Nonlocal “realistic” Leggett models can be considered refuted by the before-before experiment

Antoine Suarez
Center for Quantum Philosophy,
P.O. Box 304, CH-8044 Zurich, Switzerland
suarez@leman.ch, www.quantumphil.org
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Nonlocal “realistic” Leggett models can be considered refuted by the *before-before* experiment. “Single preferred frame” models are not refuted by this experiment but bear severe oddities.

Key words: time-ordered nonlocality, before-before experiment, Leggett’s inequality, single preferred frame, influences from outside space-time.

1. Introduction

Recently, several experiments testing Leggett nonlocal hidden variables models have been presented [1–4]. Such models fulfill the so called Leggett’s inequality, whereas quantum mechanics violates it [5]. The experimental results show a violation of this inequality, and are in agreement with the predictions of quantum mechanics.

The mathematical derivation of the Leggett’s inequality as such does not require time-ordered nonlocality. This is particularly clear in [4] because the way the inequality is derived avoids any description of the nonlocal links. Nevertheless, as soon as one embeds Leggett’s inequality in a model supposed to describe the physical reality, one is led to characterize the non-local links: either they are time-ordered (and hence timing-dependent) or not.

Section 2 considers time-ordered Leggett models assuming that one event can be considered the cause (occurring before in time), and the other the effect (occurring later in time). In *Section 3* I argue that such models, and in particular the “realistic” models proposed in [1, 2], can be considered refuted by the before-before experiment [6–9].

Section 4 considers Leggett-like models that take account of my comment in Reference [9], and do not assume any time-order between the nonlocal correlated events [4]. I stress that such models are necessarily nondeterministic, and discuss the physical meaning of their experimental refutation.

Section 5 argues that the before-before experiment actually also falsifies the relativistic testable version of Bohm nonlocal realistic theory. The experiment does not refute models assuming a “single preferred frame”, but these should be abandoned by other reasons.

Section 6 sums up the conclusions.

2. Nonlocal “realistic” Leggett models

The concept of “nonlocal realism” has been introduced to characterize theories that pretend to explain quantum entanglement assuming both nonlocal influences and “realism” [1, 5]. Nonlocal influences means actions producing correlated events in two space-like separated regions. “Realism” means that the results of observations are a consequence of pre-existing properties carried by physical systems.

One defines nonlocal “realistic” models fulfilling the Leggett’s inequality through the following description (see [1] and related supplementary information):

A source emits pairs of photons in a maximally entangled state, and it is assumed that the single photons in the pair carry well-defined polarizations. One of the photons with polarization vector $\mathbf{u}$ is sent to Alice’s laboratory and measured with a polarizing beam-splitter set at angle $\mathbf{a}$, and the other photon with polarization vector $\mathbf{v}$ is sent to Bob’s laboratory and measured with a polarizing beam-splitter set at angle $\mathbf{b}$. A polarization measurement gives either a result of $+1$ or -1 depending on whether a single photon is transmitted or reflected by its polarizer.

Gröblacher *et al.* choose an explicit nonlocal dependence of Bob’s outcomes on Alice’s ones, though, they note, that one can also choose any other example of a possible non-local dependence. Thus, the local polarization measurement outcomes A are predetermined by the polarization vectors $\mathbf{u}$ and an additional set of hidden variables λ specific to the source. The local polarization measurement outcomes B are predetermined by the polarization vectors $\mathbf{u}$ and $\mathbf{v}$, the set of hidden variables λ, the settings $\mathbf{a}$ and $\mathbf{b}$, and any possible non-local dependence of Bob’s outcomes on Alice’s ones.

It is a crucial trait of the Leggett’s “realistic” models that there exist subensembles of definite polarizations before measurements, described by a probability distribution $\rho_{\mathbf{u},\mathbf{v}}(\lambda)$. Then, the non-signalling condition imposes that the local averages performed on the subensemble of definite (but arbitrary) polarizations $\mathbf{u}$ and $\mathbf{v}$ obey Malus Law, i.e.:

$$\bar{A}(\mathbf{u}) = \int A(\mathbf{a},\mathbf{u},\lambda)\rho_{\mathbf{u},\mathbf{v}}(\lambda)d\lambda = \mathbf{u}\cdot\mathbf{a} \tag{1}$$

$$\bar{B}(\mathbf{v}) = \int B(\mathbf{a},\mathbf{b},\mathbf{u},\mathbf{v},\lambda)\rho_{\mathbf{u},\mathbf{v}}(\lambda)d\lambda = \mathbf{v}\cdot\mathbf{b} \tag{2}$$

All nonlocal dependencies are put on the side of Bob, in Equation (2): his measuring device has the information about the setting of Alice, **a**, and her polarization **u**. Theories in accordance with this description fulfill the Leggett's inequality [1], while they violate the Bell's inequality to the same extent of quantum mechanics. Both inequalities are tested by performing coincidence measurements (A,B) with different settings. The experiments show violations of the inequalities, in agreement with the predictions of quantum mechanics [1–3]. Gröblacher *et al.* concluded that "giving up the concept of locality is not sufficient to be consistent with quantum experiments, unless certain intuitive features of realism are abandoned" [1].

According to the postulate of "nonlocal realism" all measurements A and B are determined by the "pre-existing" properties (hidden variables) the particles carry [1, 5]. However, the individual B outcomes cannot be considered to be predetermined by the polarization vectors **v** the photons B carry when they leave the source and the set of local hidden variables λ specific to the source, for the B outcomes depend non-locally on the A outcomes, as Equation (2) indicates. The influence coming from the pre-existing polarization of photon B does not matter for the value of the individual B outcomes, but only for their statistical distribution. Therefore, "nonlocal realism" implies that the individual outcomes in Bob's laboratory are determined by "pre-existing" space-like separated outcomes in Alice's laboratory, and these are determined by the hidden variables the corresponding photons A carry when they leave the source, according to the causal chain sketched in Figure 1.

The term "pre-existing" has an obvious *temporal* meaning. Hence, for coincidence measurement outcomes (A, B) in the laboratories of Alice and Bob, "nonlocal realism" means that each individual outcome A at Alice's side precedes in time and causes the correlated individual outcome B at Bob's side. Thus, one is led to the conclusion that the postulate of "nonlocal realism" requires the assumption of *time-ordered nonlocal influences*. "Nonlocal realism" (as defined in [1, 5]) fails if experiment proves wrong that *one of two non-locally correlated events occurs before and is the cause of the other.*

3. "Realistic" Leggett models can be considered refuted by the before-before experiment

Time-ordered nonlocal influences imply that it is possible to establish the timing of the outcomes by means of a *real* clock. The trouble is that since Bob and Alice stay space-like separated the timing will depend on the inertial frame of the measuring observer. However, any "realistic" theory must assume that the photon always travel a definite trajectory determined by the particle's properties, and the outcome becomes determined at the corresponding polarizing beam-splitter at the moment the particle hits it (Figure 1); additionally, a photon experiencing the inertial frame of the beam-splitter becomes doppler shifted when it is reflected by a beam-splitter in motion. Therefore it is coherent to assume that the inertial frame of Alice's polarizing beam-splitter defines the clock measuring the time for her outcome, and the inertial frame of Bob's polarizing beam-splitter defines the clock measuring the time for his outcome.

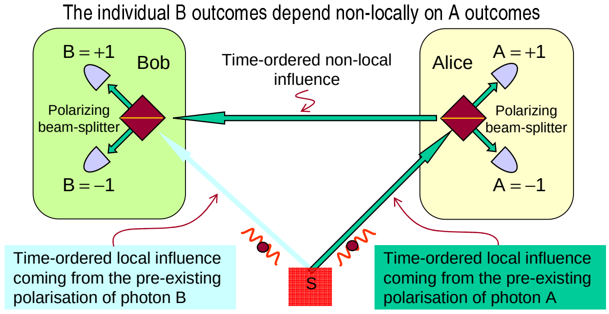

FIG. 1: Causal chain built of time-ordered nonlocal influences and time-ordered local ones. The figure shows (dark-green, counterclockwise) the causal chain corresponding to the choice of Reference [1]: the individual B outcomes depend nonlocally on pre-existing A outcomes, and these depend locally on the polarization of photon A when it leaves the source; a similar (not shown) causal chain could be drawn (light-blue, clockwise) for the alternative case of the individual A outcomes depending nonlocally of B outcomes.

Consider now a relativistic experiment with beam-splitters in motion in such a way that each of them, in its own reference frame, is first to select the output of the photons (before-before timing). Then, each outcome will become independent of the other, and the nonlocal correlations should disappear [6, 7]. This means that theories assuming time-ordered non-local influences predict the disappearance of non-local correlations in before-before experiments, and the same holds for theories sharing "non-local realism".

A before-before experiment has been done in 2001 [8], though not using polarizers but interferometers. The result was that the correlations doesn't disappear. The experiment ruled out the view that an observable event (the effect) always originates from another observable event (the cause) occurring before in time [8, 9]. Hence it proved "nonlocal realism" (as defined in [1]) wrong.

Nonlocal correlations have their roots outside of space-time [10], "the spacetime does not contain the whole physical reality" (Nicolas Gisin).

The before-before experiment demonstrates that Nature works out the quantum correlations in a nonlocal and non-deterministic way. This means that the measurement outcomes (for instance $A = +1$ and $B = -1$, in the experiment sketched in Figure 1) imply a true *choice* on the part of Nature, and are not determined by pre-existing properties the particles carry independent of the act of measurement [9, 10].

It is important to stress that to drawing these consequences one tacitly assumes the freedom of the experimenter. If one rejects this freedom one can explain the nonlocal correlations in a fully deterministic and local relativistic way by pictures like "Super-determinism" or "Many Worlds" [12]. One can speak with Anton Zeilinger's about "two freedoms" [13]: The freedom of the experimenter implies the freedom on the part of Nature.

Note that the relative motion of beam-splitters is central in the argument because we are considering "realistic" models. By contrast, the "collapse of the wave function" cannot be considered a "realistic" view in the sense of [1]. The "collapse" entails a choice on the part of Nature about which detector clicks, and therefore a nonlocal influence between the detectors. But the "collapse" picture also assumes tacitly that the nonlocal influence between the detectors is not time-ordered or nondeterministic. Thus, if one wishes to save time-ordered causality one is forced to assume that the outcomes are determined at the beam splitters (like De Broglie and Bohm did).

I also think that 'determinism' (on the part of Nature) would be a more appropriate name for the concept denoted "realism" in [1]. In any case, to avoid confusion one should clearly distinguish between "realism" as used in [1], and "realism" as the view that the "collapse of the wave function" can happen without the presence of a conscious human observer. The before-before experiment has proved that nonlocal choices happen in Nature, and in this sense refuted "realism" as defined in [1]. The independence of quantum measurement from the presence of human consciousness has not been proved wrong by any experiment to date.

4. Leggett-like models excluding time-order

In Reference [3] one explains the tested Leggett model with "a first particle to be measured" and the other receiving thereafter the information: "the particle that receives the communication is allowed to take this information into account to produce non-local correlations, but it is also required to produce outcomes that respect the marginals expected for the local parameters alone." This explanation apparently contradicts the implications of the before-before experiment [8, 9].

In the more recent work [4] the authors avoid such an explanation and explicitly assume the result of the before-before experiment: "nonlocal correlations happen from outside space-time, in the sense that there is no story in space-time that tells us how they happen." Accordingly, the experimental results they present refute a Leggett-like model that does not assume any time-order of the events. [4]

Such a model necessarily accepts non-determinism on the part of Nature: if there is no story in space-time that tells us how the correlation happens, there is no such story that tell us how each of the correlated outcomes happens. Therefore it is no longer appropriate to think of trajectories and polarizations of quantum "particles" in the classical way: the output port the "particle" takes cannot be derived from the eventual preceding trajectory; similarly, it is confusing to assume that each photon is perfectly polarized in some direction, since the single local outcomes do not exclusively result from the properties of the polarized state.

Even after accepting this, one may be tempted to restrict Nature's freedom, forcing it to *mimic* or *simulate* certain classical features that are not required by the statistical distributions imposed by the quantum formalism. Leggett-like models mimic polarizations by assuming non-vanishing marginals for singlet state, and this leads to a contradiction with quantum predictions [4]. Thus, the experimental violation of the Leggett's inequality strengthens the view that it is not appropriate to restrict Nature's freedom in the quantum phenomena by forcing it to imitate certain classical features.

Notice however that even the orthodox picture cannot help using classical features. Any setup demonstrating quantum interference exhibits always two well defined classical paths connecting the source with each detector. This is so even if the interferences show that the quantum "particles" do not follow such paths as visible bodies are supposed to do.

5. Preferred frame models

If one assumes that Bohm's time-ordered nonlocality belongs to physical reality, one has to cast it into a description using *real* clocks and accepting the experimental result of the relativity of time. As said above, the essential ingredients of a realistic theory lead naturally to accept that the relevant clocks are those defined by the inertial frames of the beam splitters. In this sense, Bohm's model is the adequate time-ordered nonlocal description for entanglement experiments with beam splitters at rest. And its natural extension to experiments with beam splitters in motion is the model leading to the prediction that the nonlocal correlations should disappear in the before-before experiment [8, 10]. Therefore, this experiment proves nonlocal determinism in the testable relativistic extension of Bohm's model wrong.

Models assuming that the "realistic" mechanism happens in a single preferred frame even in relativistic experiments with devices in motion, are not refuted by the before-before experiment, but such models bear a fundamental oddity: since they assume that each event has a cause preceding it in time, they actually dispose of the freedom of the experimenter. But then (as said in Section 3) one can get rid of the spooky nonlocal influences as well by choosing pictures like "Super-determinism" or "Many Worlds" [12]. Giving up the "mystery of freedom" and maintaining the "mystery of nonlocality", "single preferred frame" adopts somewhat an incoherent attitude.

Additionally, in the particular case, possible in principle, of both measurements taking place at exactly the same time in this frame, the model implies the disappearance of the nonlocal correlations, just like the before-before model. Any time-ordered nonlocal model necessarily predicts disappearance of quantum correlations in certain situations. The only difference is that the before-before experiment can and has been done, whereas an experimental setup allowing us to perform perfect simultaneous measurements is not feasible.

Finally, models postulating only one preferred frame avoid to define which *real* clock (inertial frame) has to be used for establishing the time order of the events. Thus a single preferred frame ("quantum ether") is "experimentally indistinguishable" in principle and not testable against quantum mechanics [15, 16]. An untraceable "quantum ether" is for all experimental purposes the same as freely deciding which event depends on which one. Thus, if you wish nonlocality, you can have it together with freedom by choosing orthodox (Copenhagen) quantum mechanics.

6. Conclusion

The before-before experiment is a key result to a proper understanding of nonlocal correlations. Provided one accepts that the experimenter is free, this experiment demonstrates that there is no time-order behind the non-local correlations, and rules out "realistic" Leggett models, which assume time-ordered nonlocality.

Leggett-like models excluding time-order assume that the outcomes are not pre-determined. Their experimental refutation supports the view that it is misleading to attempt to limit freedom in Nature through constraints stronger than the statistical distributions imposed by the quantum formalism.

Finally, the "single preferred frame" is not refuted by the before-before experiment, but is not a coherent picture: it does not make sense to maintain the spook of nonlocality giving up the experimenter's freedom, since one can get rid of both "mysteries" (freedom and nonlocality) by choosing deterministic local pictures that are fully compatible with relativity, like Super-determinism and Many-Worlds.

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