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Do EPR-Bell correlations require a non-local interpretation of quantum mechanics? I: Wigner approach

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Abstract

Bell inequality experiments teach us that, to explain the data, a hidden variable theory must be non-local. But, to also apply this conclusion to quantum mechanics is unjustified. The key assumptions required to obtain a Bell inequality are (1) locality and (2) the assignment of meaningful (non-negative) probabilities to seemingly physical correlations (Bell expresses these correlations via "hidden variables"). Since the Bell inequality is violated by experiment, at least one of these assumptions is wrong. The widespread conclusion that locality must be relinquished is unwarranted; rather, the previously mentioned correlations are not physical observables—they are not elements of physical reality.

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At a recent international conference on quantum informatics, one of us (M.O.S.) asked the assembled scientists how many believed that the EPR-Bell correlation experiments required a nonlocal interpretation of quantum mechanics. More than half of the approximately 200 participants raised their hands. This is not surprising since the literature abounds with "yes votes". For example beautiful recent experiments showing violation of Bell's inequality begin with the statement that quantum theory is non-local [1]. Are we forced to conclude from such experiments that

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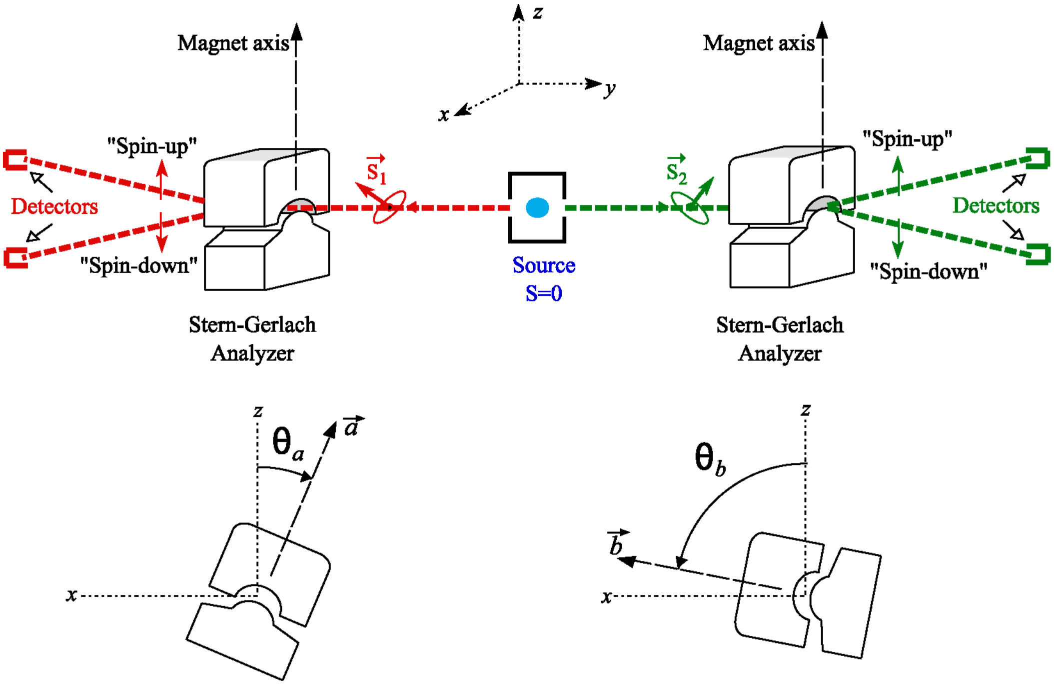

Fig. 1. Schematic for Bohm's version of the EPR argument.

quantum mechanics requires a "spooky action-at-a-distance" interpretation? It is the purpose of this Letter to show that this is not the case and to illuminate the concepts of physical reality and non-locality.

Concerning the EPR "paradox" (and by implication, the present Bell experiments) Einstein argued that we must "relinquish" (his words) either reality or locality. He brings a sharp focus to the problem by clearly defining these constructs as per the following famous quotes:

Reality: "If, without in any way disturbing a system, we can predict with certainty the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity" [2].

Locality: "The real factual situation of the system S_2 is independent of what is done with the system S_1, which is spatially separated from the former" [3].

Bohm's version of the EPR argument is based on the spin singlet state of a system consisting of two spin one-half particles labeled 1 and 2. The corresponding state vector can be written

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\big\{|\uparrow\rangle_1|\downarrow\rangle_2 - |\downarrow\rangle_1|\uparrow\rangle_2\big\}. \tag{1}$$

A schematic of Bohm's version for the EPR argument showing relevant parameters is provided in Fig. 1.

If the component of the spin of one particle is measured in some direction $\vec{a}$ and is found to be $+1/2$, then a measurement of the spin of the other particle can be predicted with certainty to be $-1/2$ if measured in the same direction $\vec{a}$. Furthermore, this result follows regardless of the spatial separation of the particles or the direction $\vec{a}$. This is the quantum mechanical prediction and the experimental fact. It is this strong EPR correlation of spatially separated particles that has been the source of debate for more than 60 years; it is also the basis for the EPR conclusion that quantum mechanics is an incomplete theory. In particular, Einstein was inclined towards the notion that the theory should be supplemented by some additional "hidden" variables. Bell showed that a description of the EPR correlation based on a local hidden variable theory moves the problem from a strictly philosophical discussion into the realm of experimental physics. In the