J. Opt. B: Quantum Semiclass. Opt. **4** (2002) S469–S472 PII: S1464-4266(02)37847-9

One less quantum mystery

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Received 28 November 2001
Published 29 July 2002
Online at stacks.iop.org/JOptB/4/S469

Abstract
A classical model for 'Franson'-type Einstein, Podolsky and Rosen (EPR) experiments is described and compared with alternative, local, realistic models to be found in the literature. A brief analysis is presented which shows that such a model is possible because of unrecognized assumptions in Bohm's reformulation of the EPR gedanken experiment which preclude its use for addressing EPR's challenge.

Keywords: Nonlocality, Bell's theorem, EPR correlations, quantum mechanics

1. Introduction

One of the persistent fundamental mysteries of quantum mechanics (QM) lies in the question: How does it defy special relativity? How can it, as a well verified theory, get away with being nonlocal?

This, of course, is the question that Einstein, Podolsky and Rosen (EPR) evoked with their now legendary paper [1] and a central issue that continues to perplex physicists and philosophers alike. In many ways, Bohm's variant of EPR's original formulation of the problem is the clearest ever made, namely: consider the spontaneous disintegration of a stationary spinless particle into twin daughters, each with spin-$\frac{1}{2}$, that fly off in opposite directions. According to currently orthodox QM, neither daughter has a specific spin value until one of them is measured to yield, say, $+1/2$, when it becomes instantly true that, by symmetry, the other must be $-1/2$ [2]. How is this correlation *instantly* transferred without violating the fundamental precept of special relativity, that *all* interaction is limited by the speed of light? EPR, as is widely appreciated, were using this observation to argue that QM, since it cannot be nonlocal, must be incomplete. Nowadays this argument is turned on its head when it is argued that any completion or extension must respect the innate nonlocal aspects of QM.

In recent times it has become customary to argue that since this superluminal effect cannot be exploited for communication, in fact no violation is involved. This argument appears to have its genesis in papers by Eberhard [3], which show that no practical application can be developed to exploit this instantaneous effect, so no experiment will ever be done to conflict with Einstein's speed limit. This, however, is not the end of the matter. Costa de Beauregard [4] has been arguing for years that if QM admits instantaneous interaction, just on logical grounds alone, the existence of *retrocausality* is the consequence. He seems to have taken the view that insofar as nonlocality in QM is empirically verified, we now must work out how to accommodate our logic to that fact. So far, however, apparently few if any logicians have joined him. In the end, we note, special relativity does not put a speed limit on communication, but on *interaction* via light—general relativity extends it to gravity—thereby covering all known long-range interaction[1]—regardless of whether this interaction can be modulated so as to convey intelligence, i.e. used to communicate.

This situation, in this writer's view, forecloses the likelihood that any rationalization of nonlocality will be found flawless, thereby leaving to us the task of showing how the presumption of nonlocality and instantaneous interaction is a sophism. In pursuit of this latter tactic, this writer re-examined in [6] the arguments put forth by Bell in, e.g., [7], to the effect that nonlocality is an intrinsic characteristic of QM. In time he learned that he was not alone in this approach, and that at least two others preceded him in discovering the fundamental flaw in Bell's reasoning (more below) [8, 9]. Armed with the conviction that Bell's 'theorem' is wrong, he then proceeded to the following constructive stage of formulating classical models for those experiments that have widely been taken to verify Bell's conjectures [10].

In this report, it is the purpose to examine the classical model of the 'Franson' variant of those experiments thought to verify Bell's famous conjecture. Below, first we describe the generic structure of this type of experiment and our classical model of it. Then we compare it with similar attempts that

[1] However, see [5] for a contrary, but seemingly irrelevant to optics, view.

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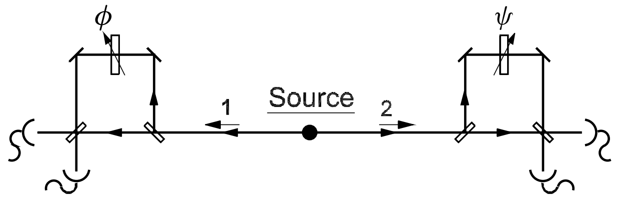

Figure 1. In a 'Franson'-type experiment two identical pulses are directed through two interferometers, each comprised of a short path and a long path in which there is an additional adjustable phase shifter. By using fast coincidence discrimination, coincidences between pulses that traversed unequal paths can be excluded. The resulting interference is a function of the adjustable phase shifters.

can be found in the literature. Finally, we conclude with some observations on just why the viewpoint espoused herein is really much better supported by well-accepted precepts of physics than would be expected on the basis of current opinion.

2. 'Franson' experiments

Experiments of this type exploit time delays between pulses to define the orthogonal states played by the two states of polarization in the customary realization of the EPR-B Gedanken experiments such as those, e.g., done by Clauser's or Aspect's groups [11, 12]. The original 'Franson' experiment measures the photocurrent correlation between two detectors positioned after interferometers which divide identical incoming pulses such that half take a short route and half take a long route which includes an adjustable delay [13]; see figure 1.

The logic of this set-up is built on the notion that each photoelectron registered at either end must result from a pulse that took either the short or the long path. Thus, a coincidence event, simultaneous ejection of photoelectrons at each end, can result from two distinct combinations, namely pulses that both took short, or both took long paths. Insofar as the observer cannot distinguish between these combinations, it is said that QM dictates that the wavefunction for each side be comprised of a linear combination of individual wavefunctions for each combination, which then should exhibit wave interference. When the experiment is done, such interference is indeed seen; and, more remarkably, the coincidence intensities do not satisfy Bell inequalities. The conclusion, that these observations speak in favour of the occurrence of nonlocality in QM, however, presupposes that it is impossible to explain these results with classical physics—a supposition we here contest by exhibiting a classical model or explanation.

We see two possible means of modelling this set-up classically. One would be to write out terms for the long- and short-route pulses that had a time-separated modulation or time-limited coherence. Such separated pulses, when multiplied together and integrated, give zero, because regions where they are finite do not overlap, thereby fulfilling the definition of orthogonality in a Hilbert space sense. This approach has the disadvantage of leading to ungainly expressions. A much simpler tactic is to assign the signals in the long and short paths to orthogonal dimensions of a vector space; the resulting calculations are then transparent and devoid of irrelevant, gratuitous complexity. For example:

$$E_r = \frac{1}{2^{3/2}}[\exp(-\mathrm{i}(kx-\omega t)+\phi), \exp(-\mathrm{i}(kx-\omega t+r\pi)] \quad (1)$$

$$E_l = \frac{1}{2^{3/2}}[\exp(-\mathrm{i}(kx-\omega t)+\varphi), \exp(-\mathrm{i}(kx-\omega t)] \quad (2)$$

where ϕ and φ are the extra phase shifts introduced in the long paths and r is the difference in number of reflections (phase shifts of π) between the paths to the detectors in consideration. (Note that one factor of $1/\sqrt{2}$ is the normalization, and two more such factors account for the effects of two beam splitters.) Here we also make use of the 'analytic signal representation'. This is a particularly propitious technique wherever the principal interest is in the long-time behaviour of the envelope of a signal, which is exactly the situation in this case. Then, the fourth-order coincidence function among N photodetectors (here $N = 2$) is proportional to the single-time, multiple-location second-order-in-intensity cross-correlation:

$$P(\theta_1, \theta_2, \ldots, \theta_N) = \frac{\left\langle \prod_{n=1}^{N} E^*(r_n, \theta_n) \prod_{n=N}^{1} E(r_n, \theta_n) \right\rangle}{\prod_{n=1}^{N} \langle E_n^*(r_n) E_n(r_n) \rangle}. \quad (3)$$

To apply this formula to the physical situation executed in the experiments, it is useful to introduce the convention that the tensor product in equation (3) be replaced by a vector inner product; i.e.,

$$P(\phi, \varphi) = \frac{(E_r^* \cdot E_l^*)(E_l \cdot E_r)}{(E_r^* \cdot E_r)(E_l^* \cdot E_l)}. \quad (4)$$

The dot product algebraically enforces the orthogonality in calculations that time delay enforces in the experiment, which in the experiment is achieved by using fast electronics so that the coincidence window is held narrower than the time-of-flight difference between the short and long paths [14][2]. Putting equation (2) in (4) quickly gives the observed correlation as a function of the phase shifts:

$$P(\phi, \varphi) = \tfrac{1}{8}(1 \pm \cos(\phi - \varphi)), \quad (5)$$

which exhibits the oscillations with 100% visibility characteristic of idealized versions of these experiments. (The plus sign in equation (5) holds for symmetric detector paths, the minus for asymmetric.)

There is nothing from QM in this model. It is simply a straightforward application of the fourth-order (in fields), classical coherence theory. The interference structure is encoded by equation (4), which, in effect, is just an elaboration of the 'square law' for photodetection.

3. Comparison with alternative models

There are two other local realistic models of 'Franson'-type experiments known to this writer. Neither appears to have been conceived to model faithfully actual experiments; rather they appear to be contrivances for the purpose of demonstrating a technical counterexample. As such, they can be regarded as successful; that is, they meet the technical specifications for a local, realistic theory. This is already a very significant result. Unless they contain as yet undiscovered error, in spite of Franson's criticism [15], as they stand they are indeed valid

[2] Shih *et al* point out that a classical 'Franson' interference can be made to conform with QM simply by reducing the coincidence window—surely, however, the distinguishing feature of QM is more profound than that.

technical counter-examples to Bell's theorem. This is true in spite of the fact that these models are often accompanied by statements to the effect that Franson-type (or, for that matter, EPR-B-type) experiments *cannot* be explained using classical physics, which really should not follow. In any case, besides Bell's 'theorem', there are no supporting arguments for this latter assertion.

Both of these models hypothesize artificial probabilities for the detection of a single pulse and both take it that these probabilities are different at each arm's detector. Santos, for example, considers individual detection rates of the form

$$P_1(\lambda, \phi) \propto [1 - V(1 + H(\pi + \phi - \lambda))] \tag{6}$$

$$P_2(\lambda, \varphi) \propto [\pi H(\pi - \varphi - \lambda) \sin(\varphi - \lambda)], \tag{7}$$

where $H()$ is the Heaviside step function and V is the visibility factor [16]. Aerts *et al* [17] use essentially the same individual rates but justify them differently: they consider that the local value for each single probability is the product of a frequency weighting function and the measured dichotomic result. Like Santos' detection rates, these weighting functions are tailor-made to yield the correct, known, joint probability, equation (5). These weighting functions for the two detectors are not identical, however, and symmetrization would be obtained, apparently, by randomly switching weighting functions back and forth. One of the weights so incorporates the factor $\pi \sin(\lambda - \phi)$ that the computation for the coincidence comes out correct. It should be noted that Santos deliberately tailored his detection rates to yield a joint coincidence compatible with Bell's hypothesis, namely that the joint probability, given that some 'hidden variables', λ, are involved, satisfies

$$P(\phi, \varphi) = \int \rho(\lambda) P_1(\phi, \lambda) P_2(\varphi, \lambda)\, \mathrm{d}\lambda. \tag{8}$$

These assumptions, however, are not compatible with common realizations of EPR experiments for which each detector is identical, and for which each photodetector obeys the 'square law':

$$P(t) \propto \int E^2(r, t)\, \mathrm{d}V. \tag{9}$$

As physics, this law states that the probability of the ejection of a photoelectron within a detector mass is proportional to the electric field energy density falling on that mass. All empirical evidence shows that if 'hidden variables' are to account for underlying structure, then when they are averaged out, the resulting expression must be very close to equation (9). Neither of these alternative local hidden variable models satisfy this desideratum.

By way of contrast, the model proposed herein is in full accord with equation (9) but does not satisfy Bell's ansatz, equation (8). In this model the 'hidden' variable is the dichotomic variable representing the route taken: long or short. There is no violation of 'locality' in a classical model, because there is no collapse of a wavepacket upon measurement. Without the collapse, the result of a measurement on one side does not imply that its 'companion' particle is somehow affected. All that it means in this case is that 'pre-correlated' electromagnetic fields evoke correlated photoelectrons with a certain probability on each side. For this model one presupposes no 'photon' character for light. It is simply assumed that classical, continuous radiation impinges on each detector and evokes a photocurrent. The result of the calculation indicated by equation (5) is then the correlation of the photocurrent intensities. Since this result cannot be distinguished from a result interpreted as the result of collapsed 'photon' wavefunction coincidences, the necessity of the latter interpretation is pre-empted.

4. Conclusions

We show that 'Franson'-type EPR experiments can be modelled using only classical physics. Parallel analysis leads to the same conclusions for the traditional EPR-B, that is, all EPR experiments as modified by Bohm [10]. These experiments are designed to test Bell's 'theorem'. It is generally believed that if observations violate the inequalities considered in Bell's theorem, then this shows both that QM is nonlocal and that it cannot, therefore, be extended by insinuating *local* hidden variables[3]. Insofar as classical physics is manifestly local, however, the existence of a classical model yielding results identical to those observed in experiments undermines this deduction.

This is possible, obviously, only if there is an error in the proof of Bell's theorem or in the experiments; in fact, there are two.

One was introduced when Bohm transferred the venue of the EPR argument from phase space to polarization space. The operators spanning phase space, $\hat{x}$ and $\hat{p}$, according to the principles of QM, exhibit Heisenberg uncertainty $[\Delta\hat{x}, \Delta\hat{p}] = \hbar/2$, which ultimately results from the fact that they do not commute: $[\hat{x}, \hat{p}] = i\hbar$. On the other hand, the operators spanning polarization, $[\hat{E}_x, \hat{E}_y] = 0$, space do commute. These latter operators are not Hamiltonian conjugate variables, and their creation and annihilation operators commute. Likewise, spin operators for the directions orthogonal to the magnetic field are not Hamiltonian conjugate variables; thus they too do not suffer Heisenberg uncertainty in spite of not commuting. In this case, noncommutation is similar to that of angular momentum operators in classical mechanics. Thus, Bohm's transfer of venue moved the physical situation out of a space in which a test of EPR's contention is possible to one where it is not. As a consequence, the experiments carried out involving entanglement of polarization modes, which for practical purposes includes all done to date, do not test EPR's contention, which is that Heisenberg uncertainty is the result of ignorance, not some new kind of fundamental ontic ambiguity. A test of EPR's contention can be carried out only in phase and quadrature spaces, where there is Heisenberg uncertainty, and this has not yet been done.

A second and perhaps even more fundamental error concerns Bell's encoding of nonlocality. In his formulation of his famous 'theorem,' Bell was thinking within the categories of QM. He argued that in the separate arms of the EPR-B experiment, each daughter particle is represented by a wavefunction constructed as a singlet state containing both

[3] We ignore the many technical questions and specialized versions of the inequalities that have arisen over the years pertaining to practical obstacles to executing the relevant experiments. Herein the focus is on the fundamental, ideal or general principle.

possible outcomes. This ontic ambiguity is then to be resolved by a measurement which induces collapse to the single outcome actually observed. If the symmetry of the correlation is to be maintained, then the wave must collapse for the partner particle also, and it must do so instantaneously. It is at this point where Bell introduced his conception of nonlocality. He argued that if nonlocality is to be precluded, then the wavefunction for each daughter particle must be determined only by the local variables and a global 'hidden variable'; i.e. that equation (6) must hold. The integrand of this equation: $\rho(\lambda)P_1(\phi,\lambda)P_2(\varphi,\lambda)$, however, contains an error in the application of Bayes' formula, which reads

$$P(\varphi,\phi,\lambda) = \rho(\lambda)P_1(\phi|\lambda)P_2(\varphi|\phi,\lambda). \tag{10}$$

Bell takes it that the presence of both φ and ϕ in P_2 would be a violation of locality. In Bayes' formula, however, this is not the case; it indicates only that P_2 is a *conditional probability*, not that P_1 and P_2 have any causal relationship other than through a common cause in the past light cones of both measurement events[4] [8]. Thus, the real question here is: is it necessary to exploit the concepts of duality and wave collapse as the means to express the correlation between the two sides of an EPR set-up, or can a common cause in the intersection of past light cones and Bayes' formula serve this function. The very existence of our model shows that the latter suffices for optical experiments, thereby obviating the arguments for the existence of nonlocality in QM.

Although this conclusion might seem to introduce a sweeping change in QM, it does not. In fact there are only a very few experiments where the concept of nonlocality seems efficacious, but all that is changed in fact is the vocabulary used to discuss them. The point is: classical optics is fully adequate to explain these phenomena without recourse to nonlocality, thus pre-empting one of QM's more persistent mysteries.

Note added in proof. Since submission of this paper, Hess and Philipp have also published what this writer considers to be an independent rediscovery of an elaborated version of Jaynes' criticism of Bell's analysis. They show that Bell failed to consider time-dependent correlations, but they do not note that time-independent correlations established by causes common to the past light cones of all detections are sufficient to undermine Bell's conclusions; see [18, 19]. In addition, Adenier has shown, by carefully parsing the meaning of the expectations in the quantum rendition of a Bell inequality, that the limit is always 4, which is never violated in experiments [20].

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