The Importance of Bell's Theorem

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Abstract

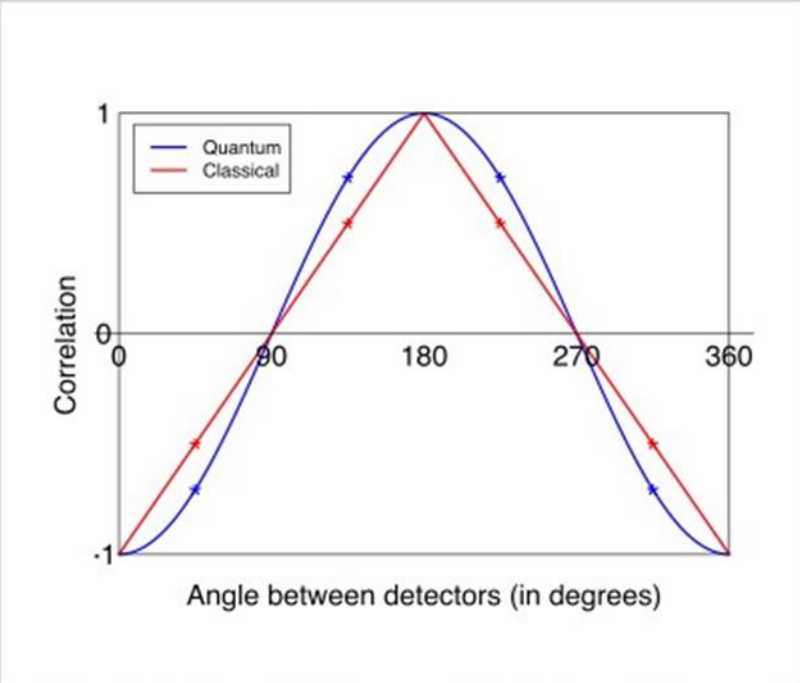
Bell's theorem reveals a logical problem that forces us to find a realistic physical explanation for a quantum-mechanical phenomenon. That explanation should reunite physicists and make physics comprehensible again.

It all started with a discussion between Einstein and Bohr. The idea was that according to Quantum Theory pairs of particles could arise from a splash of energy. Because of conservation laws for energy and momentum the particles of a pair must have opposite properties like direction of movement and spin direction. These particles are called entangled particles. From the idea of entanglement Einstein deduced that particles must have definite properties at every moment (EPR article, 1935). Bohr, on the contrary, based himself on the uncertainty relations of Heisenberg, stating that non-commuting properties, like for instance position and momentum, cannot both exactly be known at the same time. The more is known about one property the less is known about the other. This phenomenon relates to the notion that in Quantum Mechanics quanta behave both as particles and as waves. So particles show wave behaviour and waves show particle behaviour. Particles and waves together are called quanta. Bohr came up with the idea of complementarity. He stated that when a quantum is being measured it shows either particle behaviour or wave behaviour, never both at the same time. He also stated that a property of a quantum only can be known from a measurement. As measurement means interaction, this means that only interactions are important. In between interactions nothing can be known about the properties of a quantum. Bohr then stated that quanta as well can be considered to have no properties at all. (Physicists say they are in superposition, whatever this physically means.) Einstein didn't agree with this point of view. He said that QM was incomplete, what Bohr objected to. It seems that the debate lasted all their lives.

Physicists looked for a way to decide the debate experimentally. David Bohm thought of an experiment in which spin of entangled quanta was detected. According to QM there should be a certain correlation between the probabilities for combinations of opposite spin results and combinations of equal spin results for pairs of quanta to occur in respect of the difference in setting of the detectors in the experiments. John Bell calculated on a logical basis also a maximal possible correlation (Bell's inequalities). When the experiments finally could be performed (Alain Aspect and others) it appeared that Bell's inequalities were being violated. The experiments showed results that were given by QM, not the results that Bell calculated. This is called the violation of Bell's inequalities. Bell wanted to prove Einstein's viewpoint. Now it seemed that Einstein was wrong.

The problem is that the violation of Bell's inequalities couldn't be explained. Logically Bell was right but the experiments showed otherwise. This situation lasts for almost half a century now. Many ideas go round and all are different. The inventers of the ideas are all equally convinced of the correctness of their idea. The problem of explaining QM's correlation physically and explaining the violation of Bell's inequalities seems very hard to fathom. Partly this has to do with defining notions: what is non-locality?, what is entanglement?, what is correlation?, what is a probability?. Partly it has to do with assumptions about the experiments: we cannot see quanta and their interactions. So we have to assume all kind of things about what happens in experiments. And we even often don't agree about what to do with the results of the experiments: what combinations to count as a valid result or not, and so on.

Concerning definitions of notions: what is non-locality? Non-locality is the effect of things, originating from one thing, at different places. So a thing divides in parts that depart in different directions. When from a pair of shoes one is sent to one place and the other is sent to another place, then this is an example of non-local correlation. There is of course no interaction between the shoes nor between the places where they arrive. What is entanglement? This notion is related to non-locality. Basically entanglement means that quanta have opposite properties, either because the quanta originated from one quantum (conservation laws) or because of resonance effects. Now the question is: can there exist immediate interaction between entangled quanta after the quanta have parted, in such a way that the effect of a quantum at one place can immediately influence the effect of the other quantum at the other place? According to Einstein this is not possible. Non-localists say that Bell experiments show that there must be some kind of interaction between the quanta after their departure. Localists say that this is not possible. So there are different views of entanglement: one in which there is some kind of interaction between entangled particles and one in which this interaction is not possible. In my opinion entanglement only means that quanta have opposite properties and the only interaction between them is at the moment of their creation. What is correlation? Correlation in Bell experiments is very precisely defined: it is the probability for a combination of equal spin results to occur minus the probability for a combination of opposite spin results to occur. So the correlation in Bell experiments is a very tricky notion: it is based on probabilities and probabilities are not physical objects. What is a probability? A probability is a number as part of a total number. It is rational fraction between the limits 0 and 1. Probabilities can be obtained theoretically by calculating on a logical basis (Bell as well as QM) or experimentally by counting the results in a large number of cases. And of course the theoretical outcomes must match the experimental outcomes.



The best possible local realist imitation (red) for the quantum correlation of two spins in the singlet state (blue), insisting on perfect anti-correlation at 0°, perfect correlation at 180°. Many other possibilities exist for the classical correlation subject to these side conditions, but all are characterized by sharp peaks (and valleys) at 0°, 180°, and 360°, and none has more extreme values (±0.5) at 45°, 135°, 225°, and 315°. These values are marked by stars in the graph, and are the values measured in a standard Bell-CHSH type experiment: QM allows $\pm 1/\sqrt{2} = \pm 0.7071\ldots$, local realism predicts ±0.5 or less.

Source: Wikipedia

The problem is that Bell found probabilities that were different from QM’s probabilities, although both were calculated on a logical basis. What went wrong? Well, most people don’t bother because QM gives the correct results and for them that seems to be enough explanation. They make shift with the violation of Bell’s inequalities. But calculation from a theory is not the same as understanding what is physically going on, of course. Many people, physicists as well as non-physicists, cudgelled their brains about the problem and came up with all kind of theories. Long before the experiments were under discussion Einstein suggested that there may be ‘hidden variables’ to make up for the incompleteness of Quantum Theory. So Bell made his calculations including an extra variable. In his theorem he stated that no ‘hidden variable’ theory could explain QM’s correlation in a local Universe.

There are people who believe in some kind of interaction between entangled quanta, even after their departure. This interaction is either an unknown physical interaction or a non-physical interaction. It should explain the correlation and the way quanta interact is then prescribed by QM. There are explanations based on field theories and on ‘cellular automata’ and some say that the interaction takes place via an abstract mathematical space. Many people are not content with the idea of interaction between quanta after their departure. They believe it should be possible to physically explain the correlation. According to them immediate interaction at a distance is not possible. They usually believe that Einstein was right in his statement that quanta must have definite properties. They come up with many different explanations. There are theories about super-determinism, meaning that everything is determined from the 'beginning of time'. Why only Bell experiments show consistent, different from expected, results is an enigma to me. Some have trouble with the handling of the data from the experiments. They suggest another way of counting the results. Some think that 'spin flipping' can account for QM correlation. Some suggest a probability density depending on the angle between the setting of the detectors. This is of course true, but why? Some state that Bell's inequalities don't apply to the experiments and seem to be able to prove that mathematically. Some apply Malus' law in case photons are used in the experiments and obtain naturally the correct outcome. One uses 'perspective' to show that Bell's probabilities as well as QM's probabilities are both needed to reach the correct correlation. We should be locked up in a room until we reach consensus.

Usually there is consensus about correct theories among physicists. Nobody doubts about the Relativity Theory or the Quantum Theory. However, there is no consensus about the meaning of the mathematics of the Quantum Theory. Physicists are very discorded concerning the interpretation of Quantum Mechanics. There are big differences between the views of physicists. Concerning Bell experiments the state of quanta in between interactions (= before measurement) is random. But there is a difference in randomness. A definite but unknown state of quanta (Einstein) means that the particles of an entangled pair can have an anti-parallel spin direction which is unknown and thus random. In contrast, an indefinite state of quanta (Bohr) means that the spin direction of each particle of an entangled pair emerges randomly when they are being measured. In that case no correlation whatsoever can occur. Another possibility is that QM somehow describes the spin direction of the particles, when they are being measured, in such a way that the correct correlation emerges. In this case there are hidden variables. In case of anti-parallel spin directions correlation definitely occurs. Which correlation that is we still have to find out. But in case of indefinite state of quanta either there is no correlation or there are hidden variables. As experiments definitely show correlation this means that this correlation cannot be explained without hidden variables. These hidden variables can as well be anti-parallel spin directions in a realist explanation that has not been discovered yet. So we have to look for a realist explanation.

But now we are in trouble. Bell's theorem says that QM's correlation, confirmed by experiments, cannot be explained by any hidden variable theory: QM's correlation cannot exist in a local Universe. Is this theorem correct? It is based on logically derived probabilities. Are these probabilities wrong then?

One of the previous mentioned attempts for an explanation uses 'perspective' in the explanation of the correct correlation. Here perspective is considered to be the position from which an object is observed. This position defines the direction of observation. This also is the direction of detection as detection is equal to observation. As in Bell experiments the particles move towards the detectors, and their spin directions, represented by vectors, are being projected onto the detectors (in this model of explaining), the projection direction is opposite to the detection direction.

Let us now look at the notion of perspective for a moment, perspective considered as a direction of observation. According to prof. Icke there are three principles in physics: relativity, quantisation and symmetry. According to me perspective is the fourth principle. It is like a symmetry. As time is a point (position) in a 4-dimensional spacetime, in the same way (a change of) perspective is a (broken) symmetry. Prof. Icke: "a symmetry is a change that leaves something unchanged". A change of perspective is a change of the position of an observer/detector. It changes the image of the observed but it leaves the observed unchanged. In relation to Bell experiments perspective shows the difference between spin and 'handedness' of a particle. Handedness is the direction of rotation of the particle according to an observer. Spin is the direction of the rotation of a particle according to the particle. If the observer moves to a position opposite in respect of the particle then the handedness becomes opposite: according to the observer the particle rotates in the opposite direction, although the spin of the particle didn't change. We now can imagine that entangled particles, having opposite spin (Einstein's view) do not at all seem to have opposite spin when the two particles are observed from opposite directions. And this is exactly what detectors in Bell experiments do: they measure the particles from opposite positions. So in Bell experiments entangled particles are not at all observed as having opposite spin. They do have but they are not detected like that. Because entangled particles have opposite spin there is a certain correlation between the number of combinations of equal spin result and the number of combinations of opposite spin result. The numbers define the correlation and this is not the correlation expected by Bell because of the effect of perspective. The combinations of equal spin result and the combinations of opposite spin result are perfectly random. However the probability with which they occur is perfectly defined from the perspective of the particles: it is not Bell's probability but QM's probability. It can easily be demonstrated that from the perspective of the particles QM's probability can be perceived as the projection density of their anti-parallel spin directions (vectors) per unit of area. This density only depends on the angle between the settings of the detectors, as the correlation formula correctly reflects.

There are a few articles, explaining the correlations in Bell experiments, that tick all the boxes of realism. In one (https://vixra.org/abs/2112.0118) photons are used as entangled quanta. This allows the application of Malus' law, leading to the correct correlation in a natural way. Another one (https://vixra.org/abs/2204.0148) uses pairs of particles with anti-parallel spin. In this article the principle of perspective is applied to explain why both Bell's probabilities as well as QM's probabilities are at work in Bell experiments. Both are needed to obtain the correct correlation. In this way not only QM's correlation is accounted for but also the violation of Bell's inequalities is explained.

The explanation in both articles is so easy to demonstrate that it should not be difficult for physicists to reach consensus about it. According to this explanation Einstein was right after all: quanta do have definite properties in between interactions and no hidden variables are needed. Only Bell's statement that QM's correlation is not possible in a local Universe was false.

The importance of Bell's theorem is that it forced us to find a physical explanation for the results in experiments. The possibility to find a realistic solution for a problem that existed almost half a century gives us a clue for the interpretation of Quantum Mechanics, I think.