only possible to make minor technical improvements. In fact we need a new idea for making a truly important improvement, so I think that now it's enough for me.

What do you think that Einstein would have made of the result of your experiment had he been alive?

Oh, of course I cannot answer this question, but what I am sure of is that Einstein would certainly have had something very clever to say about it.

He usually did, yes!

3

John Bell

John Bell is a theoretical physicist at the Centre Européen pour la Recherche Nucléaire (CERN) near Geneva. His key theorem, proved in 1964, forms the basis for the recent experimental tests of the conceptual foundations of quantum mechanics by Aspect and others. Bell's theorem was described by Berkeley particle physicist Henry Stapp as 'the most profound discovery of science'.

Your famous result that we all know as 'Bell's inequality' can obviously only be properly discussed by using mathematics. But could you explain briefly in ordinary language what it is about?

It comes from an analysis of the consequences of the idea that there should be no action at a distance, under certain conditions that Einstein, Podolsky and Rosen focussed attention on in 1935 – conditions which lead to some very strange correlations as predicted by quantum mechanics.

By no action at a distance you mean no faster-than-light signalling?

Yes. Strictly speaking no faster-than-light signalling. In a less rigid sense no action at a distance simply means that there are no hidden connections between things.

The Nobel prize winning physicist Brian Josephson once described Bell's inequality as the most important recent advance in physics. How do you respond to that?

Well, I would say that's probably a little bit exaggerated. But if you're primarily concerned with the philosophy of physics, I can see his point.

Now, recently, it has actually been possible to put the inequality to the test rather well. One of the best experiments has been performed by Alain Aspect in Paris. What do you think of the results of this experiment? What do you think they tell us about the nature of the physical world?

✓ Well, to begin with, one must say that the results were expected, in that they agreed with the predictions of quantum mechanics. After all, quantum mechanics is an extremely successful branch of science, and it was difficult to believe that it could be wrong. Nevertheless it was thought worth while, and I thought it worth while, to do this very particular experiment, which isolates what is one of the most peculiar features of quantum mechanics. Previously we were just relying in a way on circumstantial evidence. Quantum mechanics had never been wrong. And now we know that it will not be wrong even in these very tricky conditions.

Of course one person who was somewhat disbelieving was Einstein, and he made the famous remark that God does not play dice with the universe. Would you say that after this experiment, and after your work, you're convinced that God does indeed play dice with the universe?

No, no, by no means. But I would also like to qualify a little bit this 'God does not play dice' business. This is something which is often quoted, and which Einstein did say rather early in his career, but afterwards he was more concerned with other aspects of quantum mechanics than with the question of indeterminism. And indeed, Aspect's particular experiment tests rather those other aspects, specifically the question of no action at a distance. sic

You don't think it tells us anything about the determinism or indeterminism or the physical world?

To say it tells you nothing, that would be going too far. I think that it is very difficult to say that any one experiment tells you about any isolated concept. I think that it's a whole world view which is tested by an experiment, and if the experiment does not verify that world view, it is not so easy to identify just which part

is suspect and has to be revised. Certainly the experiment says that Einstein's world view is not tenable.

Yes, I was going to ask whether it is still possible to maintain, in the light of experimental experience, the idea of a deterministic universe?

You know, one of the ways of understanding this business is to say that the world is super-deterministic. That not only is inanimate nature deterministic, but we, the experimenters who imagine we can choose to do one experiment rather than another, are also determined. If so, the difficulty which this experimental result creates disappears. ? absolute space + time

Free will is an illusion – that gets us out of the crisis, does it?

That's correct. In the analysis it is assumed that free will is genuine, and as a result of that one finds that the intervention of the experimenter at one point has to have consequences at a remote point, in a way that influences restricted by the finite velocity of light would not permit. If the experimenter is not free to make this intervention, if that also is determined in advance, the difficulty disappears.

Turning to this issue of the experimenter, inevitably it raises questions about mind, choice, free will and so on. Do you in fact believe that mind has a fundamental role to play in physics?

I neither believe, nor disbelieve that. I think that mind is a very important phenomenon in the universe, certainly for us. Whether it is absolutely essential to introduce it into physics at this stage, I am not sure. I think the experimental facts which are usually offered to show that we must bring the observer into quantum theory do not compel us to adopt that conclusion. The Aspect experiment is a little more tricky than the others, and I can see the logic of people who say that it goes in the direction of showing that mind is essential. It's a hypothesis that we can certainly explore, but I don't know that it's the only one. vs free choice

Do you believe there are still paradoxes in the question of measurement and the role of the observer?

Yes I believe that there certainly are paradoxes. The problem of measurement and the observer is the problem of where the measurement begins and ends, and where the observer begins and ends. Consider my spectacles, for example: if I take them off now, how far away must I put them before they are part of the object rather than part of the observer? There are problems like this all the way from the retina through the optic nerve to the brain and so on. I think, that – when you analyse this language that the physicists have fallen into, that physics is about the results of observations – you find that on analysis it evaporates, and nothing very clear is being said.

So that these issues haven't been fully resolved, at least to your satisfaction?

N.B. "field"

Absolutely not. And the experiment of Aspect and the Einstein–Podolsky–Rosen correlations do not help to resolve this problem, but make it harder, because Einstein's view that behind the quantum world lies a familiar classical world was a possible (and now discredited) way of solving this measurement problem – a way of reducing the observer to an incidental role in the physical world.

Very

Bell's inequality is, as I understand it, rooted in two assumptions: the first is what we might call objective reality – the reality of the external world, independent of our observations; the second is locality, or non-separability, or no faster-than-light signalling. Now, Aspect's experiment appears to indicate that one of these two has to go. Which of the two would you like to hang on to?

Weird

Well, you see, I don't really know. For me it's not something where I have a solution to sell! For me it's a dilemma. I think it's a deep dilemma, and the resolution of it will not be trivial; it will require a substantial change in the way we look at things. But I would say that the cheapest resolution is something like going back to relativity as it was before Einstein, when people like Lorentz and Poincaré thought that there was an aether – a preferred frame of reference – but that our measuring instruments were distorted by motion in such a way that we could not detect motion through the aether. Now, in that way you can imagine that there is a preferred frame of reference, and in this preferred frame of reference things do go faster than light. But then in other frames of reference when they seem to go not only faster than light but backwards in time, that is an optical illusion.

Well, that seems a very revolutionary approach!

Revolutionary or reactionary, make your choice. But that is certainly the cheapest solution. Behind the apparent Lorentz invariance of the phenomena, there is a deeper level which is not Lorentz invariant.

Of course the theory of relativity has a tremendous amount of experimental support, and it's hard to imagine that we can actually go back to a pre-Einstein position without contradicting some of this experimental support. Do you think it's actually possible?

e.g. field

Well, what is not sufficiently emphasized in textbooks, in my opinion, is that the pre-Einstein position of Lorentz and Poincaré, Larmor and Fitzgerald was perfectly coherent, and is not inconsistent with relativity theory. The idea that there is an aether, and these Fitzgerald contractions and Larmor dilations occur, and that as a result the instruments do not detect motion through the aether – that is a perfectly coherent point of view.

And it was abandoned on grounds of elegance?

Well, on the grounds of philosophy; that what is unobservable does not exist. And also on grounds of simplicity, because Einstein found that the theory was both more elegant and simpler when we left out the idea of the aether. I think that the idea of the aether should be taught to students as a pedagogical device, because I find that there are lots of problems which are solved more easily by imagining the existence of an aether. But that's another story. The reason I want to go back to the idea of an aether here is because in these EPR experiments there is the suggestion that behind the scenes something is going faster than light. Now, if all Lorentz frames are equivalent, that also means that things can go backward in time.

Yes, and that is the big problem.

cf Hameroff Penrose

It introduces great problems, paradoxes of causality and so on. And so it's precisely to avoid these that I want to say there is a real causal sequence which is defined in the aether. Now the mystery is, as with Lorentz and Poincaré, that this aether does not show up at the observational level. It is as if there is some kind of conspiracy, that something is going on behind the scenes which is not allowed to appear on the scenes. And I agree that that's extremely uncomfortable.

I'm sure Einstein would turn in his grave!

?

Absolutely. And that's very ironic, because it is precisely his own theory of relativity which creates difficulties for this interpretation of the quantum theory (which is in the spirit of Einstein's unconventional view of quantum mechanics).

To sum up then, you would prefer to retain the notion of objective reality and throw away one of the tenets of relativity: that signals cannot travel faster than the speed of light?

Yes. One wants to be able to take a realistic view of the world, to talk about the world as if it is really there, even when it is not being observed. I certainly believe in a world that was here before me, and will be here after me, and I believe that you are part of it! And I believe that most physicists take this point of view when they are being pushed into a corner by philosophers.

But it's always seemed to me that the practice of physics is merely creating models which describe the observations that we can make on the world, and relate them together, and we have either good models or less good models, depending on how successful they are. The idea of the world 'really existing', and our theories somehow being 'right' or 'wrong' or being approximations to this reality, I think is not a very helpful one. How do you respond to that?

Well, I do find it helpful, the idea that there is a real world there, and that our business is to try to find out about it, and that the technique for doing that is indeed to make models and to see how far we can go with them in accounting for the real world.

Do you believe that there could be an ultimate theory which would be the 'correct theory' of the universe, and would describe everything exactly?

I don't know about that, but I do believe there will be theories that are better than the ones we have, in that they describe more of the universe and connect more of it up.

So you believe that the present formulation of quantum theory, which has been so tremendously successful over the last 50 years, is still only tentative, and will be replaced at some stage in the future by a better theory?

I'm quite convinced of that: quantum theory is only a temporary expedient.

Einstein

What evidence is there that quantum theory is in any way unsuccessful in explaining everything we have to explain?

Well, it does not really explain things; in fact the founding fathers of quantum mechanics rather prided themselves on giving up the idea of explanation. They were very proud that they dealt only with phenomena: they refused to look behind the phenomena, regarding that as the price one had to pay for coming to terms with nature. And it is a fact of history that the people who took that agnostic attitude towards the real world on the microphysical level were very successful. At the time it was a good thing to do. But I don't believe it will be so indefinitely. Of course, I cannot produce theorems to that effect. If you go back to, say, David Hume, who made a careful analysis of our reasons for believing things, you find that there is no good reason for believing that the sun will come up tomorrow, or that this programme will ever be broadcast. It's a habit we have, of believing that things will continue very much as they did before. However, it is a fact that this seems to be a good habit! I cannot make that a theorem, because I think Hume's analysis is sound, but nevertheless I do believe it's a good habit, to look for explanations.

So, if we think ahead to perhaps 50 years in the future, where we may *have a theory which replaces quantum mechanics, can you see this coming about because of continuing anxiety over the interpretational problems we've been talking about? Or do you think that there will be some experiment, for example something that could be performed at CERN, such as very high energy particle collisions – exploring the micro-microworld – that could perhaps expose an area where quantum mechanics will fail?*

Well, now you're asking me to guess. It seems to me possible that the continuing anxiety about what quantum mechanics means will lead to still more and more tricky experiments which will eventually find some soft spot, some point where quantum mechanics is actually wrong.

So the Aspect experiment is not the ultimate experiment that can be done to test these ideas?

I think not. It is a very important experiment, and perhaps it marks the point where one should stop and think for a time, but I certainly hope it is not the end. I think that the probing of what quantum mechanics means must continue, and in fact it will continue, whether we agree or not that it is worth while, because many people are sufficiently fascinated and perturbed by this that it will go on.

What other sort of experiments could we envisage that would test further?

One can point to various defects in the existing experiments, including that of Aspect. Strictly speaking these experiments do not demonstrate the awkward correlations. You find that the counters that are used are too inefficient, that the geometry is inefficient, that the ideal set-up has not been realized, and there is an enormous extrapolation required from the experiment which can actually be done.

So you can envisage refinements of the present basic set-up which will be much more convincing?

You can envisage them, but I don't want to say that I encourage experimenters just to go on brutally like that, making the counters more efficient and so on, because I'm inclined to believe myself that the efficiency of the counters is not the important thing.

What do you think about attempts to use superconductivity and low temperature physics to explore some of the weird quantum effects on a macroscopic scale?

ULTRA
COLD

They do not seem to me to be promising. I think there is a very interesting analysis by A. Leggett, who concluded that the kind of macroscopic things you see in superconductivity are rather unrelated to the kind of macroscopic things which would be embarrassing for a realistic view of the world and so on – that really they are not relevant. One tends to say, 'Oh, superconductivity shows macroscopic quantum mechanics', but not in the sense we are concerned with in Einstein–Podolsky–Rosen correlations.

And you can't imagine a more elaborate arrangement that might expose these defects in quantum mechanics?

I cannot, but I hope that's only because of my limitations. I think it is very probable that the solution to our problems will come through the back door; some person who is not addressing himself to these difficulties with which I am concerned will probably see the light. An analogy that I like is that of the fly buzzing against a window when the door is open. It can be extremely useful to stand back from your problems and just wander about for a time, and it is quite possible that those of us who are somewhat fixated on these questions will not be those who see the way through.

This is so often the way in scientific discovery isn't it?

Absolutely, and this of course is the argument for pure research, which often tends to be rather undirected.

I hope the politicians are listening! Do you see the difficulties with quantum mechanics as purely philosophical or interpretational, or do you think that there are some real experimental problems?

I think there are *professional* problems. That is to say, I'm a professional theoretical physicist and I would like to make a clean theory. And when I look at quantum mechanics I see that it's a dirty theory. The formulations of quantum mechanics that you find in the books involve dividing the world into an observer and an observed, and you are not told where that division comes – on which side of my spectacles it comes, for example – or at which end of my optic nerve. You're not told about this division between the observer and the observed. What you learn in the course of your apprenticeship is that for practical purposes it does not much matter where you put this division; that the ambiguity is at a level of precision far beyond human capability of testing. So you have a theory which is fundamentally ambiguous, but where the ambiguity involves decimal places remote from human abilities to test.

Of course Eugene Wigner has suggested that he can insert a very definite division between the observer and the observed, because he invokes the mind as a completely separate entity which is somehow coupled to the world, and he says that it's the entry into the mind of the observer that resolves the paradoxes which we've been discussing. So he's bringing the idea of a non-material mind to play a prominent part in the physical world. Do you have any sort of sympathy for that point of view?

Well, it's an idea that's worth exploring. But in my opinion, the difficulties associated with it are underestimated, simply because nobody has developed the theory beyond the talk stage. As soon as you try to put such theories down in mathematical equations, as soon as you try to make them Lorentz invariant, you get into great difficulties. For example, the interaction between the mind and the rest of the world, how does that occur? Does that occur over a finite region of space, at an instant of time? Clearly not, because that is not a Lorentz invariant concept.

By Lorentz invariant you mean that it doesn't have a consistent description for all observers depending on how they're moving?

That's correct. And the only way to get such a consistent description, if you assume the mind has access to a single point in time, is to also assume that it has access to only a single point in space.

This is the big difficulty that there has always been with mind; that it can't be located anywhere in space, and yet one presumably wants it to be located in time.

Absolutely, and yet Wigner wants somehow to couple that up into the equations of physics. It has simply not been done. It is simply talk, for the present.

There are of course a variety of other interpretations of the quantum formalism, and there is a certain amount of controversy over them. One of these is the many-universes interpretation. Do you have any strong feelings about it, for or against?

Yes, I have strong feelings against it, but I have to qualify that by saying that in this particular Einstein–Podolsky–Rosen situation there is some merit in the many-universes interpretation, in tackling the problem of how something can apparently happen far away sooner than it could without faster-than-light signalling. If, in a sense, everything happens, all choices are realized (somewhere among all the parallel universes), and no selection is made between the possible results of the experiment until later (which is what one version of the many-universes hypothesis implies), then we get over this difficulty. ✓

But it does seem an extremely bizarre means of getting over it.

It's extremely bizarre, and for me that would already be enough reason to dislike it. The idea that there are all those other universes which we can't see is hard to swallow. But there are also technical problems with it which people usually gloss over or don't even realize when they study it. The actual point at which a branching occurs is supposed to be the point at which a measurement is made. But the point at which the measurement is made is totally obscure. The experiments at CERN for example take months and months, and at which particular second on which particular day the measurement is made and the branching occurs is perfectly obscure. So I believe that the many-universes interpretation is a kind of heuristic, simplified theory, which people have done on the backs of envelopes but haven't really thought through. When you do try to think it through it is *not* coherent.

Well, that's a very interesting and blunt response. We've been talking here about some fairly strange areas of physics; how did you first become interested in the foundations of quantum theory and in particular how did you come across your famous inequality?

Well, as a student I was very conscious of these problems: the apparent subjectivity of quantum mechanics, and this way of talking which seems to force you to bring in the observer but actually doesn't. I was, from a very early stage, convinced that it must be possible to formulate physics in a more professional way, in which this vagueness does not intrude. I actually avoided these questions for a number of years because I saw that people smarter than I had made little progress with them, and I got on with other more practical things. But then in Geneva in 1963 when I was busy with other things I met Professor Jauch at the University. He was concentrating on these issues, and in discussion with him I became determined to do something about them. One of the things that I specifically wanted to do was to see whether there was any real objection to this idea put forward long ago by de Broglie and Bohm that you could give a completely realistic account of all quantum phenomena. De Broglie had done that in 1927, and was laughed out of court in a way that I now regard as disgraceful, because his arguments were not refuted, they were simply trampled on. Bohm resurrected that theory in 1952, and was rather ignored. I thought that the theory of Bohm and de Broglie was in all ways equivalent to quantum mechanics for experimental purposes, but nevertheless was realistic and unambiguous. But it did have the remarkable feature of action-at-a-distance. You could see in the equations of that theory that when something happened at one point there were consequences immediately over the whole of space unrestricted by the velocity of light.

Did that worry you at that early stage, because of the inevitable paradoxes that would follow as a consequence?

The de Broglie–Bohm theory was developed for non-relativistic quantum mechanics only, and this instantaneous propagation of effects made it clear that that theory would have difficulties when you tried to extend it to the relativistic context.

Did you arrive at your result quickly? It's a very powerful and all-embracing result, proven in a very elegant way. Or was it something that you made tentative steps with and saw your way to the answer, and then went back and did the nice polished version?

It's a bit like the question of how long does a measurement take! How long does it take to make a discovery? Probably I got that equation into my head and out on to paper within about one weekend. But in the previous weeks I had been thinking intensely all around these questions. And in the previous years it had been at the back of my head continually. So it's really not possible to say how long it took to produce the result.

2013.07.27
after party
at Wendel's