Testing Bell's Inequalities

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The results of precise tests to explore the validity of quantum mechanics by applying Bell's theorem (that some quantum mechanical predictions cannot be mimicked by any local realistic model in the spirit of Einstein's ideas) agree with the quantum mechanical predictions.

It is a great privilege, in these sad circumstances, to have the opportunity to recount the great influence John Bell had on my life as a physicist. Testing Bell's inequalities was more than a run-of-the-mill experiment. Indeed, when I read the paper "On the Einstein-Podolsky-Rosen (EPA) paradox" [1], I found it extremely clear and completely convincing, but there was something special about this paper: it led to two contradictory conclusions. The first part showed that EPR correlations predicted by quantum mechanics are so strong that one can hardly avoid the conclusion that quantum mechanics should be completed by some supplementary parameters (the so-called "hidden variables"). But the second part, elaborating on this result, demonstrated that the hidden-variables description in fact contradicts some predictions of quantum mechanics, which is to say both theories predict different results. In the face of these two perfectly convincing and contradictory results, there is only one way out: ask Nature how it works.

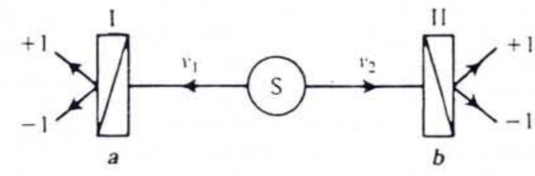
The big surprise was the realization that, at the end of the sixties, there was no experimental result to answer the question. The contradiction discovered by John Bell is so subtle that it appears only in very peculiar situations that had not been investigated: it was therefore necessary to design and build specific experiments.

Bell's Theorem

1. Hidden variables

The reasoning behind Bell's theorem deals with correlations between events, each of which appears to be random. Such correlations may arise outside physics. Take, for instance, the occurrence of some well-defined disease and let us assume that biologists have observed its development in 50% of the population aged 20, and its absence

*Fig. 1 - Einstein-Podolsky-Rosen Gedankenexperiment with photons. The source S emits pairs of photons ν which are analyzed in polarization in two directions (**a** and **b**). In an EPR situation, the results of the measurement of polarizations are found to be strongly correlated.*



in the remaining half. Now, on investigating specific pairs of (true) twin brothers, they find a perfect correlation between the outcomes: if one brother (or sister) is affected, the other is also found to be inflicted with the disease; but if one member of the pair has not developed the disease, then the other is also unaffected. In face of such a perfect correlation for twin brothers, the biologists will certainly conclude that the disease has a genetic origin. They may invoke a simple scenario: at the first step of conception of the embryo, a (random) genetic process produced a chromosome sequence — one which is responsible for the occurrence, or absence, of the disease — that has been duplicated and given to both brothers.

An EPR situation is a case where quantum mechanics predicts strong correlations of this type. Consider, for instance, the situation illustrated in Fig. 1 where a source emits a pair of photons ν_1 and ν_2 travelling in opposite directions. Each photon impinges onto polarizers which measure the linear polarization along both of two directions (**a** or **b**) determined by the orientation of the corresponding polarizer. There are two possible outcomes for each measurement and these we can label + and −. Quantum mechanics allows for the existence of a two-photon state (EPR state) for which the polarization measurements taken separately appear random but which are strongly correlated. More precisely, denoting $P_+(\mathbf{a})$ and $P_-(\mathbf{a})$ as the probabilities that the polarization of ν_1 along **a** is found equal to + or −, these probabilities are predicted to be equal to 0.5; similarly the probabilities $P_+(\mathbf{b})$ and $P_-(\mathbf{b})$ for photon ν_2 are equal to 0.5 and independent of the orientation **b**.

A. Aspect (on the right) with John Bell in about 1985 in Paris.

On the other hand, the joint probability $P_{++}(\mathbf{a},\mathbf{b})$ for observing + for both photons is equal to $0.5\cos^2(\mathbf{a},\mathbf{b})$. In the case of parallel polarizers $[(\mathbf{a},\mathbf{b}) = 0]$, this joint probability is $P_{++}(0) = 0.5$; similarly, $P_{--}(0) = 0.5$, while $P_{-+}(0)$ and $P_{+-}(0)$ are zero. The results for the two photons of the same pair are thus always identical, both + or both −, *i.e.*, they are completely correlated. The situation is thus exactly analogous to the case for the twin brothers, and it seems natural to link this correlation to some common property of the two photons of a pair, analogous to the common genome of the two twin brothers. This common property changes from pair to pair, which accounts for the random character of the single events.

The above reasoning constitutes the first part of John Bell's paper. A natural generalization of the EPR reasoning, it leads to the conclusion that quantum mechanics is not a complete description of physical reality. Indeed, invoking some common property which changes from pair to pair, we claim that the complete description of a pair must include something, in addition to the state vector which is the same for all pairs. This something can be called *supplementary parameters*, or *hidden variables*. At this stage, these hidden variables are supposed to be able to render an account of the correlations between both measurements, for any set (**a**,**b**) of orientations.

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2. *Inequalities*

The second part of Bell's reasoning starts from this requirement for hidden variables. Assuming their existence and some very natural properties, one can show that the expected correlations, for the joint measurements above, cannot take any set of values, but that they are subject to certain constraints. More precisely, if we consider four possible sets of orientations [(**a**,**b**), (**a**,**b'**), (**a'**,**b**) and (**a'**,**b'**)], the corresponding correlation coefficients (which measure the amount of correlation) are restricted by the so-called Bell's inequalities, which state that a given combination S of these four coefficients is between -2 and $+2$ for any "reasonable" hidden-variable theory [2].

Now comes the crucial point: there exists a set of orientations for which the quantity S predicted by quantum mechanics, in the EPR situation presented above, is equal to 2.8, *i.e.*, it violates Bell's inequalities. The hidden-variables theories envisaged above are then unable to render an account of the EPR correlations predicted by quantum mechanics (these quantum mechanical correlations are not as easy to understand as the common medical fate of twin brothers).

In the face of this contradiction, John Bell made clear the reasonable properties that he had assumed for the hidden-variables models. The essential assumption, absolutely necessary to resolve the conflict, is locality: this assumption states that the result of a measurement by a polarizer cannot be directly influenced by the choice of the orientation of the other, remotely located, polarizer. This assumption indeed sounds very reasonable. Moreover, it can be considered to be a consequence of Einstein's causality, by considering an experiment in which the settings of the polarizers can be changed at random in a time which is short compared to the time light takes to propagate between the two polarizers.

Of the many papers that followed Bell's paper, we will extract the conclusion that Bell's inequalities apply to a wider class of theories than local hidden-variable theories. Any theory in which each photon has a "physical reality" localized in space-time, determining the outcome of the corresponding measurement, will lead to inequalities that sometimes conflict with quantum mechanics. Bell's theorem can thus be phrased in the following way: *some quantum mechanical predictions (EPR correlations) cannot be mimicked by any local realistic model in the spirit of Einstein's ideas.*

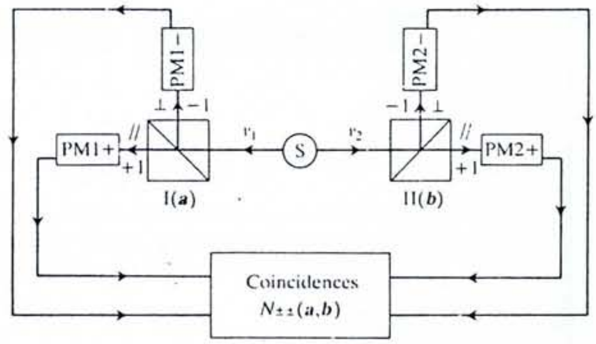

Fig. 2 — The experiment with two-channel polarizers and photomultiplier (PM) counters. Using four-fold coincidence systems we obtain directly the polarization correlation coefficient of photons ν emitted by the source S in the set of orientations (**a**,**b**)*. Note the close similarity with Fig. 1.*

First Experiments [3]

When physicists realized the wide generality of Bell's theorem, they met with a great surprise: at the end of the sixties, there was no experimental result available for testing Bell's inequalities *versus* quantum mechanics. Moreover, in the case where a conflict is predicted (as above) one finds that taking into account the inefficiencies of a real experiment usually reduces the degree of correlation predicted by quantum mechanics so that there is no longer any conflict. The possibility then arose that the conflict with Bell's inequalities may indicate a place to look for a limit to the validity of quantum mechanics.

It was therefore tempting to perform a sensitive experiment for a situation where quantum mechanics predicts a conflict with Bell's inequalities. In order to have such a situation, several conditions must be fulfilled:

- the creation of a pair of systems in a non-factorable quantum state of the EPR type;
- the ability to perform two-valued measurements on each system;
- the disposal of an adjustable parameter for these measurements so that different values of this parameter correspond to non-commuting observables.

The first experimental test was based on pairs of γ photons produced in the *annihilation of positronium*. This would be an ideal system, except for the fact that no polarizer exists capable of making a two-valued measurement: polarization must be inferred from a Compton scattering using calculations relying on quantum theory. The test is thus indirect and somewhat circular. The first measurements gave contradictory results, but by the mid-1970's clear agreement with the quantum mechanical predictions was established.

An experiment based on *pairs of protons* obtained by scattering had the same problem (no polarizers). It also gave a result in agreement with quantum mechanics.

The system best able to fulfill the above conditions comprises *pairs of visible photons* produced in well-chosen atomic radiative cascades. As a matter of fact, for visible light there exist polarizers, *e.g.* based on birefringent crystals, with two output channels and an adjustable orientation. The first three experiments, carried out in the early seventies, gave a relatively small signal and some results were contradictory. By introducing a laser to excite the cascade, the fourth experiment gave a convincing result in agreement with quantum mechanics. For practical reasons, all these early experiments used only one-channel polarizers, so once again the comparison of the experimental results with Bell's inequalities was indirect and relied on supplementary assumptions. However, they had given convincing indications in favour of quantum mechanics and they opened the way to second-generation experiments.

Closer to the Gedankenexperiment

Thanks to the progress in lasers, we could design and build in the late seventies [4] a much more efficient source of pairs of EPR photons correlated in polarization. We used the same radiative cascade in calcium-40 as employed in the first experiment by Clauser and Freedman [2], but now we could selectively excite the upper level of the cascade with two-photon absorption. As a consequence, the light emitted by our source was very pure, encompassing only photons of the desired pairs. Very important also was the very high emission rate which allowed us to achieve a 1% statistical accuracy for joint detection within only hundred seconds (a similar level of accuracy required hours in the previous experiments).

A first experiment based on the same scheme as the previous ones (with one-channel polarizers) gave a clear-cut result in agreement with quantum mechanics. Meanwhile, we had obtained (from the Philips Research Laboratory) two-channel polarizers based on multidielectric coatings. Fig. 2 shows the experimental set-up, which closely resembled the ideal one of Fig. 1. Using the four-fold coincidence system it was possible to monitor simultaneously the four coincidence rates corresponding to the + and − results. This yields directly, without any auxiliary calibration, the joint detection probabilities in a given set of orientations (**a**,**b**) from which we derive the correlation coefficient. By repeating the measurement in different orientations we can test directly Bell's inequalities.

The results are shown in Fig. 3. We have plotted, as a function of the angle t, the quantity S which is subject to the Bell's inequalities:

$$-2 \leq S \leq 2$$

There are obviously angles for which one of the Bell's inequalities is violated. The maximum violation corresponds to a value

$$S = 2.70 \pm 0.015$$

that is to say a violation by more than 40 standard deviations. In spite of its close resemblance to the ideal experiment, the actual experiment suffers from one remaining problem: owing to the limited efficiency of the photon detectors, a comparison with Bell's inequalities requires the assumption that the detected photons constitute a faithful sample. Nevertheless, the result in favour of quantum mechanics and against local hidden-variables theories is very convincing.

Testing Locality

As already emphasized, the locality condition is essential to obtain Bell's inequalities. But, as stressed by John Bell, in a experiment of the type described above, "the settings of the instruments are made sufficiently in advance to allow them to reach some mutual rapport by exchange of signals with velocity less than or equal to that of light", in which case the locality condition does not apply [1]. We have thus tried to realize a scheme "in which the settings are changed during the flight of the particles", so that locality be a consequence of Einstein's causality (no interaction can propagate faster than light).

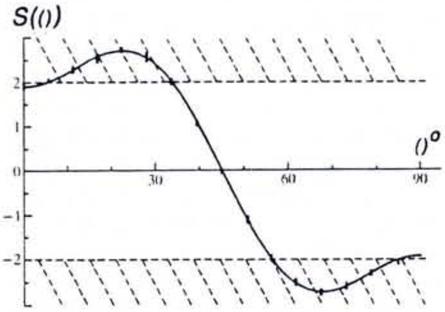

Fig. 3 — The results of the experiment of Fig. 2. The quantity S is a function of the correlation coefficients and should lie between −2 and 2 according to Bell's inequalities. The solid curve is the prediction of quantum mechanics taking into account inefficiencies of the apparatus.

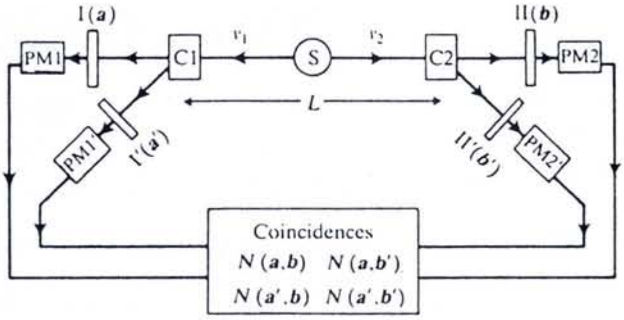

Fig. 4 — The experiment with optical switches. The switch C1 with the two polarizers I and I' is equivalent to a single polarizer changed from orientation **a** *to orientation* **a'**. *The time between changes is shorter than the time of flight of the light. As before, the source S emits pairs of photons ν and photomultipliers (PM) detect the photons.*

We have in fact only partially realized this programme. First, we do not in practice change the setting of a polarizer but we instead replace each polarizer with a system involving a switch that is able to redirect the light towards one of two polarizers in two different orientations. The time between two changes is 10 nanoseconds, shorter than the time of flight of the photons (20 nanoseconds, corresponding to six meters). Unfortunately, the switches (based on the interaction with an acoustic standing wave) did not work at random but periodically. This is far from ideal, even if the two switches are driven by independent generators.

Owing to the complication of the systems, the signal was smaller than in the static experiment of Fig. 3, and the results were not as precise. We nevertheless obtained a significant violation of Bell's inequalities by five standard deviations, and a good agreement with quantum mechanics. The level of confidence of this result is not as high as in the earlier experiments, so it would be very interesting to perform another experiment of the same type. This might be done with one of the new sources of pairs of photons produced in the parametric down-conversion of photons [5] which should eventually give better results than our source.

The Non-Locality Heritage

Let us assume that quantum mechanics will also work in ideal experiments with no inefficiencies present. In the words of John Bell [6]: "It is difficult for me to believe that quantum mechanics, working very well for currently practical set-ups, will nevertheless fail badly with improvements in counter efficiency and other factors...". What can we conclude? We cannot do better than let John Bell explain possible attitudes:

— "There are influences going faster than light, even if we cannot control them for practical telegraphy. Einstein local causality fails, and we must live with this."

— "The orientations **a** and **b** are not independently variable as we supposed. Whether apparently chosen by apparently independent radioactive devices, or by apparently separate Swiss National Lottery machines, or even by different apparently free-willed experimental physicists, they are in fact correlated with the same causal factors as the A and B (the outcomes of the measurements). Then Einstein causality can survive. But apparently separate parts of the world become deeply entangled, and our apparent free will is entangled with them."

— "The whole analysis can be ignored. The lesson of quantum mechanics is not to look behind the predictions of the formalism. As for the correlations, well, that's quantum mechanics."

John Bell repeatedly made it clear that the last attitude was not his. To renounce raising difficult questions would not have been acceptable to him. The first was apparently his favorite; like the second, it leaves us with a world, the various parts of which may be deeply entangled. After John Bell, we can no longer ignore that the quantum physical reality is somewhat non-local.

ADDITIONAL REFERENCES

[1] Bell J.S., *Physics* **1** (1964) 195. As the other papers by J.S. Bell on the foundations of quantum mechanics, this paper may be found more easily in [page 72, 1].

[2] Instead of the original form of the Bell's inequalities, we use this form, more convenient for experimental tests, first derived first by Clauser J.F., Horne M.A., Shimony A.and Holt R.A., *Phys. Rev. Lett.* **37** (1965), 465.

[3] Excellent reviews of the situation in 1978 are given in: Clauser J.F. and Shimony A., *Rep. Progr. Phys.* **41** (1978) 1881; Pipkin F.M., *Adv. in Atomic & Molecular Physics* **14** (1978) 281. See also an interesting more recent experiment: Perrie W. *et al.*, *Phys. Rev. Lett.* **54** (1985) 1790.

[4] These experiments were carried out in 1978-82 at the Institut d'Optique d'Orsay, Université de Paris Sud, with P. Grangier, G. Roger and J. Dalibard. See *e.g.*: *Atomic Physics* **8** (1983) 103.

[5] Shih Y.H. and Alley C.O., *Phys. Rev. Lett.* **61** (1988) 2921; Ou Z.Y. and Mandel L., *Phys. Rev. Lett.* **61** (1988) 50; Rarity J.G. and Tapster P.R., *Phys. Rev. Lett.* **64** (1990) 2995.

[6] Bell J.S., *Comm. on Molecular Physics* **9** (1980) 121.