Defending Quantum Objectivity

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A recent argument, attributed to Masanes, is claimed to show that the assumption that quantum measurements have definite, objective outcomes, is incompatible with quantum predictions. In this work, a detailed examination of the argument shows that it has a much narrower field of application than previously recognized. In particular, it is found: i) that the argument only applies to hidden-variable models with a particular feature; and ii) that such a feature is not present in most hidden-variable models, including pilot-wave theory. It is concluded that the argument does not succeed in calling into question the objectivity of quantum measurements.

1 Introduction

A number of recent arguments in the field of quantum foundations seek to call into question the objectivity of quantum measurement results. In particular, they try to challenge the assumption that quantum measurements yield definite, objective outcomes. These new arguments, often involving so-called extended Wigner's friend scenarios, are touted as having the added advantage of being formulated in terms of actual results of measurements—and not in terms of potentially unreliable theoretical elements, such as Bell's λ's or PBR's ontic states.

One such argument is reported in a talk by Matthew Pusey [14], where it is attributed to Lluis Masanes (see also [8, 1, 9]). The argument is described as easier to understand, but containing all the essential features of the more popular no-go result in [6].[1] The proposed construction involves a gedankenexperiment with four observers, in a sort of crossbreed between Wigner's friend and Bell-type scenarios. The proposal surely demands extreme technical capabilities, but is argued to be compatible, at least in principle, with quantum theory.

This work offers a detailed examination of the argument. To do so, section 2 introduces the argument, section 3 presents the analysis and section 4 states the conclusions.

[1]The result in [6] has been convincingly argued to crucially depend on an implicit assumption, to the effect that when a measurement is carried out inside of a closed lab, such a measurement leads to a collapse for inside observers, but does not do so for outside observers (see [2, 15, 16, 10, 4, 17, 12]). In consequence, the result is not as robust or general as intended.

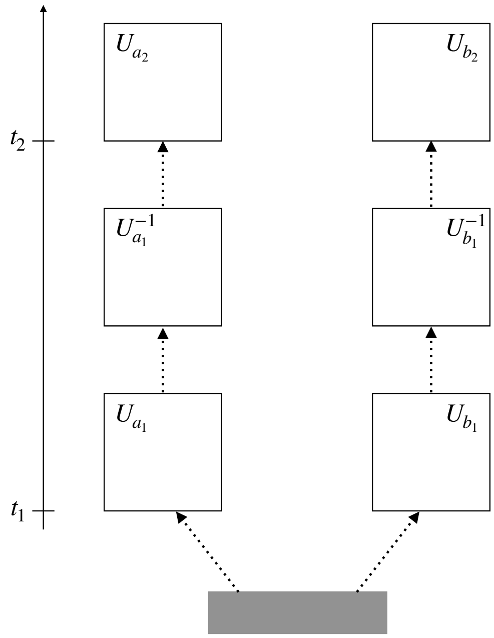

Figure 1: Schematic representation of the gedankenexperiment.

2 The argument

The gedankenexperiment employed by the argument starts with the two spin-$\frac{1}{2}$ particles of a singlet state being sent to two spatially separated laboratories, where observers $\mathcal{A}_1$ and $\mathcal{B}_1$ perform spin measurements along directions a_1 and b_1, respectively; we denote these measurement results, which take values $+1$ or -1, by A_1 and B_1. Next, observers $\mathcal{A}_2$ and $\mathcal{B}_2$, who are outside of the laboratories of $\mathcal{A}_1$ and $\mathcal{B}_1$, respectively, come and *undo* these initial measurements. The idea behind this is that, from the point of view of, say, $\mathcal{A}_2$, all that happens when $\mathcal{A}_1$ measures, is some complicated unitary transformation. Therefore, $\mathcal{A}_2$ can, at least in principle, come and apply the inverse of such a unitary to $\mathcal{A}_1$'s laboratory to nullify the measurement. The last step is for $\mathcal{A}_2$ and $\mathcal{B}_2$ to perform spin measurements on the original particles of the singlet, along directions a_2 and b_2, respectively; we denote the corresponding results by A_2 and B_2 (a schematic representation of the proposed gedankenexperiment is presented in Figure 1).

To develop the argument, we start by assuming that all the observers involved obtain objective results when they measure. That is, we assume that all the measurements performed yield definite, objective outcomes. As a result of such an assumption, there must exist a *joint probability distribution* for all four results, $p(A_1, B_1, A_2, B_2)$. Given such a joint probability distribution, one can calculate the marginal probabilities $p_{12}(A_1, B_1)$, $p_{23}(B_1, A_2)$, $p_{34}(A_2, B_2)$, $p_{14}(A_1, B_2)$ and, with them, the expectation values of products of pairs of results $E_{12}(a_1, b_1)$, $E_{23}(b_1, a_2)$, $E_{34}(a_2, b_2)$, $E_{14}(a_1, b_2)$.[2] Now, as shown by Fine [5], the expectation values computed by these marginals necessarily satisfy the CHSH inequality

$$|E_{12}(a_1, b_1) + E_{23}(b_1, a_2) + E_{34}(a_2, b_2) - E_{14}(a_1, b_2)| \leq 2. \tag{1}$$

That is, to assume a joint distribution for all four outcomes, leads to the same consequences than imposing Bell's locality. Of course, an important difference is that, in this case, all four measurements are actually performed in each run of the experiment.

Next, we employ quantum mechanics to make predictions for the expectation values in Eq. (1). We start with $E^q_{12}(a_1, b_1)$, for which we notice that the situation exactly corresponds to a standard Bell scenario. In consequence,

$$E^q_{12}(a_1, b_1) = -\cos(a_1 - b_1). \tag{2}$$

Similarly, $E^q_{34}(a_2, b_2)$ seems easy to compute. The state starts being a singlet, then comes a big identity in its evolution, followed by standard Bell-type measurements. As a result,

$$E^q_{34}(a_2, b_2) = -\cos(a_2 - b_2). \tag{3}$$

The "mixed" terms, with one measurement by $\mathcal{A}_1$ ($\mathcal{B}_1$) and the other by $\mathcal{B}_2$ ($\mathcal{A}_2$) seem more challenging. However, one might reason as follows. $\mathcal{A}_1$ ($\mathcal{B}_1$) measures its particle. Then, to predict the result of $\mathcal{B}_2$ ($\mathcal{A}_2$), she updates the state according to the result obtained, and evolves the state on the other side. However, that evolution simply amounts to the identity, corresponding to the doing and undoing of the measurement. As a consequence, for these mixed terms, we obtain the same predictions as in the

[2] As should be clear from the context, subscripts in p and E indicate which entries of $p(A_1, B_1, A_2, B_2)$ are being conserved while calculating the marginals.

original Bell scenario, namely

$$E^q_{14}(a_1, b_2) = -\cos(a_1 - b_2), \qquad E^q_{23}(b_1, a_2) = -\cos(b_1 - a_2). \tag{4}$$

The problem, of course, is that we know that these quantum predictions can violate the CHSH inequality. That is, for adequate values of a_1, b_1, a_2, b_2,

$$|E^q_{12}(a_1, b_1) + E^q_{23}(b_1, a_2) + E^q_{34}(a_2, b_2) - E^q_{14}(a_1, b_2)| > 2. \tag{5}$$

We arrive, then, at a contradiction. In detail, the assumption that all measurements performed in the experiment yield definite, objective outcomes, which is what allowed for Eq. (1) to be established, is found to be incompatible with the predictions of quantum mechanics in Eq. (5).

From all this, it is concluded that quantum measurement outcomes cannot be taken to be objective, at least not in a straightforward way. That is, the argument is taken to entail that not every quantum measurement can be thought of as having a definite, objective, physical outcome. Moreover, the argument is read as implying that, at least in some sense, whatever maneuver is employed to deal with Bell's theorem, such a maneuver cannot be restricted to the microscopic level. That is, that the measure taken to address the CHSH violation in the Bell case, must also have an effect on actual, macroscopic experimental results.

3 Analysis

What are we to make of this argument? Does it really show that the objectivity of measurement results must be called into question, i.e., that we have to throw away the sensible idea that well-conducted measurements have definite, physical outcomes? To begin with, we point out the obvious fact that, for the argument to run, one has to assume that, during measurements, the evolution of the quantum state is purely unitary. Otherwise, the whole idea of undoing the measurements clearly does not go through. That is, it was only because we assumed that the measurements performed by the first observers could be fully described by a complicated unitary, that we were able to argue that such measurements could be undone by the application of another unitary—namely, the inverse of the one describing the measurements. In contrast, if one assumes that measurements involve some sort of breakdown of unitarity, the argument simply does not work. From this, it clearly follows that theories that take this latter position, such as objective collapse models [7, 13], are simply not affected at all by the argument.

We just saw that the argument requires the assumption that the evolution of the quantum state is always unitary. Does that mean that we can at least conclude that *purely unitary* quantum theory is inconsistent with the assumption that measurements have definite outcomes? Not really. The argument presupposes 1) that measurements always yield definite results, and 2) that the evolution of the quantum state is always unitary. Now, in [11] it is shown that those two assumptions are incompatible with another assumption, namely 3) that the physical description given by the quantum state is complete. In other words, the assumptions of the argument imply that the quantum description is incomplete, so it must be supplemented by so-called hidden variables.

One might complain that the incompatibility result in [11] depends upon assuming some level of objectivity or realism that goes against the spirit of the new type of arguments under discussion. That is, that the whole point of these new arguments precisely is to stay clear of theoretical constructs, such as hidden variables. However, if the objective of these new results is to *argue against* an objective position, it would amount to begging the question to assume from the onset that such a position should not be taken.

We conclude, then, that with its assumptions, the argument presupposes the existence of hidden variables. The next question is whether this recognition makes any difference in the derivation of the inconsistency. We recall that a key element of this derivation was the calculation of the mixed correlations between a result from the first set of measurements and one from the second. In the reconstruction of the argument given above, we took those mixed expectation values to be given by Eq. (4), i.e., to be equal to minus the cosine of the difference of the angles of the measurements involved. Moreover, such a result was essential for the conclusion that the corresponding CHSH inequality could be violated. However, in light of the fact that the argument requires the existence of hidden variables, it is not clear that such a behavior for the mixed correlations really obtains.

To see this, we note that the mixed expectation values being given by Eq. (4), implies that if, say, a_1 and b_2 are equal, then the results of $\mathcal{A}_1$ and $\mathcal{B}_2$ would be perfectly anticorrelated. That, of course, implies that if a_1 and a_2 are equal, then the measurements of $\mathcal{A}_1$ and $\mathcal{A}_2$ would be perfectly correlated. However, since the result of a measurement is determined by the behavior of the hidden variables, for this perfect correlation to obtain, *it is necessary for the inverse unitary to also reverse the evolution of the hidden variables in such a way that they have exactly the same values before both pairs of measurements (or, at least, new values that guarantee the required perfect correlation)*. That is, it is necessary for the undoing of the measurements to also reverse the evolution of the hidden variables, such that their values at t_2 are related to those at t_1 (see Figure 1) so to ensure the correlations needed. Otherwise, there is simply no reason to expect a perfect correlation between the first and second sets of measurements when the angles of the measurements are repeated. This, of course, implies that, in general, there is simply no reason for the mixed correlations to be as strong as needed for CHSH to be violated—from which it follows that the argument is only relevant against hidden-variable models with this particular feature regarding the behavior of the hidden variables during the inverse unitary.

Above it was mentioned that the argument has been read as implying that the procedure employed to address the CHSH violation in the Bell case must have an effect at the macroscopic level. However, now it is clear that this is not necessarily the case. In particular, we see that a model may very well violate the CHSH inequality in the standard Bell scenario, not do so in this case, and remain empirically viable. There is, of course, ample evidence for the violation of CHSH for the Bell case. Needless to say, the same cannot be said for the gedankenexperiment under discussion. In any case, the point is that the violation of CHSH in one case is perfectly compatible with its fulfillment in the other. Does this mean that models for which CHSH is not violated in this case, make predictions which are incompatible with those of standard quantum mechanics? Not really. What happens is that the inherently vague nature of the collapse postulate in the standard framework—the ambiguity as to what causes it and what it entails—allows for a range a predictions. Models that remedy this vagueness, on the other hand, yield a precise prediction in that range.

We just saw that, in order for the argument to run, the hidden-variable models considered must posses a particular feature. The important question, then, is which hidden-variable models have it. For starters, it seems clear that hidden-variable models with *indeterministic* elements in the evolution of the hidden variables, will not possess the required feature. Therefore, they are not affected by the argument. What about deterministic models? In that instance, it seems hard to say something generic, so the analysis must proceed in a case by case basis. There is, of course, a particularly significant deterministic hidden-variable model, the de Broglie-Bohm pilot-wave theory (dBB) [3]. We turn next to the evaluation of that important case.

dBB is the best-developed example of a hidden-variable model. The framework proposes that a complete characterization of an N-particle system is given by its wave function $\psi(x,t)$ *together* with the actual positions of the particles $\{X_1(t), X_2(t), \ldots, X_N(t)\}$, which are taken to always possess well-defined values. The wave function is postulated to satisfy at all times the usual Schrödinger equation

$$i\hbar\frac{\partial\psi}{\partial t} = -\sum_k \frac{\hbar^2}{2m_k}\frac{\partial^2\psi}{\partial x_k^2} + V(x)\psi \tag{6}$$

and the positions to evolve according to the deterministic "guiding" equation

$$\frac{dX_k(t)}{dt} = \frac{\hbar}{m_k}\,\mathrm{Im}\left[\frac{\frac{\partial\psi}{\partial x_k}}{\psi}\right]\Bigg|_{x=X(t)}. \tag{7}$$

In dBB, the observed outcome of, say, the measurement of the spin of a particle along a given direction, is directly associated with the actual trajectory of the particle measured. Therefore, two particles with exactly the same wave function, but different initial positions, could lead to different results regarding a measurement of spin along a given direction. Going back to the gedankenexperiment of the argument, what we said above about dBB implies that, unless the positions of the particles are exactly the same at t_1 and t_2, there is no reason for the correlations needed for the argument to actually obtain.

Does dBB posses this required feature? That is, does the dBB dynamics imply that, during the inverse unitary evolution that reverses the first set of measurements, the particles go back to the positions they had before those measurements took place? Well, as is well-known, dBB is indeed time-reversal invariant, which might suggest for it to have the feature needed for the argument to run. In particular, the involution of complex conjugation, which renders the Schrödinger equation time-reversal invariant, also reverses the sign of the velocities of the particles. That is, if one sends t to $-t$ and takes the complex conjugate of the wave function, then the velocities of the particles change sign.

However, this does not imply that dBB has the required feature. This is because, what the inverse unitary does, is to send t to $-t$, but it does *not* involve a complex conjugation. As a result, during the inverse unitary, the velocities of the particles do not change sign, so particles do not go back to their original positions. This is easy to see by the fact that the velocities of the particles at a time, given by Eq. (7), are a function of the *instantaneous* wave function at that time (e.g., there are no time-derivatives on the right hand side of Eq. (7)). Therefore, if all the inverse unitary does is to reverse the time order, then there is no reason for the velocities to change sign. What about the possibility of the particles not returning to their original positions, but having new values that guarantee the required correlations? It seems clear that there is absolutely no basis to predict that this would happen. At any rate, the burden of proof falls on whoever wants to argue to the contrary. All this means that dBB does not possess the required property, so it is fully immune to the argument.

4 Conclusions

Recent arguments aim at calling into question the objectivity of quantum measurement results. In particular, an argument attributed to Masanes, purportedly shows that the assumption that quantum measurements yield definite, objective outcomes, is incompatible with quantum predictions. However, by examining the argument in detail, it is found that it, in fact, has a much narrower field of application than previously recognized. On one hand, the argument only applies to models with a purely unitary evolution of the quantum state. Therefore, frameworks without this feature, such as objective collapse models, are unaffected by the argument. On the other hand, the presuppositions of the argument imply that the quantum state is incomplete, so the argument requires the introduction of hidden variables.

Regarding hidden-variable models, the analysis has shown that the argument does not apply to all of them—only to those with the very particular feature that the inverse unitary also reverses the evolution of the hidden variables, such that they end-up with exactly the same values before both pairs of measurements. Moreover, it is found that such a feature is not present in generic hidden-variable models and, in particular, that it is absent in the de Broglie-Bohm pilot-wave theory—the most important hidden-variable model. From all this, it is concluded that the argument explored does not succeed in calling into question the objectivity of quantum measurements.

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