OBJECTIVE LOCAL MODELS FOR WOULD-BE 'NONLOCAL' PHYSICS

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Appeared in: **Instantaneous Action-at-a-Distance in Modern Physics: *Pro and contra;***
A. Chubykalo, V. Pope and R. Smirnov-Rueda (eds.), (Nova Science Publishers, Commack NY, 1999)pp. 363-372.

A brief review of little known objective local models to be found in the literature for Dirac's Radiation Reaction Formula, Bell's Analysis of the Einstein-Podolsky-Rosen-Bohm Experiment and the Ahronov-Bohm Effect is presented. The negative consequences for these classical demonstrations of nonlocal interaction are drawn: interaction off the past light-cone is an artifact.

I. INTRODUCTION

Instantaneous 'action-at-a-distance' (IAAD — a.k.a. nonlocal interaction) is, at a very intuitive level, problematic. It defies the very notion that causes must precede their effects. As such, it is very surprising that it has become a cornerstone of the dogma of modern physics. While there are various reasons for this, including some in the realms of emotion, religion and psychology, there are in fact only a small group of arguments, effects, calculations and myths that constitute the core of rationalizations for IAAD. Perhaps the three most well known, partly because of their accessibility are: the Aharonov-Bohm effect, Bell's Theorems and Dirac's derivation of the formula for radiation reaction.

What is much less well known, is that for each of these effects there are equally accessible objective local models. It is my purpose in this paper to review these simple models. While they are not, in the brief form given herein, clinchers; they do show that nonlocality is in these cases an artifact and certainly give sufficient cause to reasonably doubt the prevailing orthodoxy.

II. RADIATION REACTION

'Action-at-a-distance' (AAD) stands in a yin-yang relationship to 'field' in the science of mechanics. Both are laden with fundamental features providing fodder for analytical as well as philosophical ruminations.

As an historical matter, field theory is, apparently, now close to its apogee. Quantum field theory affords calculations of uncanny accuracy, and it is in part for this reason unfashionable to research the advantages of AAD. Nevertheless, field theory is afflicted with serious defects. The infinities somehow exorcised by renormalization are perhaps the most infamous. In addition, though, there are more such gremlins in classical electrodynamics, the mother of all field theories, such as pre-acceleration and run-away solutions.

Indeed these very defects motivated Wheeler and Feynman to seek an AAD formulation of (special) relativistic mechanics. Their researches resulted in two opaque publications elaborating a line of development with roots extending back at least to Tetrode in 1922.[1] The most conspicuous feature of their theory is the inclusion of AAD on both the forward and backward light cones.

Maxwell's electromagnetic field theory arose in part to address the common-sense objection to Newtonian AAD, that 'effects' must follow their 'causes,' that they can not even be coincident with their cause when any distance is between them. So much seems incontestable. As bad as IAAD is, however, forward interaction must be worse.

There are, of course, customary rationalizations for the obvious objections to advanced interaction. Wheeler and Feynman call upon a combination of advanced and retarded interaction to combine in just a way, convincing to themselves at least, that this formalism conforms with common sense and observation. Their key assumption here is that certain 'adsorbers' at infinity react or pre-act propitiously. This can be criticized simply by noting that even if this formalism is accepted, that it can not be applied to few body situations so as to yield well posed equations of motion.[2]

The most convincing argument for advanced interaction, however, is that it is required for the derivation of the verified form for radiation reaction as calculated by Dirac.[3] Thus, this argument in the end is pivotal support for advanced interaction.

But is all this necessarily so? Perhaps not. Consider the following: Assume that the universe as a whole is electrically neutral so that any particular charge e_j, located at $\mathbf{x}_j$ will induce among all other charges a coincidental virtual negative image charge, a kind of Debye sheath around itself. Radiation reaction, then, can be taken as the reaction of a charge with its own induced image. The equations of motion, one for the charge, one for the image, with only retarded fields, $F|_{ret}$, for this system are:

$$m_j(\ddot{\mathbf{x}}_j)^\mu = \frac{e_j}{c}(\sum_{k\neq j} F_k|_{ret})^{\mu\nu}(\dot{\mathbf{X}}_j)_\nu, \quad j = 1,2; \tag{1}$$

where dots over the coordinate indicate differentiation with respect to the system's proper time.

Solving this system is made easier by the following: One, to first order, $\mathbf{x}_1$ equals $\mathbf{x}_2$ (disregarding effects due to reaction lag caused by the finite speed of light—indeed, this approximation is the source of certain artifacts of the theory of electromagnetism). Two, the interaction from the induced image implodes on the charge as if from an oppositely charged system of concentric spherical shells. To an accelerated charge, in its own frame, this interaction is identical to that of a pre-counter- accelerated shell, which in turn is identical to the sign-changed, time-reversed outgoing interaction of the charge itself; i.e., $F_2|_{ret} \propto F_1|_{adv}$. Also, $e_2 = -e_1$. With these substitutions into the equation of motion for the image, the two equations can be added to get:

$$m(\ddot{\mathbf{x}}_1)^{\mu} = \frac{e}{2c}(F_1|_{ret} - F_1|_{adv})^{\mu\nu}(\dot{\mathbf{x}}_1)_{\mu}. \quad (2)$$

This equation is precisely the starting point of the derivation of an explicit form of the force resulting from radiation reaction and will not be repeated here. This derivation gives a very plausible physical model for radiation reaction without granting ontological status to advanced interaction. As such, it undermines the claim that advanced interaction is necessary to account for observed effects.

III. BELL'S ANALYSIS OF THE EINSTEIN-PODOLSKY-ROSEN (EPRB) EXPERIMENT

The Einstein-Podolsky-Rosen argument, as modified by Bohm (EPRB), captures the essence of the argument for nonlocality in Quantum Mechanics (QM). It proposes an experiment which, in one variant, concerns the case in which an entity, with no net angular momentum, emits a pair of photons such that total radiation is unpolarized; i.e., it carries off no net angular momentum. Note that this specification applies in detail, that is, for each pair of emissions separately, not just on the average. As each photon, with respect to any particular direction, must have a particular polarization, parallel to $\hat{x}$ say, the other must have, with respect to the same direction, the opposite (perpendicular) polarization. However, as either photon can have parallel or perpendicular polarization, a quantum state describing this photon before it has been measured, must comprise both possibilities. This requirement, and some others not here germane, lead to the so called singlet state as the proper choice.[4]

For this state, as is well known, QM gives two results that constitute the nub of the results comparable to experiment. The first is the coincidence intensity:

$$P(+,+) = \frac{1}{2}\cos^2(\phi), \quad (3)$$

where this represents the intensity of coincidences for which measurement reveals that both photons are found to have parallel polarization when the measurements are made on each with respect to coordinate systems that make angle ϕ with respect to each other. There are three other similar terms to cover all four possible combinations of two outcomes. The total correlation then is by definition:

$$Corr(\phi) = \frac{P(+,+) + P(-,-) - P(+,-) - P(-,+)}{P(+,+) + P(-,-) + P(+,-) + P(-,+)}, \quad (4)$$

which for P's given by Eq. (3) yields;

$$Corr(\phi) = -\cos(2\phi). \quad (5)$$

Nonlocality arises here in that a measurement of either photon, instantly fixes the polarization of the twin.

From the beginning the question has been asked: can this experiment be understood using an objective local model? A negative generic answer has been given by Bell who proposed theorems establishing certain inequalities that should be satisfied by all objective local alternatives to QM probabilities. Experiments testing Bell inequalities, although not rigorously conclusive, tend to verify QM. Nevertheless, a minority holds that QM ultimately will be shown to be inadequate and that objective local explanations for QM phenomena, including the EPRB experiment, can be found. The usual candidate model proposed has been the following:

It is assumed that the source emits two counter-propagating pulses of radiation polarized in a particular but random direction. It is taken that this radiation is to be directed through a polarizer and then detected using a photodetector which obeys the square law; i.e., it emits photoelectrons in proportion to the square of the intensity of the absorbed radiation. That is, the probability of emission of a photoelectron in each arm of an EPRB experiment is $(\mathcal{E}\cos(\theta))^2$ where θ is the angle between the polarization direction of the signal and the axis of the polarizer used in the detector. A coincidence detection is set then proportional to the product of detection probabilities in each channel, that is, $\cos^2(\theta)\cos^2(\theta-\phi)$ where ϕ is the angle between the axes of the measurement polarizers if the coordinate system is aligned with one of them.[5]

Finally, the total probability is obtained by averaging over many pairs of signals, each with its own randomly given polarization angle θ, that is

$$\frac{1}{2\pi}\int_0^{2\pi}[\cos(\theta)\cos(\theta-\phi)]^2 d\theta = 1/4 + 1/8cos(2\phi). \quad (6)$$

This expression seems perfectly rational, and as it yields $Corr(\phi) = cos(2\phi)/2$, does not violate a Bell Inequality. It would be a resolution to the conundrums evoked by Bell's Theorems were it to agree with experiment. However, this result has a nonzero minimum, whereas Eq. (3) does go to zero and this difference has been observed; Eq. (6) seems not to conform to Nature.[5] Moreover, for this model, detailed balance is not possible. That is, if, for example, it is taken that the emission is such that the signal sent to station A is polarized in the vertical direction, and that to B in the horizontal direction, but the measurement polarizers are at $\pm\pi/4$ to the vertical, then each station will 'see' a signal with intensity $1/\sqrt{2}$. That is, there will be a finite coincidence current even though the signals should cancel out; thus, Eq. (6) does not conform to the hypothesis either.

These simple observations would settle any dispute (at least for idealized, *gedanken* experiments) regarding the existence of a local realist alternative to QM were the above semiclassical model exhaustive. In fact it is not.[6] A different result is obtained if to the above semiclassical model the following modifications are made:

a. The source is assumed to emit circularly polarized signals; clockwise in one direction and counter-clock in the other. Thus, the signal propagating in the $\hat{z}$ direction and impinging on photodetector A, say, is:

$$A(\theta) = \hat{x}cos(\theta) + e^{i\pi/2}\hat{y}sin(\theta), \tag{7}$$

where $\hat{x}, \hat{y}$ are orthogonal unit vectors, the factors $cos(\theta), sin(\theta)$ project the individual components of the circularly polarized signal onto the axis of the polarizer and the factor $exp(i\pi/2)$, represents the fixed phase difference between the the orthogonal components which give circular polarization, and all other, here irrelevant, factors are suppressed. Likewise, the oppositely polarized signal impinging on the photodetector B, oriented at angle ϕ with respect to A, is:

$$B(\theta,\phi) = \hat{x}cos(\theta-\phi) + e^{i3\pi/2}\hat{y}sin(\theta-\phi). \tag{8}$$

b. Use is made now of a generalized coincidence probability inspired by second order coherence theory:

$$P(a,b) = \langle \frac{A \cdot BB \cdot A}{|A|^2 + |B|^2} \rangle, \tag{9}$$

where the angle brackets indicate an ensemble average over all values of θ, the angle of attack of each separate signal, or, on an ergotic principle, over the random phases of the individual atomic sources. The dot product is with respect to the orthogonal set $\{\hat{x}, \hat{y}\}$. [13]

Taking all the above into account, provides the following expression for the coincidence count rate:

$$P(+,+) = \frac{\int_0^{2\pi}(cos(\theta)cos(\theta-\phi) + sin(\theta)sin(\theta-\phi))^2 d\theta}{2\int_0^{2\pi}(cos^2(\theta) + sin^2(\theta))d\theta}. \tag{10}$$

Evaluated, this integral equals the QM result, Eq. (3):

$$P(+,+) = \frac{1}{2}\cos^2(\phi). \tag{11}$$

This fully objective local model yields results identical to QM and therefore in accord with those laboratory observations reported in [5] verifying QM. Although it is, perhaps, too simple to realistically describe an EPRB experiment, it is a counterexample to the result of Bell's Theorems to the effect that no objective local theory (e.g., a hidden variable theory) can duplicate QM.

The structure of Eq. (9) can be understood as follows: Its denominator is proportional to the total Intensity of all fields in an EPRB experiment, and therefore, proportional to the total number of photoelectrons evoked in "square law" detectors. The numerator is likewise proportional to the number of coincidence counts. Thus, the ratio is by definition the probability of coincidences. The numerator is similar to Eq. (6), $I_A I_B$, where $I_{A,B}$ is the intensity of radiation impinging on measuring stations A and B. It differs from Eq. (6), however, in that it is in a form from coherence theory involving field strengths which allows phase to contribute to the product. The verity of this form is established by coherence theory.[7].

The essential difference introduced by this modification is that in general, second order coherence theory does not admit factorization; i.e., $\langle ABBA \rangle \neq \langle AA \rangle \langle BB \rangle$.[7] Nonfactorizability does not here imply nonlocality or any other nonclassical phenomena. Indeed, there are a number of classical phenomena; e.g., the Hanbury-Brown—Twiss Effect, described using just this feature.

Nonfactorizability of higher order correlations in coherence theory has an exact parallel in probability theory. A coincidence probability, $P(A,B)$, can not in general be factored as $P(A)P(B)$. Only in the special case that the events at A are *statistically independent* from those at B it this possible. Statistical independence, however, is directly contrary to the initial assumption of EPRB.

Like QM nevertheless, Eq. (9) leads to a violation of Bell Inequalities. Such inequalities, however, are derived under the assumption that the coincidence probability can be factored. Indeed, Bell's fundamental assumption was that the coincidence probability is to be written as

$$P(a,b) = \int A(a,\lambda)B(b,\lambda)\rho(\lambda)d\lambda, \tag{12}$$

where $\rho(\lambda)$ is the ensemble density with respect to 'hidden variables' λ. This form presupposes that for each λ, the coincidence probability factorizes; but this cannot be so for correlated events. Nonfactorizable coincidences always can be written as: $P(A,B) = P(A)P(B|A)$ where $P(B|A)$ is a conditional probability. It is trivial to show that the derivation of Bell inequalities does not go through with conditional probabilities.

There is speculation in the literature that by ascribing the factors preventing factorization of a coincidence probability to the 'hidden' category and to a 'common cause,' it becomes factorizable.[8, 9] This analysis is subtle, complex and opaque.[10] All the same, at the end of the discussion, the signal pair retains its correlation and therefore its statistical *dependence*, so that conditional probabilities are necessarily involved. EPRB coincidence probabilities are fundamentally and irrevocably involved. But, because nonfactorizability can be attributed to a "common-cause," namely the balanced nature of the emission at the source, nonlocality is not implied, all information is propagated within the past light cones of both events.

In the modified model, this commonly-caused structure contributes to the product forming the coincidence probability as it is constituted from electromagnetic fields strengths, phases and all, directly in the general, nonfactorized form. The modified model is also consistent with the hypothesis in that it accommodates detailed balancing; e.g., complete cancellation for orthogonal polarizers regardless of signal orientation.

Remaining turbidity in this matter, this writer believes, attaches largely to the question: can the need for superposition states in other applications also be obviated in semiclassical models of other QM phenomena? From the modified model, it can be seen that EPRB correlations are, given the vector character of electromagnetic radiation, in fact essentially the angular analogue of the Hanbury-Brown—Twiss Effect. Recognizing this subtle fact motivates using the same structure to describe the EPRB experiment with an objective local model, and consequently without nonlocality.

IV. AHARONOV-BOHM EFFECT

By integrating the phase, ϕ, of an electron's wave function around a solenoid, Aharonov and Bohm showed that there is a finite residual phase difference. This difference can be made observable in a double slit diffraction experiment configured so that the separate paths pass on opposite sides of the solenoid. According to received wisdom, this effect is not explicable using only classical physics because the magnetic field outside a solenoid vanishes and therefore there should be no force on a charge passing a solenoid.[11]

This conclusion is wrong, however. It is based on an incomplete application of the principles of electrodynamics.[12] Consider the following; the electric field in terms of potentials is given by

$$\mathbf{E} = -\nabla V(\mathbf{x},t) - \frac{\partial \mathbf{A}}{\partial t}, \tag{13}$$

where V, the scalar potential does not contribute, the vector potential for a solenoid is given by

$$\mathbf{A} = \frac{\Phi}{2\pi}\frac{(-y\mathbf{i}+x\mathbf{j})}{x^2+y^2}, \tag{14}$$

and Φ is the magnetic flux in the solenoid.

The equation of motion for a charge passing the solenoid becomes

$$\dot{\mathbf{p}} = -q\frac{\partial \mathbf{A}}{\partial t}, \tag{15}$$

so that one can write

$$\begin{aligned} \Delta v_x &= \frac{1}{m}\int_{-\infty}^{t} \frac{dp_x}{dt'}dt' \\ &= -\frac{q}{m}\int_{-\infty}^{+\infty} \frac{\partial A_x}{\partial t'}dt' \\ &= -\frac{q}{m}A_x. \end{aligned} \tag{16}$$

Further, the relative displacement resulting from this velocity perturbation is then

$$\begin{aligned} \Delta x &\simeq \int_{-\infty}^{+\infty} \Delta v_x dt' \\ &= \pm\int_{-\infty}^{+\infty} \frac{q\phi d}{2\pi m((x')^2+d^2)}\frac{dx'}{v_0} \\ &= \frac{q\phi}{2mv_0}, \end{aligned} \tag{17}$$

where it is taken that the electron's trajectory passes distance d away from the solenoid. If account is now taken of counter passage on the other side of the solenoid and of the De Broglie relationship, $\lambda = h/(mv_0)$, the final result is the celebrated Aharonov-Bohm result:

$$(\Delta\phi)_{net} = \frac{2\pi}{\lambda}(\Delta x)_{net} = \frac{q\Phi}{\hbar}. \tag{18}$$

Essentially this calculation shows that this effect can be explained as the consequence of the apparent E field due to the motion of the electron through the static vector potential. It is not an effect exclusively described by QM where it has been given special significance. It has been argued that as the passing particle is materially affected by the presence of the flux inside the solenoid, although the particle itself is outside the solenoid, where fields seen by a static particle are zero, a kind of IAAD is in evidence. But, such a claim is unwarranted; other explanations have not been irrefutably excluded.

V. CONCLUSION

These three alternate models undermine the classic arguments for nonlocality. There are, to be certain, other phenomena and arguments that seem to demand nonlocality for clarification. But, again, if imagination is left unrestrained, they too may well yield to mundane explanations.

Extraordinary claims require extraordinary proof. The existence of nonlocal interaction off the past light cone is certainly extraordinary. As long as models like those presented in this short review stand—however lacking in conventionality they may be—nonlocality must be regarded with deep suspicion and can not be accepted as verified fact.

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[4] J. S. Bell, 'Speakable and unspeakable in quantum mechanics,' (Cambridge University Press, Cambridge, 1987).
[5] J. F. Clauser, *Phys. Rev.* A **6** (1), 49 (1972) discusses the experimental consequences of the semiclassical model of the EPRB experiment which he credits to M. D. Crisp and E. T. Jaynes, *Phys. Rev.* **179**, 1253 (1969); **185**, 2046 (1969). In principle, the semiclassical model was suggested by W. H. Furry, *Phys. Rev.* **49**, 393 (1936).
[6] A. F. Kracklauer, quant-ph/9810081.
[7] L. Mandel and E. Wolf, 'Optical Coherence and Quantum Optics,' (Cambridge University Press, Cambridge, 1995) p. 447.

[8] Ref. (4), p. 152.
[9] See J. Bub, 'Interpreting the Quantum World,' (Cambridge University Press, Cambridge, 1997) p. 64, for a survey of analysis of the "factorization" issue.
[10] In part, the literature on factorization is encumbered by failure to distinguish between the signal and noise. It would be possible to decouple noise added at each measuring station, or elsewhere, as such noise is statistically independent. The basic signal, however, must remain correlated to be faithful to the physics.
[11] M. Peshkin and A. Tonomura, 'The Aharonov-Bohm Effect,' (Lecture Notes in Physics, Vol. 340) (Springer, Berlin, 1989).
[12] H. Rubio, J. M. Getino and O. Rojo, *Nuovo Cimento* **106** (4), 407 (1991).
[13] *After-the-fact note:* Although the denominator in Eq. (9) is incorrect, because it equals 1, as does the correct version, the argument is unaffected. Subsequent work has removed this mistake.