Article

Do Quantum Measurements Reveal Pre-existing Properties?

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Abstract: The EPR paradox was caused by the provision that quantum variables must have pre-existing values. This type of "hidden property realism" was later falsified by Bell's Theorem. Yet, modern interpretations of quantum entanglement still insist on the reality of pre-existing properties, whether explicitly or implicitly. Instead, they treat Bell's inequality as a Locality Criterion. This is a questionable practice, considering that classical joint measurements also violate such inequalities for mutually exclusive wave properties. In particular, consecutive measurements of polarization produce the same coefficients of correlation as parallel measurements with polarization-entangled quanta, yet they are explicitly local. Nonetheless, they also require nonlocal interpretations if pre-existing properties are taken for granted. The solution is to reject the models with pre-existing properties for both classical and quantum wave-like phenomena.

Keywords: Bell's theorem; EPR paradox; quantum entanglement; non-locality; classical superposition; quantum superposition; Malus' law; joint measurements; correlation

1. Introduction

Quantum observables can be interpreted in two ways. They can be described as *pre-existing* properties of quantum projections, or simply as qualities that are *created* by the act of measurement. Einstein, Podolsky and Rosen (EPR) argued in 1935 [1] that quantum entanglement supports the first alternative. Yet, their Reality Criterion had a strange implication: joint measurements with entangled quantum systems appeared to require action at a distance for non-commuting observables. This problem was solved by Bell in 1964 [2] by showing that pre-existing properties cannot reproduce the predictions of quantum theory. Jointly distributed variables have limited coefficients of correlation, in a manner that quantum variables do not. Therefore, experimental violations of Bell-type inequalities [3-11] refute the so-called Einstein realism, and the non-locality that it entails. Unfortunately, Bell interpreted his inequality as a Locality Criterion, suggesting that any violation would require non-locality, not just the correlations of pre-existing properties. His view became very influential and still informs the interpretation of quantum entanglement to this day. Yet, from a mathematical point of view, Bell's Theorem only works for pre-existing properties [12, 13]. It does not extend to locally created properties. Accordingly, we need to ask a philosophical question: do physicists prefer non-local explanations for objective or for subjective reasons? Could it be that human intuitions find it hard to grasp the statistical patterns of created properties, and chronically slide back towards variables with pre-existing values? If this is the case, then it may not be enough to explain the dynamics of created properties from first principles. A deeper social impact might require indirect approaches to this problem as well. For example, Khrennikov showed in 2008 [14] that Bell inequalities belong to a wider class of statistical relationships, known as Boole inequalities. Such expressions are used in other branches of science without concerns about locality. In the same vein, this letter is intended to advance the debate with an experimental counterexample to Bell's Locality Criterion. Consecutive classical measurements produce the same coefficients of correlations as parallel quantum measurements, yet their mechanism of correlation is explicitly local. Therefore, no "detector communication" is required for quantum Bell violations either.

2. Bell violations with consecutive classical measurements

It is often suggested that Bell violations are a special quantum effect, implying that classical projections cannot display the same kind of behavior. Yet, this cannot be true because quantum and classical observables are known to obey the Correspondence principle [15]. Namely, quantum distributions are quantitatively identical to classical distributions for large numbers of detection events. For example, two orthogonal polarizers are able to block a quantum beam completely. In other words, all the quanta that pass through a vertical polarizer cannot also pass through a horizontal filter (in ideal conditions). Yet, this rule can be broken by introducing a diagonal polarizer in-between the two original filters. According to Malus' Law, 25% of the quanta that can pass through the vertical filter will also pass through the horizontal filter in this case. It is very well known that classical optical projections *also* obey Malus' Law and display *the same* kind of behavior when they interact with polarizing filters or beam-splitters [16]. Yet, if classical projections also obey Malus' Law, then they also violate Bell inequalities.

A depolarized laser beam can be split 50-50 by a polarizing beam-splitter (PBS), at any angle of measurement. The outcome is a pair of projections with orthogonal linear polarization (*e.g.*, vertical and horizontal, diagonal and anti-diagonal, etc.). Yet, even if the increment of measurement is just 1°, there are 360 ways to split a single input beam in this manner. With finer increments, the number of output orthogonal pairs can become arbitrarily large. Where do all these properties come from? Do they correspond to pre-existing spectral components of the input projection, or are they created by the interaction between the beam and the PBS? Thanks to Bell's Theorem, we know how to find the answer. For example, if we add another PBS in each output projection (Figure 1a), we can determine the coefficient of correlation between any two states of polarization. If it turns out that such coefficients cannot violate a Bell-type inequality, then we are dealing with states of oscillation that are "always there" in the input beam. In contrast, if Bell violations are the norm, then we are dealing with created properties. The most convenient way to conduct such a test would be to use the measurement scheme proposed by Clauser, Horne, Shimony and Holt (CHSH) [17]. The only difference is that *consecutive* measurements with classical projections will be considered, instead of *parallel* measurements with polarization-entangled photons. The interpretive value of this choice will be explained below.

As a reminder, the CHSH inequality is:

$$\mathbf{S}=|\,E(\mathbf{A},\mathbf{B}) + E(\mathbf{B},\mathbf{C}) + E(\mathbf{C},\mathbf{D}) - E(\mathbf{A},\mathbf{D})\,| \leq 2. \quad (1)$$

In order to predict the highest possible violations with optical states of polarization, the four variables need to be separated by an angle of 22.5°. For example, if variable **A** corresponds to a PBS setting with T_A=0° (and R_A=90°), then the remaining variables can be defined such that T_B= 22.5, T_C=45° and T_D=67.5°. As shown in Figure 1a, pairwise measurements can be performed by designating the first PBS as "Alice", and the second PBS in each output projection as "Bob". To give just one example, if PBS_{Alice} is aligned to transmit 0° polarizations, then PBS_{Bob} cand be aligned to transmit 22.5° polarizations. The Alice PBS always has an output of 50-50, because the input projection is depolarized. The Bob PBS will always transmit and reflect radiation in strict accordance with Malus' Law. In this case, Bob is predicted to observe an 85-15 split in Alice's transmitted channel, and a 15-85 split in Alice's reflected channel. The coefficient of correlation is determined according to the standard rule:

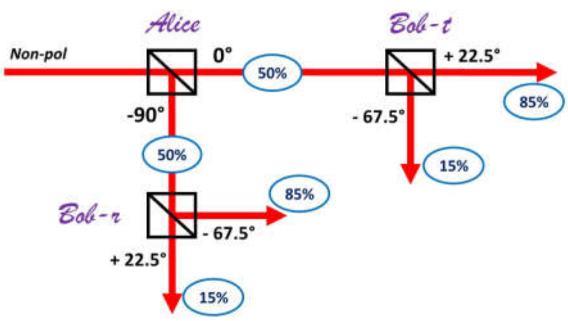
$$E(\mathbf{A},\mathbf{B})= (T_AT_B + R_AR_B - T_AR_B - R_AT_B)/100\%. \quad (2)$$

Three joint measurements – E(**A**,**B**), E(**B**,**C**) and E(**C**,**D**) – have the same relative angle of 22.5°. Therefore, they must yield a coefficient of correlation of approximately 0.7. However, the final joint measurement corresponds to an angular separation of 67.5°, and the approximate coefficient of correlation of E(**A**,**D**)= − 0.7. As a result, we can see that the four coefficients of correlation produce a violation of the inequality (1) mentioned above:

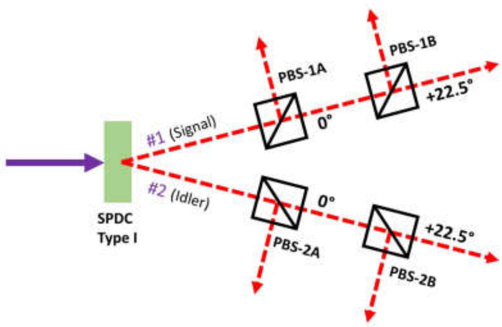
$$S = |0.7 + 0.7 + 0.7 - (-0.7)| = 2.8. \quad (3)$$

Moreover, this is not just any random violation. This is exactly the same result that is predicted by quantum theory for joint measurements with polarization-entangled quanta and confirmed by the celebrated experiments of Aspect and collaborators [3-5]. On closer inspection, this result is not surprising in light of the Correspondence principle.

As a corollary of the above, Bell violations can happen for many kinds of wave-like observables, if they do not commute. This cannot be interpreted as a uniquely "quantum" phenomenon. More importantly, consecutive measurements with classical projections reveal several technical details that are not available in quantum experiments with entangled quanta. First of all, we can see that Malus' Law does not depend on the order of measurements. For any two variables, Alice can measure the first and Bob the second, or vice versa, without any effect on the resulting coefficient. Secondly, if Alice makes one measurement, then it is irrelevant which of two other observables is chosen for measurement by Bob. The outcome is the same, without any need for "back propagation". In other words, once Alice makes the first measurement, her contribution is over. The second measurement can be in any of the two allowed orientations, and Bell violations still happen. Therefore, it is not true that Alice and Bob need to know what the other party is going to measure, and their local distributions do not need to change in any way in response to such knowledge. Finally, note again that Bell violations are possible for high intensity classical projections. They can even be replicated with oscillating ropes, or other types of classical oscillators that can be polarized. In short, Bell violations happen by default for any system that obeys Malus' law. It is not necessary to invoke metaphysical processes in order to explain this behavior.



(**a**)



(**b**)

Figure 1. Bell experiments with consecutive and parallel joint measurements. Classical measurements of polarization produce the same distributions as quantum measurements, but the interpretation is less ambiguous. (**a**) A non-polarized laser beam is split 50-50 by a polarizing beam-splitter (PBS) designated as "Alice". A second PBS is added in each output projection, designated as "Bob-t" for the transmitted channel, and "Bob-r" for the reflected channel. The correlations between consecutive measurements of polarization are governed by Malus' Law, and Bell violations follow by default. (**b**) Identical polarization-entangled photons are produced via Type I spontaneous parametric down-conversion (SPDC). Each beam has an experimental set-up similar to the classical example on left. The quantitative features of this arrangement show that parallel measurements of photon polarization have the same underlying mechanism as the described consecutive classical measurements. Bell violations do not require communication between Alice and Bob.

3. Interpretive equivalence of consecutive and parallel measurements

A possible objection to the preceding conclusion is that parallel measurements are different from consecutive measurements. In a quantum Bell experiment, entangled quanta are measured only once. In contrast, consecutive measurements allow Alice to change the physical properties of the quantum that is received by Bob. In order to address this concern, let us consider a pair of beams with polarization entangled quanta. For simplicity, let us assume that entangled quanta produce identical measurement outcomes, when measured in the same way. (In practice, this can be achieved with Type I parametric down-conversion [18-19]). As shown in Figure 1b, every projection has two polarizers. First, let us consider what happens if both beams have the first PBS oriented at 0° and the second at 22.5°. In each path, the quanta are expected to obey Malus' Law for consecutive measurements. Yet, the two quanta must always be transmitted at the same time (or reflected at the same time) by the first PBS (1A and 2A respectively), because they are maximally correlated. This means that some of the measurements across the two beams are interchangeable. In particular, measurement A of quantum 1 will obey Malus' Law in coincidence with measurement B in its own path, as well as with measurement B in the path of quantum 2. The same is true for quantum 2. Next, we can reverse the order of measurements in the path of quantum 2, so that measurement 2B is happening ahead of 2A. As shown above, the order of observation does not matter, and Malus' Law is still obeyed. Yet, this means that measurement 1A will display the same coefficient of correlation with the second measurement in its own path (1B) as with the first measurement (2B) in the path of quantum 2. Again, no communication between the two paths is required for this phenomenon. The crucial detail is that measurement 1A can remain fixed, while measurement devices at 1B and 2B can be switched between alternative settings. Malus' Law is obeyed in any configuration, but PBS-1A is sampling the same random variables at all times. Therefore, it is not true that Alice needs to know what Bob is doing, in order for their joint measurements to violate Bell-type inequalities, even at large distances.

As a corollary of the above, Malus' Law is an intrinsic rule of any polarized system. If an object is "such that" it obeys Malus' Law for any order of consecutive measurements, then it is also "such that" it obeys Malus' Law for parallel measurements of polarization with its identical clone. A quantum cannot help but satisfy the prescriptions of Malus' Law in such measurements. Therefore, it can only behave in this way, and there is no qualitative difference between the two alternative methods for observing the same coefficient. An obvious feature of consecutive measurements is that Alice has a direct impact on the input of Bob. Nonetheless, it is a mistake to interpret this effect as a *necessary* condition for the manifestation of Malus' Law. In other words, Alice's device does not "cause" a quantum to behave according to Malus' law in Bob's device. It simply defines the way in which the intrinsic propensity to obey this law would manifest itself in particular coincident observations. Another way to think about this is that any measurement is a transformation. Alice transforms her quantum in a chosen way. If Bob chose to repeat the same exact measurement, Bell violations would not be observed. Yet, Bob can also choose to transform his input beam in two incompatible ways. The two alternatives cannot be reconciled as coexisting properties of Alice's output projection. This is why Alice and Bob obtain correlations that cannot be explained with jointly distributed variables. In short, it is not Alice's effect on Bob that determines the violation. It is Bob's local choice to rotate the polarization profile in opposite directions that produces this effect. Likewise, if Alice and Bob make parallel measurements, the underlying mechanism is not substantially different. Identical inputs with identical transformations produce identical outputs. If Alice makes a measurement, Bob's quantum is "such that" it would produce the same outcome for a parallel transformation. Therefore, it is also "such that" rotating the input state produces output states that obey Malus' Law, relative to Alice's anchor state. Intuitively, it may feel as if Alice has to change her behavior in response to Bob's choice when Bell violations occur, yet this is only true for pre-existing properties (not for transformations).

4. Discussion

As suggested at the beginning of this analysis, the physical reality behind binary measurements of polarization is not self-explanatory. When a beam passes through a PBS, it is split into two components. The vector sum of these components is equal to the input vector, but how should we think about the input projection? According to the established tradition in classical wave mechanics, any act of decomposition is supposed to reveal the physical spectrum of pre-existing components of the input beam (rather than its virtual structure). In other words, the observable net profile of any optical projection can be interpreted as an illusion. The "true underlying reality" must consist of various spectral components, acting together without perturbing each other. For example, if a laser beam is measured by a PBS with the fast axis in the vertical plane, then the input beam must have contained two components: one vertical and one horizontal. However, if the PBS is rotated to the diagonal plane, then the input beam contained a different set of pre-existing components: one diagonal, and the other antidiagonal. The problem with this explanation is that classical entities cannot move in two directions at the same time. Yet, the PBS can be used to measure hundreds of different angles of observation. Therefore, it is not possible to explain how all of these alternative "pre-existing" configurations are possible at the same time. In order to maintain a classical description of the underlying reality, new physical factors must be invented, such as to explain the "retro-causal" connection between observable features and the implied input pre-existing features. For this to work, incoming waves must "know" what the measurement setting is going to be and must change their properties all the way back inside the laser. Notice that such nonlocality is needed to explain *individual* alternative measurements, before we even start to consider joint observables. Hence, even if the mechanism behind Malus' Law is explained with metaphysical processes, having remote measurements does not add anything new the big picture.

Another alternative is to assume that polarization measurements do not reveal pre-existing components, but rather "create" them. In other words, the net state of the incoming projection is assumed to be physically real, while the interaction with the PBS is assumed to produce two new components whose total angular momentum is equal to the input value of the "parent" state. If polarization measurements are interpreted as transformations, then there is no mystery to explain. Output profiles of wave transformations are contextual, and there is no requirement for alternative outcomes to be statistically compatible with each other (unlike pre-existing particle properties). This interpretation is particularly resonant with the principle of "completeness" of quantum theory. If the net state is all that there is, then there are no pre-existing components that correspond to observable outcomes. Yet, this means that popular interpretations of quantum behavior, stating that particles are "in many states at the same time", express preconceived notions about classical superposition, and actually contradict the basic features of quantum superposition. Surprisingly, quantum superposition is ontologically classical, and classical superposition is non-classical. Still, in both cases, Bell violations emerge from the different possible interactions with a single PBS, without need for mutual effects between different measurement devices.

The novelty of this contribution is not in the facts that were described above. Such examples were often invoked in various debates about quantum behavior, throughout the history of modern physics. To give just one example, this solution was already suggested in the EPR paper [1]. In the penultimate paragraph, the authors discussed the possibility that non-commuting measurements might be real only in their context of observation. Yet, they dismissed this scenario as unreasonable. In retrospect, this might have been due to their unspoken commitment to "classical superposition" [20]. Likewise, supporters of the Copenhagen interpretation found it easier to embrace nonlocality than to question the conceptual status quo regarding wave behavior. As far we can see, quantum non-locality is taken for granted to this day, while quantum superposition is widely interpreted in terms of pre-existing spectral components [21]. Accordingly, the point of the preceding argument is not that classical behavior is poorly known, but rather that that such a parallel between classical and quantum Bell violations was blocked from consideration by the established paradigm. Thus, it is high time to shift the focus from "quantum weirdness" to the unsuspected interpretive problems of classical wave mechanics.

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