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Quantum Non Locality, an Enigma

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Abstract

Non locality is a quantum phenomenon without classical counterpart. In this article, the well-known total null spin state of two entangled particles jointly generated, the singlet state, is analysed. It is concluded that special relativity is not violated for space time physical processes because the non local correlation is some kind of bidirectional relationship outside space time.

Subject Areas

Quantum Mechanics

Keywords

Quantum Non Locality, Bidirectional Correlation

1. Introduction

Non locality is one of the weirdest phenomena in Quantum Mechanics. In theoretical physics, quantum non locality refers to the phenomenon by which the measurement statistics of a multipartite quantum system do not allow an interpretation with local realism. Quantum non locality has been experimentally verified [1] under a variety of physical assumptions.

Bell-type theorems [2] do not refer to any particular theory of local hidden variables, but instead show that quantum physics violates general assumptions behind classical pictures of nature.

Bell tests have consistently found that physical systems obey quantum mechanics and violate Bell inequalities, which is to say that the results of these experiments are incompatible with local hidden-variable theories.

Although both the locality and detection loopholes had been closed in different experiments [3], a long-standing challenge was to close both simultaneously in the same experiment. This was finally achieved in three experiments in 2015.

Most advocates of the hidden-variables idea believe that experiments have ruled out local hidden variables. They are ready to give up locality, explaining the violation of Bell's inequality by means of a non-local hidden variable theory, in which the particles exchange information about their states. This is the basis of the Bohm interpretation of quantum mechanics, which requires that all particles in the universe be able to instantaneously exchange information with all others. One challenge for non-local hidden variable theories is to explain why this instantaneous communication can exist at the level of the hidden variables, but it cannot be used to send (human) signals.

The paper is organized as follows. The next section presents an illustrative example of the meaning of Bell's theorems and inequalities. Then, an analysis of the physical non local process is developed, beginning with the assumption that there is some distinguished reference frame in the experiment. If the non local process is some kind of cause effect phenomenon, it is necessary that there is a well determined time ordering for the measurement events. Then, it is considered the case in which both measurement events are simultaneous in the distinguished frame. We must conclude that the non local physical process is some kind of bidirectional relationship. Finally, an addendum ponders the fact that most probably, there are many quantum states for which a joint probability distribution for a family of incompatible magnitudes does not exist, such that marginal probabilities for subfamilies of compatible magnitudes reproduce the quantum prediction, and that in many cases it is not related at all with a non local phenomenon.

2. Nonlocality: The Singlet State

Bell presents an analysis of the singlet state: two particles are jointly generated in a total null spin state. This means that there is perfect anticorrelation between the spin values (one up and the other down) in every spatial direction. Once the spin of one particle is measured in a given spatial direction we can assign a well defined spin state to the other particle, with opposite spin value in that direction. This obviously determines a probability distribution, according to Quantum Mechanics, for the spin values of the second particle in other spatial directions. Bell's inequalities prove that for some family of (at least three) spatial directions a classical probability distribution for the spins whose marginal probability for two directions reproduce the quantum prediction does not exist, because the quantum probabilities violate Bell's inequalities. The hypothetical probability distribution for three or more directions is not observable because it is a family of incompatible magnitudes. The spin in two directions becomes observable because we can measure one spin direction in each particle of the pair.

Instead of reproducing the proof of Bell's theorem, we present an illustrative example. Let's consider three directions in the XY plane, $(1,0)$, $\left(\cos\left(\frac{2\pi}{3}\right),\sin\left(\frac{2\pi}{3}\right)\right)$ and $\left(\cos\left(\frac{4\pi}{3}\right),\sin\left(\frac{4\pi}{3}\right)\right)$. Taking advantage of the symmetries, we have the following identities for the hypothetical distribution of probability of the spin values:

$$p_{+++} = p_{---} \equiv p$$

$$p_{++-} = p_{+-+} = p_{-++} = p_{+--} = p_{-+-} = p_{--+} \equiv q$$

Now we impose the conditions that the marginal probabilities for spin values in two directions match the values of Quantum Mechanics, those corresponding to the observed relative frequencies in experiments.

$$p_{++*} = p_{+++} + p_{++-} = p + q = \frac{1}{2}\cos^2\left(\frac{\pi}{3}\right) = \frac{1}{8}$$

$$p_{+-*} = p_{+-+} + p_{+--} = 2q = \frac{1}{2}\sin^2\left(\frac{\pi}{3}\right) = \frac{3}{8}$$

and all other marginal conditions (for directions one and three and for directions two and three) are redundant. We get the unique solution $q = \frac{3}{16}$ and $p = -\frac{1}{16}$. The non negativity constraint $p \geq 0$ is violated.

Therefore, there is not a joint probability distribution for values of spin in three or more spatial directions such that the marginal probabilities for subfamilies of two directions (observable in the singlet state) reproduce the quantum prediction.

3. Analysis

There is an overwhelming evidence that Special Relativity is a precise description of the space time and a right framework for all physical processes as far as gravity does not play any role. However, in the singlet state the values of spin in all directions (three or more) can not be determined at the generation event; otherwise there would be a table of relative frequencies whose marginals would reproduce the quantum predictions, the experimental observed values. The two measurement events can be spatially separated, *i.e.*, without a well defined temporal order. How can one measurement event send a message to the other such that the correlation is fulfilled? Different reference frames determine different time orderings for the two measurements.

The usual hypothesis is that there is a special reference frame, against Special Relativity. The special frame is the laboratory frame, in which the total momentum of the two particles vanishes. It seems difficult to find another physical characterization of a special frame. For this special frame we have a definite time ordering, and then it is established which measurement event sends information to the other, in a cause-effect process.

However, there is a particular case in which there is not well defined ordering between the measurements, when the two measurements are simultaneous in the special reference frame. In this particular case the only explanation is that the correlation is some bidirectional process, not a cause-effect one. Now, when there is a well defined temporal order between the two measurements in the special frame we have two possibilities, the physical process is either a cause-effect one or it is some kind of bidirectional connection, as in the simultaneous case. The hypothesis that the physical process is the same that in the simultaneous case is clearly simpler, we do not need two different processes for the same phenomenon of correlation.

In some sense, this option is more compatible with Special Relativity, because there is no need of a special reference frame. For two arbitrary spatially separated measurement events there is always a reference frame in which the two measurements are simultaneous. As we see, this bidirectional correlation works independently of the time order for different reference frames in spatially separated measurement events. It can not be a cause-effect process because there is not a well defined temporal order, and different reference frames observe opposite temporal orders; the effect can not be prior to the cause.

If the second particle of the singlet reaches the future light cone of the first measurement event a luminal or subluminal signal emitted at the first measurement could "inform" to the second particle of the result of the first measurement, and consequently change it own physical state of spin to fulfil the perfect anticorrelation. There is not incompatibility with Special Relativity in this process.

However, we should be more conservative in our hypothesis; there is no evidence of the existence of such signal. If there is no signal the arrival of the second particle to the future light cone of the fist measurement event is just a mathematical condition without physical effects. The hypothesis that the correlation is also a bidirectional one and not a cause-effect process is preferred.

Consequently, the existence of a bidirectional correlation in the singlet state for two measurements in arbitrary spacetime events determines that the process is independent of spatial and temporal separations, it is a process outside spacetime. We can maintain the validity of Special Relativity for all physical processes **in** spacetime as long as gravity does not play any role. The nonlocality is a physical property outside spacetime.

4. Addendum

In Quantum Mechanics, given a quantum state and a maximal family of compatible physical magnitudes (when the associated self adjoint operators commute), there is a procedure to compute a joint probability distribution, selecting a basis of common eigenvectors and calculating the square modulus of the coefficients of the linear combination of the quantum state in that basis. For a family of incompatible magnitudes (the operators do not commute), the procedure does not work, there is not a basis of common eigenvectors. This fact, related to the uncertainty principle, is in the kernel of the *non classicality* of Quantum Mechanics.

Obviously, the fact that there is no procedure in Quantum Mechanics to compute such joint probability distribution does not mean it does not exist. We can ask, for each quantum state and family of incompatible magnitudes, if there exists a joint probability distribution such that the marginal probabilities for subfamilies of compatible magnitudes reproduce the quantum prediction. The problem does not have a general answer, it must be analysed case by case.

There is a very well-known example in which such probability distribution does not exist in general, the singlet state and a family of three or more spatial directions of spin (which are incompatible magnitudes). Bell's theorem [2] proves the existence of some inequalities for such hypothetical joint probability distribution which, for some selections of spatial directions, are violated by the quantum prediction.

I think that most probably there are many other examples of quantum states and families of incompatible magnitudes for which it can be proven that a joint probability distribution does not exist with the needed property (marginal distributions for subfamilies of compatible magnitudes matching the quantum prediction). In the case of the singlet state, the conclusion is that the correlation must be non local, but in other cases it is quite probable that the non existence of such joint probability distribution has nothing to do with non locality.

Conflicts of Interest

The author declares no conflicts of interest.

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