

Can *Nothing* Cause Nonlocal Quantum Jumps?

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Abstract. A paradox is discussed in which a photon can occupy one of two positions, ‘left’ or ‘right.’ Quantum mechanics allows the two possibilities—‘nothing left, photon right’ and ‘photon left, nothing right’—to be combined in a (coherent) superposition; or alternatively in an (incoherent) mixture, with similar terms, but no phase relation between them. As the phase relation is statistically significant, and can in principle be revealed experimentally, the two superposed possibilities must both be present in nature, together, for they somehow ‘communicate’ with one another through that relation. The eigenvalue $+1$ can be assigned to the presence of the photon on the right, -1 to its absence, to construct a measurable physical quantity, ‘photon-right.’ Its expectation vanishes for the aforementioned superposition. If we look for the photon on the left and do not find it, it must be on the right. The superposition accordingly collapses to the term ‘nothing left, photon right,’ whose expectation for photon-right jumps from zero to one right away. Only with a mixture could one ascribe the initial (vanishing) expectation to an *ignorance* which is then overcome once the photon is not found on the left. The issue is: what exactly happens on the left to cause the *ontic* (and not merely epistemic) jump on the right? Is it some mental event? Or is it *nothing at all*?

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INTRODUCTION

The problem of measurement—or of ‘macro-objectification,’ as Ghirardi [1] and others have called it—and the paradox of Einstein, Podolsky and Rosen¹ [3] are at root very similar; in either case we are troubled by the coherence, in other words by the phases $\theta_m = \arg c_m$, of an entangled state

$$|\psi\rangle = \sum_m c_m |\alpha_m\rangle |\beta_m\rangle = \sum_m |c_m| e^{i\theta_m} |\alpha_m\rangle |\beta_m\rangle.$$

In fact they are fundamentally so similar it may be best to speak of a single ‘problem of entanglement,’ to be faced as a single issue, and to which one can hope to find a single solution. In both cases one of the two tensor factors (of every term), say $|\alpha_m\rangle$, describes a state of a small object. In the case of measurement the other factor, the right one, describes a state of a large object close to the small one described by the left

¹ See [2].

factor. In the EPR paradox there are just two terms, $|\alpha_1\beta_1\rangle$ and $|\alpha_2\beta_2\rangle$, with expansion coefficients c_1, c_2 of equal modulus

$$|c_1| = |c_2| = \frac{1}{\sqrt{2}}$$

and phase difference $\arg c_2 - \arg c_1 = \pi$ (typically at any rate), so that

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\alpha_1\beta_1\rangle - |\alpha_2\beta_2\rangle);$$

furthermore the object described by the right factor *is also small*, and above all *far from the other*.

Since coherence is at the root of all the trouble one may feel better about the (incoherent) mixture

$$\rho = \sum_m w_m |\alpha_m\beta_m\rangle\langle\alpha_m\beta_m|,$$

in whose positive real coefficients $w_m = |c_m|^2$ the phases $\arg c_m$ no longer figure. We may prefer ρ ; but we *have*, or at any rate *start with*, $|\psi\rangle$; so why should we take, or consider, or pretend to have ρ ? Perhaps they are the same ‘FAPP’ (*for all practical purposes*); since it can be so hard to tell them apart—in other words to bring out the coherence that distinguishes between them—experimentally, why not settle for ρ , and not bother with the disturbing subtleties of $|\psi\rangle$ at all. Another approach is *to turn $|\psi\rangle$ into ρ* . Various mechanisms have been proposed; the one put forward by Ghirardi *et al.* [4] has many merits, but it only works well if the two systems are close together, and if one is large.² It has trouble—perhaps surmountable³—if both systems are small and far apart. But what if one of them ... isn’t there at all?

ENTANGLED STATE INVOLVING A SINGLE PHOTON

Suppose a single photon can be found at one of two (appropriately circumscribed) places, which are far apart, and called *left* and *right*. As the photon is indivisible, if it is found on the left it will not be on the right, and *vice versa*; it cannot appear partly here and partly there. We will use $|1\rangle$ to denote *one* photon,⁴ $|0\rangle$ for none; the product⁵ $|0\rangle \otimes |1\rangle$ (we can write $|01\rangle$) will accordingly indicate *photon on the left* (and hence not on the right). The two possibilities $|10\rangle$ and $|01\rangle$ can be combined in the superposition

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle),$$

² See [5], [6].

³ See [1].

⁴ Rather than *none*; that it is a photon (and not some other particle) interests us much less than its presence (as opposed to its absence).

⁵ The tensor product is typically used in quantum mechanics for *different systems*, and here it may appear that we just have one. But since occupation number here seems so similar to other two-valued quantities, like polarization or spin, we are viewing the left and right positions as different systems with different occupation numbers.

whose key feature is its coherence, expressed by the “–” sign between the terms, in other words by the phase $e^{i\pi} = -1$. This coherence tells us that both possibilities, $|10\rangle$ and $|01\rangle$, are present in nature; for how can one of the two be entirely discarded if they ‘communicate’ or ‘interact’ through the phase relation? They do so inasmuch as the superposition $|\psi\rangle$ is statistically distinguishable from the corresponding⁶ incoherent state, the mixture

$$\rho = \frac{1}{2}(|10\rangle\langle 10| + |01\rangle\langle 01|),$$

whose coefficients can—to some extent at any rate—be understood in terms of ignorance, as the two possibilities present are unconnected by a phase relation. Gleason’s theorem [7] tells us that different quantum states, like $|\psi\rangle$ and ρ , can always be told apart statistically; more specifically the *sensitive observables* of Capasso, Fortunato and Selleri [8,9] ensure the distinguishability of a superposition of products, like $|\psi\rangle$, from a mixture of the same products, in this case ρ . Observables used for the violation of Bell inequalities are examples.

A sensitive observable can be constructed as follows. There will be a ‘photon number’ basis⁷ $|0^l\rangle, |1^l\rangle$ on the left, and a similar basis on the right. We will need states

$$|\pm\rangle = \frac{1}{\sqrt{2}}(|0^l\rangle \pm |1^l\rangle)$$

on the left and states

$$|\theta_{\pm}\rangle = \frac{1}{\sqrt{2}}\left(\cos\frac{\theta}{2}|0^r\rangle \pm \sin\frac{\theta}{2}|1^r\rangle\right)$$

on the right; and self-adjoint operators

$$\sigma^l = |1^l\rangle\langle 1^l| - |0^l\rangle\langle 0^l|, \quad \sigma = |+\rangle\langle +| - |-\rangle\langle -|$$

on the left and

$$\theta_{\pm} = |\pm\theta_{+}\rangle\langle \pm\theta_{+}| - |\pm\theta_{-}\rangle\langle \pm\theta_{-}|$$

on the right, to define the operator

$$S_{\theta} = \sigma^l \otimes \theta_{+} - \sigma^l \otimes \theta_{-} + \sigma \otimes \theta_{+} + \sigma \otimes \theta_{-}.$$

Since $\langle\psi|S_{\pi/4}|\psi\rangle = 2\sqrt{2}$ is not equal to $\text{Tr}(\rho S_{\pi/4}) = 2$, the operator $S_{\pi/4}$ represents a sensitive observable, which can ‘see’ coherence by telling $|\psi\rangle$ and ρ apart.

INTERPRETATION OF THE JUMP

The observable $\sigma^r = |1^r\rangle\langle 1^r| - |0^r\rangle\langle 0^r|$, which we can call *photon-right*, represents the photon’s presence or absence, in other words the ‘photon number,’ on the right. Its expectation $\alpha = \langle\psi|I \otimes \sigma^r|\psi\rangle$ for state $|\psi\rangle$ vanishes, unlike the expectations

$$\alpha_0 = \langle 10|I \otimes \sigma^r|10\rangle = -1$$

$$\alpha_1 = \langle 01|I \otimes \sigma^r|01\rangle = +1$$

⁶ Where the particular correspondence depends on the basis chosen.

⁷ Superscripts are only included where necessary.

for the two terms superposed in $|\psi\rangle$. If we look for the photon on the left and do not find it, the superposition will be reduced to its second term $|01\rangle$, while the expectation of photon-right jumps from 0 to +1. Everything here will turn on this jump, and how to interpret it.

The trouble is that according to standard quantum mechanics this expectation has real—ontic, not just epistemic—meaning; so the jump in photon-right will be correspondingly real, and more than just an acquisition of knowledge, an information jump, a mere update.

It may be thought that the following happens: first we are in a state of balanced ignorance, expressed by α , in which we have no idea where the photon is. Once we discover that the photon is on the right, by looking for it on the left, we overcome that ignorance, and to update our previously imperfect knowledge replace α with the certainty expressed by α_1 . So only one of the two terms in $|\psi\rangle$ is really present in nature, only we do not know which one until we look. But how can a physically absent possibility be statistically relevant? Both terms must therefore be present in nature, which means that the expectation α , the quantity photon-right, and the jump, are all real and not just epistemic.

The jump takes place once we have found out that the photon is not on the left. One can wonder about the nature of this ‘discovery.’ Physically it would appear that very little need be involved; for only an *absence* is being established, a void or vacuum is being found. The jump is temporally circumscribed, in fact we can say that it takes place at a certain time τ , when⁸ the discovery is made on the left. But what does the discovery involve? What is it that happens at time τ on the left, that causes the jump on the right? Is it an *awareness* of the absence? A *perception* of the void? A *realization* or *understanding* that there’s nothing there? Do we have to *take down* the null result? *Register* it? *Tell a friend* [10]? *Poison a cat* [11]?

DYNAMICAL REDUCTION

It could be that perception or registration of the void depends on a *dynamical reduction* [1]—and hence on the presence of many particles—on the left, without which the state would remain in the superposition $(|01\rangle - |10\rangle)/\sqrt{2}$:

A simple estimate of the number of ions which are involved in the visual perception mechanism makes perfectly plausible that, in the process, a sufficient number of particles are displaced by a sufficient spatial amount to satisfy the conditions under which, according to QMSL, the suppression of the superposition of the two nervous signals will take place within the time scale of perception.

To avoid misunderstandings, this analysis by no means amounts to attributing a special role to the conscious observer or to perception. The observer’s brain is the only system present in the set-up in which a superposition of two states involving different locations of a large number of particles occurs. As such it is the only place where the reduction can and actually must take place according to the theory. It is extremely important to stress that if in place of the eye of a human being one puts in front of the

⁸ Simultaneity is assumed unproblematic.

photon beams a spark chamber or a device leading to the displacement of a macroscopic pointer, or producing ink spots on a computer output, reduction will equally take place. In the given example, the human nervous system is simply a physical system, a specific assembly of particles, which performs the same function as one of these devices, if no other such device interacts with the photons before the human observer does. It follows that it is incorrect and seriously misleading to claim that QMSL requires a conscious observer to make definite the macroscopic properties of physical systems. [1]

But how would perception of nothing on the left make a photon appear on the right? The void $|0\rangle$ is the result, perhaps the *consequence*, of the measurement; but $|0\rangle$ isn't necessarily all that was there *before*. Surely coherence demands that the photon had some kind of presence on the left until we looked; perhaps the state of affairs on the left before measurement is best described by the statistical operator

$$\rho^l = \frac{1}{2}(|1^l\rangle\langle 1^l| + |0^l\rangle\langle 0^l|),$$

in which case the null measurement in fact interacts with ρ^l . But what is ρ^l ? *Half* a photon? A *potential* photon? *Perhaps* a photon? And what happens to $|1^l\rangle\langle 1^l|/2$ when we look and find nothing? Does it get sent to the other side right away? Does our perception of the void *push* it off to the right? Does it reappear on the right without crossing the gap in between?

Perhaps one should wonder, more than about the ingenious theory of Ghirardi *et al.*, about quantum mechanics itself ...

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