility) can be analyzed individually.

Acknowledgements

I thank University of Arkansas Physics Professor Surendra Singh and Philosophy Professor Barry Ward for many enlightening discussions, the Department of Physics for providing this retired professor with a congenial office, James Malley of the Center for Information Technology at the National Institutes of Health as well as Mario Bunge of the McGill University Philosophy Faculty for advice, retired physics professor Ulrich Harms of Reutlingen, Germany, for discussions and support, and numerous referees for helpful criticism. I especially thank my friend Peter Milonni, Professor of Physics, Department of Physics and Astronomy, University of Rochester, for his help and advice.

Notes on contributor

Art Hobson, since retiring in 1999 from teaching physics at the University of Arkansas, Fayetteville, has been able to pursue his long-time passion of trying to sort out the widespread confusion about what quantum physics actually means. This paper, along with his book *Tales of the Quantum* (Oxford University Press, 2017) and other publications listed in this paper's references, reflect what he learned during this fascinating and continuing adventure.

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