NON-LOCALITY IN MODERN PHYSICS: COUNTER ARGUMENTS

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Abstract. Non-locality, i.e., some sort of instantaneous interaction or correlation determination, has been identified with the theory of Quantum Mechanics in recent times. Being in direct conflict with the basic principles of Relativity Theory, it posses a challenge. Herein various critical arguments raised in the past and judged to be particularly incisive are reviewed. These include, the identification of an error in the derivation of Bell Inequalities, the observation that Bohm inadvertently selected a non-quantum venue for experimental tests of Bell Inequalities and finally, an examination of the complexities that have rendered classical simulations of these experiments unsatisfactory.

1. Introduction: Mystical Ontology

Quantum Theory: Non-locality in the analysis of Quantum Mechanics arises as a consequence of the Projection Hypothesis. The wave function or probability distribution of a system of interacting entities, according to the common interpretation, retains information about all the constituent parts even after they have been spatially separated so that in principle they no longer interact. Thus, if just one of the constituents is measured, information is acquired instantly about about all the remaining components. For example, if the system comprises two components which as an ensemble has no momentum, then when the parts are separated in two, by an explosion say, the sum of the individual momenta remains null, but each is finite although opposite. Thus, if one constituent's momentum is measured, instant information is acquired about the other's momentum. Now, given the tacit assumption that Quantum Theory portrays the deepest level of being as a cloud-like entity, then the wave function or probability distribution-cloud represents the ultimate ontological essence of material particles—at least up to the moment of measurement, at which instant a distinct or much narrower probability distribution is projected into existence. This occurs, however, by agency of a measurement on one, for both, subsequently separated, entities simultaneously, in absolute conflict with Relativity Theory! This violation has been denoted, out of historical circumstances from field theory, as: 'non-locality,' and is a direct consequence of the Projection Hypothesis.

This logical blemish is independent of Probability Theory. The probability density for correlated events is given by the product of the absolute probability of one of the events, $P(a)$, multiplied by the conditional probability of the other event, $P(b|a)$, i.e.,

$$P(a, b) = P(b|a)P(a) \tag{1.1}$$

In words: The joint or coincidence probability of events specified by the identifying variables a and b equals the product of the absolute probability of the event specified by a times the *conditional probability* of the event specified by b given that the event specified by a is known to have occurred. The source and nature of the correlation is immaterial to the probability calculation. Naturally, the usual assumption is that there has been a "common cause" in the past. However, for the purposes of this calculation alone, it makes no difference in the calculation if there were non-local or instantaneous interaction causing the correlation. In application to Quantum Mechanics, the issue pertains strictly to the relevant physics.

2. Fundamental Arguments Against Non-locality

Herein the central claim is that, non-locality in physics theories must be rejected for reasons of inconsistent logic. The problem arises from two closely related missteps: the first was the Projection Postulate, which fails the "Popper" test, namely it is a non-dis-provable assertion; it is impossible to empirically evaluate what exists before measurement. Nevertheless adhering to the validity of this postulate led to the hypothetical circumstance prompting Bell to further examine the matter. Unfortunately, he then made an additional error. Finally, there exists a general consideration that actually precludes the whole issue of the application of quantum theory to virtually all of the experiments intended to test Bell's reasoning. Let us consider the last two factors in greater detail.

2.1. **Bell's Errors.** The tactic then in Bell's arguments is to derive an empirically testable statistic in the form of an inequality. If this inequality is violated by experimental data, then, he concludes, Quantum Theory is essentially non-local; i.e., it cannot be covered by a local theory with additional variables. To achieve this end, he supposes that there exists a (hypothetical) meta theory with additional variables (i.e., supplementary variables that do not appear in the current formulation of quantum theory, and customarily denoted λ), and in which there is no weirdness of the sort afflicting the interpretation of Quantum Mechanics. At the meta level then, he considers the calculation of a coincidence event, using a formula of the form:

$$P(a,b) = \int A(a|\lambda)B(b|\lambda)\rho(\lambda)d\lambda. \tag{2.1}$$

In this formula, the a and b are parameters for the experimental apparatus and λ represents parameters for subject entities of the experiments (usually 'photons' but possibly other particles).

This formula is defective, however, because the first two factors in the integrand denote probabilities at the meta, i.e., non-mystical, level of correlated events, and therefore cannot be similar in structure. One of them must be an absolute probability and the other a conditional probability. It appears that, Bell assumed that the correlation could be carried by λ. In that case the correctly rendered formulas is:

$$P(a,b) = \int_\lambda A(a|b,\lambda)B(b|\lambda\rho(\lambda)d\lambda. \tag{2.2}$$

When this complication is taken into consideration, the remaining algebraic manipulations used to derive Bell Inequalities do not go through.[1]

Moreover, independently, the derivation of Bell Inequalities involves manipulating the sum four such factors $P(a,b)$ in a single equation resulting from choosing two values for each a and b. This, again, cannot be done consistently in so far as

[1]This error appears to have been noticed first by Jaynes.[1]

each of the terms, P, does not represent a single term but rather a sequence of terms and each of the four sequences arises from a separate experiment so that it cannot be manipulated as if it were just one of the four variant sequences. This issue is dealt with in greater detail in refs. [2, 3].

2.2. **False Venue.** When the question of how to consider a quantum wave function was brought under criticism by Einstein, Podolsky and Rosen, they illustrated the issue with a *gedanken* experiment in which a stationary particle exploded into two subparts so that, with conservation of momentum in view, it would be possible to determine the position or momentum of either daughter from measurement of its partner. The description of this event was formulated in the phase space variables: position and momentum, which are Hamiltonian conjugates, that is, they are subject to quantization with the usual rules. However, exactly this sort of event is difficult to precisely arrange, stage and subject to measurement in an experiment; so, to facilitate matters, Bohm proposed an alternate venue, namely Q-bit space, at the time known as polarization-space spanned by vertical and horizontal or right- and left circular states. These variables, however, are not Hamiltonian conjugates; they are not quantizable (in contrast to variables in the k-vector or propagation direction: phase and amplitude).

While it is convenient to do experiments with the states of polarization, insofar as they are not quantized or even quantizable, experiments with them cannot be used to plumb the mysteries of Quantum Mechanics. Thus, the great bulk of experiments reported in the literature to test non-locality via Bell Inequalities pertaining to polarization states, cannot in principle reveal relevant information on this issue.

Another means of seeing the essence of this consideration is to recall that, the structure of q-bit, polarization and spin-1/2 spaces are all governed or described in terms of the group $SU(2)$. This group is homeomorphic to the group $SO(3)$ which pertains to rotations in 3-space or on a sphere. The non-commutivity of the latter group is obviously derived from geometry (not quantization) and the homeomorphism implies that the non-commutivity of the three-spaces mentioned above, as codified by $SU(2)$, can be due only to geometry also. Again, in principle therefore, experiments on these variables cannot be used to fix the implicit nature of quantum wave functions, or any other quantum feature whatsoever.

3. Classical Model of Bell Inequality Test

Insofar as the considerations presented above lead to the conclusion that optical tests of Bell Inequalities are staged in a venue which is fully classical, it should be possible to model these experiments in terms of fully classical entities and processes. This is indeed the case and there are many examples to be found in the literature.[4, 5, 6, 7, 8, 9, 10]

Here, as an example, what is perhaps the model closest in structure to Bell test experiments, is described. See Figure 3.1.

Analysis of coincidences, now, is simply a matter of applying the formula for their expectation, namely:

$$\langle a, b\rangle = \frac{\langle I(a)I(b)\rangle - \langle I(a)\rangle\langle I(b)\rangle}{[(\langle I^2(a)\rangle - \langle I(a)\rangle^2)(\langle I^2(b)\rangle - \langle I(b)\rangle^2)]^{1/2}} \tag{3.1}$$

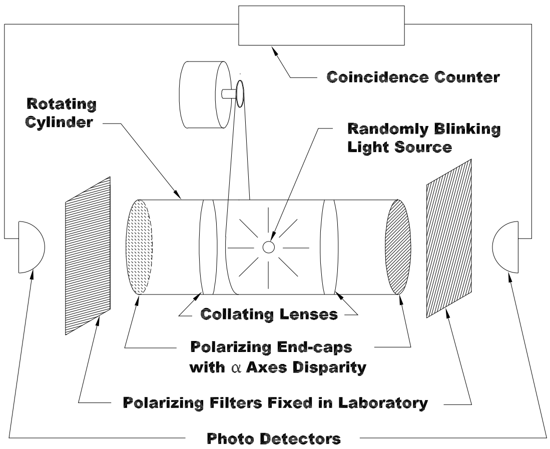

FIGURE 3.1. The apparatus consists of a cylinder rotating about is axis within which there is a randomly blinking light. The flashes are collated by lenses, followed by polarizing end caps having axes with a fixed mutual orientation. Signals emerging from the ends are analyzed for coincidences using polarizer filters fixed in the laboratory.[6]

This formula can be applied to the signals as measured for a setup as depicted in the figure. The result is:

$$\langle a, b\rangle = cos(2(b-a)). \tag{3.2}$$

This result is recognized immediately as exactly parallel to the result considered customarily to be the result of the a "quantum" calculation. (For the reasons given above, the quantum calculation is in fact just the usual classical computation applied to electromagnetic wave polarization phenomena.)

Applying the same formula to the Bell-Inequality tests would be straight forward but for the fact that, in order to make them as quantum-appearing as possible, such tests are carried out at the so-called "single photon" intensity level, where, as least in principle, a detection results in a single electron photoelectric current. That is, the intensity is either 1 or 0 for each measurable event so that the intensity appropriate for a given angle is revealed in the ratio of positive detections to the total number of pairs produced. In other words there will be events for which a detector responds or not in proportion to the intensity represented by an I in3.1. This feature encumbers a point-by-point simulation in that repetitions do not represent repetitions of the experiment but rather increased precision of a single experiment to determine the values of the I.

4. Conflict or Error?

In evaluating3.1 one encounters the integral:

$$\frac{1}{\pi}\langle I(a)I(b)\rangle = \int_0^\pi cos(2(a-\chi))cos(2(b-\chi))d\chi = \frac{1}{2}cos(2(b-a)), \tag{4.1}$$

where χ is the random bias angle due to the effect of random flashing in the rotating tube on the signal polarization. This factor of 1/2 arises essentially as the average of the cos^2 and must be deliberately introduced in a simulation in order to obtain the correct result as computed (in formal computations this factor of 1/2 is canceled by the denominator in3.1.

This complication can be better appreciated by expanding \$cos(2(a-b))\$ with trigonometric identities to obtain:

(4.2)

$$\cos(2(b-a)) = sin^2(a)sin^2(b) + cos^2(a)cos^2(b) - sin^2(a)cos^2(b) - cos^2(a)sin^2(b),$$

where the individual cos^2 and sin^2 factors can be interpreted via Malus' Law in terms of the number of hits in each channel divided by N, the number of pairs, i.e:

$$\langle a,b\rangle = \frac{N_{++} + N_{--} - N_{+-} - N_{-+}}{N_{++} + N_{--} + N_{+-} + N_{-+}}, \tag{4.3}$$

where $N_{..}$ is the number of detections in the respective channel. This is a formula cited often in the literature describing Bell-test experiments. The analysis above, however, indicates that in stead the following formula should be used:

$$\langle a,b\rangle = \frac{2(N_{++} + N_{--} - N_{+-} - N_{-+})}{N_{++} + N_{--} + N_{+-} + N_{-+}}. \tag{4.4}$$

Direct simulations have verified that if for an individual detection the bias angle is fixed and the measurement repeated, thereby enabling the calculation of the intensities, I in 3.1, then the data taken is such that the correct coincidence coefficient is obtained without the factor of 2. On the other hand, if the measurement is repeated, so as to find the ratio of detections to total pairs, but with a randomization of the bias angle for each repetition, them this factor must be inserted. Thus, in the latter case, the averaging is not of separate, equally (in)accurate individual measurements, but of an increasing sequence of estimates, each more accurate than the previous. Insofar as in a realization of an experiment no control over the random bias is possible, it would seem that the analysis of done experiments must include this factor of 2. How this has been accommodated in the data analysis of done experiments appears not to have been discussed in the literature. For this author, this discrepancy remains unresolved.

5. Conclusions

The considerations presented herein support three contentions:

(1) The interpretation of the consequences of Bell's Inequalities is in error. Their violation does not prove that there exists some kind of nonlocal interaction or correlation (entanglement) as a consequence of the principles of Quantum Mechanics.

(2) The venue for (at least) all experiments employing polarized signals is fundamentally classical and cannot therefore be used to plumb quantum structure or effects. Thus all such experiments can be understood and simulated in terms of classical electrodynamics.[12]

(3) The coincidence coefficient formula most often reported in the literature, 4.3, for analysis of data taken in Bell-test experiments at the impugned single photon level appears to be incapable of giving the result validating the usual conclusion drawn from these experiments.

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