

John Bell, Harwell and Accelerators

When John Bell graduated from Queen's in mid-1949, he was lucky that, following the invention of radar and the atomic bomb in the Second World War, physics was very much in favor with the powers-that-be. In particular, under the leadership of John Cockcroft, the Atomic Energy Research Establishment at Harwell was just getting into its stride. Doubtlessly, many physicists would have liked to get a job there, so it was remarkable that a new graduate without experience, and without even a PhD, was appointed, and more than that, there was even competition for his services. The organization's aim was fundamental research in atomic physics, with no commercial or defence work, and John Bell was highly valued.



Figure 1: Bell at Harwell [1].

Bell started working for Klaus Fuchs, Head of the Theoretical Physics Division, who had been involved at Los Alamos in building the atomic bomb. Bell did not enjoy this because Fuchs treated him very much as an underling among prima donnas, and so it was good for Bell when, in 1950, Fuchs was arrested for spying for the Russians, and Bell was able to move on to work with Bill Walkinshaw on accelerators, which was where he would have liked to have worked in the first place.

Bell only worked for three years on accelerators, but he achieved enough to show that he was a formidable physicist. The other members of the group were certainly highly experienced in working with the electromagnetism required in accelerators, but Bell was alone in having an excellent knowledge of fundamental physics, which was extremely important for his own progress.

When discussing accelerators today, one always talks the of energies involved, but of course just as important is the focusing. The reason why we don't hear so much about this is that the problems were solved fairly soon after the end of the war, to a considerable extent by Bell himself.

The search by Bell and his competitors was for 'strong focusing' and though, disappointingly from Bell's point of view, it was his competitors in USA who came up with the solution for the synchrotron, he compensated, not only by showing in detail how the method could be applied to the linear accelerator, which was actually a far from obvious extension, but also by producing a detailed mathematical account of the fundamental theory of the method. This work was described as 'seminal': by the age of 21 he was already respected as a physicist of considerable significance.

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Bell and CPT

Indeed, at this time, he was chosen by Rudolf Peierls, originally from Germany, but by this time one of the most important physicists in England, and Professor of Physics at Birmingham University, for a scheme he was initiating. He recognized that there were a number of excellent physicists who were well into highly successful careers but had not had the opportunity to carry out postgraduate research. In most cases it was because they had moved directly from undergraduate studies to war work. Bell's case was obviously different, but he was offered the opportunity to work in Peierls' group for a year.

His work concerned the so-called CPT theorem. C, P and T refer to notional operations that may be applied to any physical event. C, the charge conjugation operator, replaces a particle by its antiparticle, for example electron by a positron. P, the parity operator, reflects the event in a suitably chosen plane. The operator T replaces the event by the same event proceeding in the opposite direction.

At this time, there was interest in whether, when the combined CPT operator is applied to any physical event, the resulting reaction is another perfectly possible physical event. We may say that for all such events, CPT would be conserved.

Peierls asked Bell to study this problem, and he came up with a beautiful proof of this result. Unfortunately, though, it turned out that a German physicist, Gerhard Lüders, had already produced an independent proof of the theorem, which had indeed already been published. Nevertheless, Bell's proof was not only different from that of Lüders but rather simpler, so that it was also published in the highly prestigious Proceedings of the Royal Society and is very often used by those working in the field today.

Pauli also produced his own proof, and today the proof is always known as the Pauli-Lüders theorem, thus exemplifying the argument that credit always goes to those already famous!

However, Peierls was struck by Bell's ability, and he would be a great supporter of Bell's life, although actually he did not share Bell's scepticism towards Copenhagen. After the CPT paper. Bell published two more papers in the same journal and was then awarded his doctorate, but more importantly, Peierls arranged for him to move from working on accelerators to studying theoretical low-energy nuclear physics, still at Harwell.

Incidentally, at the time it was actually assumed, without proof, that each of C, P and T was individually conserved, so that of CPT was obvious, although the rigorous proof was still important. Over the next few years, though, it was discovered that in fact, none of C, P and T was conserved, so the conservation of CPT became even more significant.

John Bell and Mary Bell

During these years, there was also an important personal event for Bell. Mary Ross was a fellow-worker in the accelerator group, and they were married in May 1954. Mary was to continue working with accelerators for the rest of her career, while John moved to different areas of physics, but they were to live happily in Harwell and then in Geneva until John's sad death.

EPR: Einstein-Podolsky-Rosen, and Entanglement

Also in this period, Bell became far more knowledgeable about the fundamental structure of quantum theory in two distinct ways.



Figure 2: Mary and John in 1980 [1].

The first was the EPR or Einstein-Podolsky-Rosen thought experiment (often misleadingly called the EPR-paradox), which was proposed in 1935. The version of this experiment we shall study is that of David Bohm, which he produced in 1951.

The situation is rather as in the Prologue of Part 1. We may imagine a particle of zero spin decaying into two spin- $\frac{1}{2}$ particles. Clearly, for conservation of angular momentum (spin), one of them must be $|+\rangle$ and the other must be $|-\rangle$, but again, clearly, as long as we stick to the respected laws of standard quantum theory, we cannot possibly know which is which until we measure the spin of one of them.

Let us now imagine the particles are sent off in opposite directions, and then, when they may be a considerable distance apart, we measure the spin of one of them. Let us say that we obtain the result $+\frac{\hbar}{2}$. This tells us that the state of this particle is $|+\rangle$. Since this was not the case before the measurement, our mea-



Figure 3: David Bohm [1].

surement must have created this state. Equally though, and even more strangely, we know that the state of the other particle must now be $|-\rangle$. It thus seems that a measurement at one place has immediately had an effect at a spatially removed place.

Before we discuss this result, we will make a preliminary point. We might suspect that this experiment violates the law of special relativity, since it seems that something is traveling faster than the speed of light. However, this is not the case. Special relativity dictates only that we cannot send a message faster than light, and in the present case, since we cannot choose the state of the first particle, we certainly cannot send a message to the second one.

Nevertheless, as we have said, the result is highly surprising. It definitely seems that the behavior of the two particles is not independent. Erwin Schrödinger called this concept entanglement, and this term has been used ever since. He remarked that

this was ‘the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought’, Incidentally, Schrödinger, founder of wave mechanics, and Max Planck, founder of quantum theory itself, were the only two leading physicists who came down on Einstein’s side in the conceptual debate between Einstein and Bohr. That is, until Bell!

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Bohr himself was at first shocked by EPR, but, after a great deal of thought, decided that it was no more difficult to deal with than his previous challenges. His own arguments are perhaps not especially convincing for modern readers, but at the time it was obligatory for any physicist who wished to be taken seriously to claim to support them, even if, in many cases, they probably had not actually read them! Even Abraham Pais, in general a great supporter of Einstein, said that EPR said nothing about physics; it just said something about Einstein!

When Bell found out about EPR, probably not long after he moved to England, it would, of course, be obvious to him that the natural solution would be hidden variables – each particle must have had a particular state of spin from the very beginning, and the measurement merely discovered the state of the particle measured, and, of course, that of the other one. Again, though, he was aware of von Neumann’s result and felt that this simple solution would not be allowed.

One would have expected Einstein’s own response to the EPR argument to have been just hidden variables, and Bell was frustrated that it wasn’t, but it must be remembered that Einstein’s vision was much wider than this; he aimed at a grandiose united field theory encompassing the two fields known at the time, grav-

itation and electromagnetism, and only when this was achieved would difficulties like EPR slot into place. He did stress, though, that his final view of the world, which would unfairly be held against him, would be that the particles would be real, and the fields would be local — an event at one place could not instantaneously cause a second event at another place.

David Bohm and Hidden Variables

The second news about quantum theory to reach Bell in the early 1950s was a 1952 paper by Bohm. Contrary to everything Bell had been told, the paper presented an approach to quantum theory that included, in a central role, hidden variables.’ In 1952, he wrote, ‘I saw the impossible done.’ In this approach, quantum theory has wave and particle, and the wave dictates the motion of the particle, so the approach is often called the pilot-wave theory.

In 1952, I saw the impossible done.

In this theory, there is a wave-function as normal, but its square does not give a probability density but an actual density of particles. The position of the particle is the hidden variable, but it is important to realize that a measurement does not merely record this value; the measurement is a product of the complete setup of particle plus measurement device.

This approach is realistic, since it has hidden variables, and deterministic. However, it is stridently non-local; in fact, the behavior of any individual particle depends on the positions of all the other particles. This fact would be of great interest and importance to Bell.

Bell was angry that the great men of quantum theory dismissed Bohm’s ideas, but it was also disappointing that Einstein’s reac-

tion was negative. He called the ideas ‘too cheap’, but it will be remembered that his ideas were on a far grander scale.

In retrospect, it was interesting that Bohm’s ideas were actually a repeat of Louis de Broglie’s from thirty years before. These went far beyond the simple ideas we read about in the textbooks, but they were mocked at the time, and for many years, de Broglie became a follower of Copenhagen.

CERN: High Energy Nuclear Physics and Elementary Particles

Bell continued to think deeply about these matters, but left producing his own definite ideas until he had some time of his own. In the meantime, there was a great change to his and Mary’s lives. John had become concerned that, against its foundation principles, there might be some work for military purposes being carried on at Harwell, and also that it might be moving towards commercial work rather than first principles research.

For these reasons, he wanted to move to the theory group at CERN, the European Center for Nuclear Research at Geneva, and there, in addition, he would be able to work on high-energy nuclear physics and the theory of elementary particles. There was a danger from a career point of view because they were giving up permanent jobs in the British Civil Service for temporary positions – only a few of those working at CERN were made permanent, but fortunately, the Bells were (deservedly) fortunate in this way.

In his years at CERN, Bell was hugely successful, both in building up the status of the laboratory, and in a wide range of his own research, including such areas as the W-boson, neutral kaons, gauge theory, the weak interaction, the decay of the pion, and

neutral currents, and he became a Fellow of the Royal Society in 1972. However, we shall concentrate on his work on quantum theory.

Von Neumann was wrong!

The first time that Bell had time to dwell on quantum matters was when he and Mary were given a year's study leave to travel to the United States, where they spent most of the time at the Stanford Linear Accelerator Centre (SLAC). He did write several papers on particle physics and quantum field theory during this period, but also performed his great work on quantum theory.

Because Bohm's theory did exist, von Neumann's 'proof' that hidden variables were impossible must be incorrect, and first Bell needed to demonstrate where he was wrong. To understand his ideas, we need to introduce the term expectation value. As we know, when we measure a quantity in quantum theory, we will, in general, get one of several results. If we average these with appropriate probabilities, the result is called the expectation value, most misleadingly because not only do we not expect to get it, in most cases, we definitely know we won't get it!

However, there is a related result in quantum theory. Let us consider three quantities: O , P and $O + P$. There is absolutely no reason to suppose that the expectation value for measurements of $O + P$ will be the sum of that for O and that for P . Yet in fact it turns out that this is the case! Actually, a strange result.

What von Neumann did wrong was to assume that the same result must apply to his imagined hidden variables. This was quite unnecessary and incorrect, and so this assumption made his proof invalid.

Bell remarked that von Neumann's proof denying the possibility of hidden variables was actually rather 'silly'.

While Bell's proof demonstrating this result was not published until 1966, it was discovered in 1974 that an identical proof had been provided as early as 1933 by a young German philosopher Greta Hermann, who was working with Heisenberg. Her proof was ignored, partly because it was against the current beliefs, but also presumably because she was a woman. After the war, she was to become a noted professor of philosophy and mathematics.

Bell's Inequalities and the Experimental Tests

Bell now proceeded to his main result. He was delighted to see that hidden variables had certainly been shown not to be ruled out from quantum theory, but interested, perhaps a little disappointed, to see that Bohm's version was non-local. Over the years, it seems that he looked at several models himself and found that they all ran into non-locality, and he decided to find out if there was a proof that this was general. To do so, he studied systems of the EPR type, though he allowed the directions of the magnetic fields in the two wings to vary.

He actually defined three directions, **a**, **b** and **c**, and he calculated the predicted experimental results for the directions in the two wings being **a** and **b**, then **a** and **c**, and then **b** and **c**.

When he analyzed the results, he found that they were subject to the all-important inequality that the results must obey. This is usually called Bell's inequality, and his great result!

It is important to stress that, right from our study of EPR, we have been taking locality for granted. We are certainly assuming

that one of the detectors cannot communicate the direction of its measurement and its result to the other. If it could, the whole of our argument would become irrelevant.

Thus, our result is that if we have local realism, we do not have quantum theory; and, of course, if we have quantum theory, we cannot have local realism.

We may remember that Einstein had hoped for, and even expected, local realism, and for this reason, Bell has often been called the man who proved Einstein wrong, but this is extremely unfortunate, as it is just not true. The important point in this whole discussion has been that realism is allowed (hidden variables), and here Einstein was triumphantly right and Copenhagen wrong. The question of locality is extremely important but still secondary.

It is grossly unfair to call Bell 'the man who proved Einstein wrong'

The great point about Bell's work is that it was not armchair logic. It suggested that experiments could be done to check the clash between quantum theory and the results of Bell's inequality. But at first, it would be interesting to see if anybody picked up the ideas. In fact, two very different people did so. The first was Abner Shimony, a deep-thinking physicist and philosopher, and the second was John Clauser, a rather brash though exceptionally bright experimental physicist, who was ideally suited for these questions of principle because he did not believe in quantum theory in the first place!

Together with two colleagues, Richard Horne and Richard Holt, Clauser and Shimony now produced an argument always called CHSH, which changed the theoretical ideas of Bell into a blueprint for an experiment.

Now, two groups, Clauser with Stuart Freedman, and Holt with



Figure 4: Abner Shimony, © Renate Bertlemann; Central Library for Physics, Vienna. [1].

Frank Pipkin, proceeded to test the Bell results in 1972. It should be mentioned that these experiments worked with the polarization of photons rather than the spin of electrons, but the general principles are as before.

According to CHSH, in Aspect's experiments, if local realism is upheld, $S(\theta)$ must lie between -2 and +2, but we see that for quantum theory it takes considerable ranges of values not obeying this rule.

We may explain the results as follows: the experiments use an angle θ , and calculate a suitable function $S(\theta)$ from quantum theory, which is shown in Figure.6. For local realism to be obeyed $S(\theta)$ must lie between -2 and +2, and it can be seen that there are large ranges of θ for which $S(\theta)$ from quantum theory lies outside this range. The greatest deviations are at θ equal to 22.5° and 67.5° , where $S(\theta)$ equals $2\sqrt{2}$ and $-2\sqrt{2}$ respectively. These are known

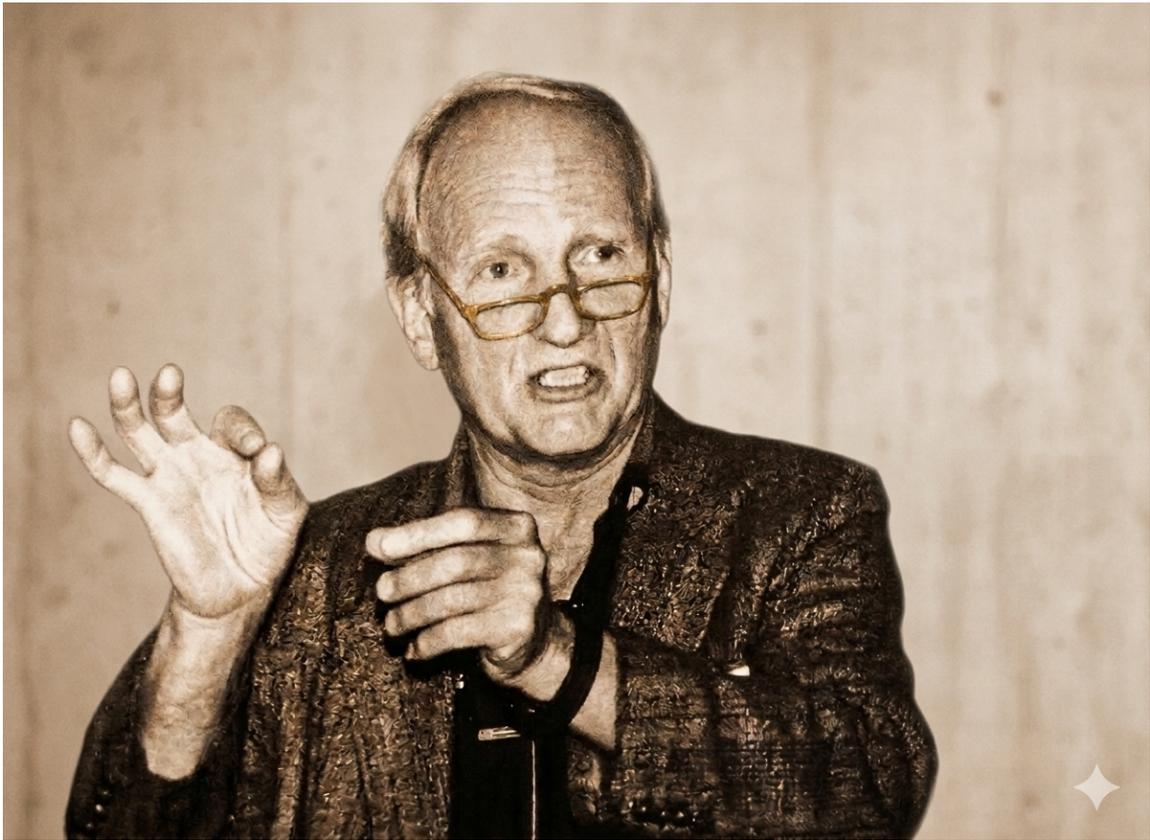


Figure 5: John Clauser. © Renate Bertlmann; Central Library for physics, Vienna. [1].

as Freedman angles.

When, after a great deal of hard work, Clauser and Freedman's results emerged, the decisively exciting news was that they ruled out local realism, and in fact were very close to those predicted by quantum theory. (The results shown in Figure 6 are actually those of a later experiment carried out by Alain Aspect, which will be described shortly.)

However, those of Holt and Pipkin were totally the opposite; rather embarrassingly, they supported local realism and ruled out quantum theory. Because of this divergence, the experiments were repeated twice fairly quickly, and it became clear that it was Clauser and Freedman whose results were correct, and so local realism was wrong and quantum mechanics was right.

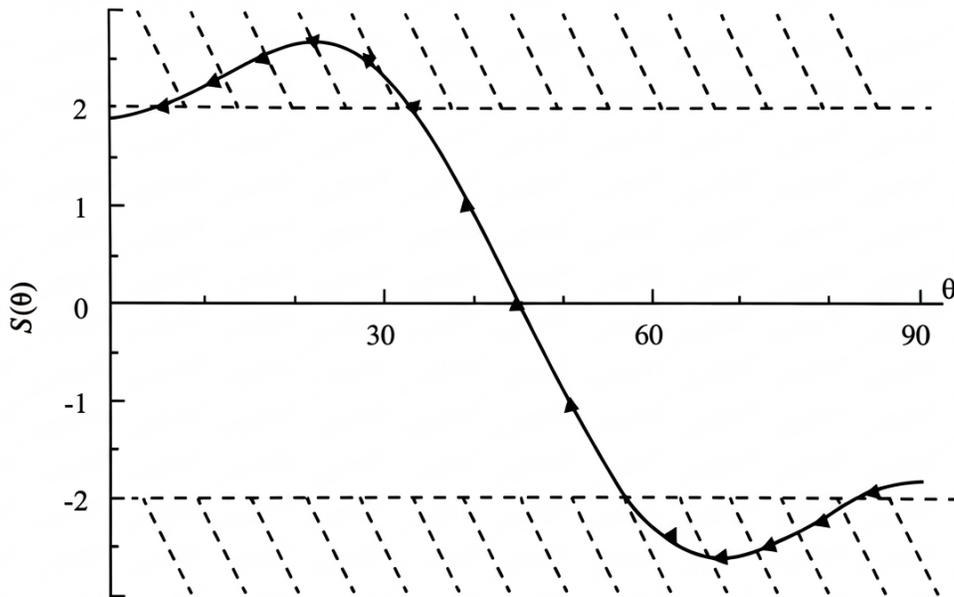


Figure 6: Experimental results following the ideas of CHSH with the results of Alain Aspect [1]. **The quantity S** , according to CHSH, must not lie in the hatched region. The solid line is the prediction of quantum theory, which lies in the hatched region for large ranges of angle θ . (The triangles are the experimental values obtained by Aspect and his collaborators, as described in Chapter 5 of [1]). From A. Aspect and P. Grangier, Symposium on the Foundations of Modern Physics: 50 Years of the Einstein-Podolsky-Rosen Gedanken-Experiment (World Scientific, Singapore, 1985).

Local Realism was proved to be wrong and quantum mechanics right.

The Loopholes

However, there were problems with the results, known as the loopholes. The detector loophole recognized that photon detection was extremely inefficient. In theory, this was a problem, and great efforts have been made to improve it, but Bell recognized that it was extremely unlikely that a rather inefficient setup would give one type of result, but its nature would completely change if the setup was made more efficient. He was, though, concerned about the so-called locality loophole, which recognized that it was possible for the two detectors to communicate at a

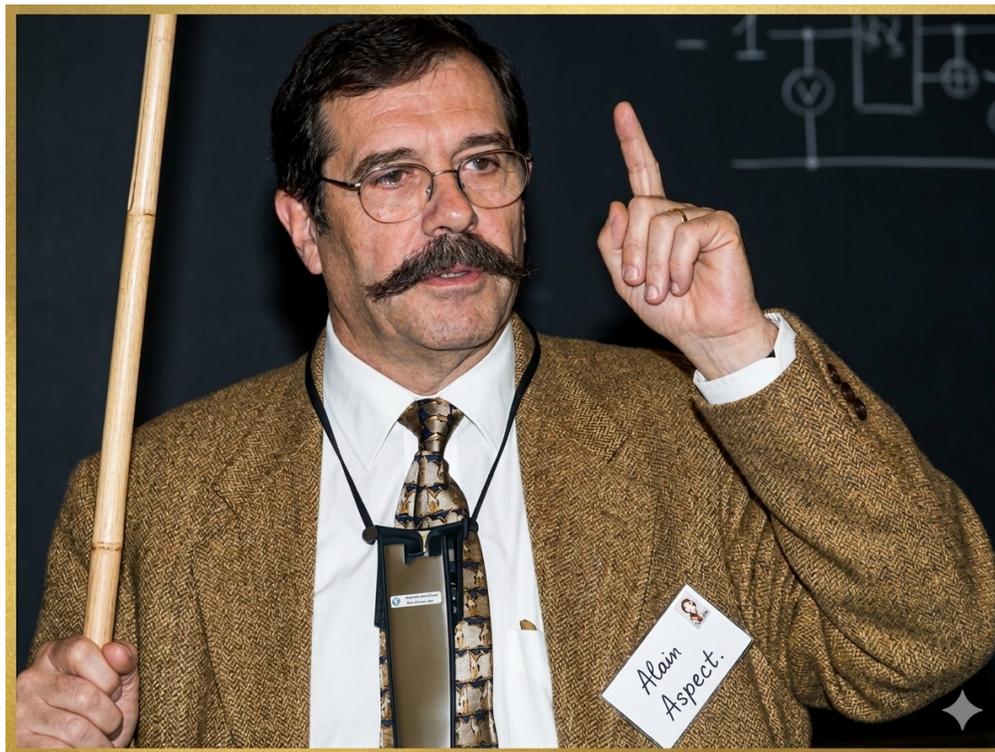


Figure 7: Alain Aspect. © Renate Bertlmann [1].

speed less than that of light.

In Aspect's experiment of 1981, in each wing of the experiment, two polarizers were pointing in different directions. There was switching between the two polarizers in each wing at different frequencies in each wing, and this was sufficiently fast that the exchange of information on the directions of the polarizers between the two wings of the experiment was impossible.

This was clearly a major step up from the Clauser experiment, and, as shown in Figure 6, the results were still the same: quantum theory was obeyed, and local reality disproved.

Conclusion

A great deal of progress had been made, and Clauser and Aspect were, deservedly but much later, to be awarded two out of three shares of the Nobel Prize for Physics in 2022, sharing it with

Anton Zeilinger, who we will meet in Part 3.

However, we will also meet in Part 3 many more advances and discoveries flowing from Bell's ideas, experimental, technical and theoretical.

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Further Reading

- [2] D. Home, *Conceptual Foundations of Quantum Mechanics: An Overview from Modern Perspectives*. New York: Plenum, 1997.