As God's Dice Fall

Was Einstein wrong and Bohr right? Experiment goes against the EPR paradox.

By DIETRICK E. THOMSEN

"I can't believe that. That's much too concrete to be real." So Martin Klein of Yale University quotes Niels Bohr. Quantum theory, of which Bohr was one of the main progenitors, is anything but too concrete. This attitude of Bohr's may reflect both what he saw in quantum theory and what he gave to it, and it could be a basis for the famous controversy between him and Albert Einstein that lasted more than three decades.

In their lifetimes neither made the other budge. They died good friends but conceptually unreconciled. Their colleagues, pupils and followers have ramified and continued the argument. Many of them and others gathered recently at the American Academy of Arts and Sciences in Cambridge, Mass., for "A Symposium Commemorating the Centennial of Niels Bohr." A series of experiments done near Paris has put a definite advantage in Bohr's court with respect to a very important part of the argument, the challenge historically known as the Einstein-Podolsky-Rosen (EPR) paradox.

Einstein is famous for remarks about God not throwing dice. These epigrams led to a general belief that his disagreement with quantum mechanics was based on problems of determinism and causality, an unhappiness with the uncertain, statistical quality of quantum mechanical predictions. Not so, said Einstein himself (in his correspondence with Max Born, cited by N. David Mermin of Cornell University in Ithaca, N.Y., in the April 1985 PHYSICS TODAY). The most basic unhappiness, prior to Einstein's admitted dislike of the statistical aspects, was over reality, the reality of physical attributes and properties.

Quantum theory comes with built-in ontological difficulties. Contradictory states of being are linked together: An object seems to be both a wave and a particle. Certain pairs of properties of objects, such as position and momentum, are linked by an uncertainty principle that says the better you know one of them the worse you know the other.

These dualities, ambiguities and un-

AIP Niels Bohr Library

Einstein (left) and Bohr disputed the meaning of reality as long as they both lived, but they were personal friends. Here they talk at the 1927 Solvay Conference in Brussels.

certainties reopened the question of what is real, an issue which had long been decided in classical physics (by a more or less Aristotelian consensus). In classical physics a wave is a wave; a particle is a particle. Position and momentum have precise meanings and values, and they are quite independent of one another and of any observer. They exist objectively.

This doesn't seem to be so in quantum mechanics. The uncertainties and the linkages seem to damage or destroy the independence and objectivity of these attributes. Yet, when an experimenter measures a position or a momentum, the datum comes up such and so with no apparent difference from a measurement in classical physics. It seems quite real.

Where do precision and actuality enter? It seems to be somewhere connected with the act of measurement. And so arises the long and agonized debate over the effect of an act of measurement on reality in quantum mechanics, a question that simply doesn't exist in classical physics. A variety of positions have been taken and are hotly argued, but the one associated with Bohr's Copenhagen school goes roughly like this: The act of measurement has a very important effect on the reality of things. The physical attributes in question (and some have gone so far as to say the objects themselves) are at most potentially real. The act of measurement makes them actual.

Einstein could not put up with any of this. He insisted that objects must have physical attributes that are always actual and real, quite independently of any observer or act of measurement. Quantum mechanics has all these uncertainties because it is an incomplete theory. It does not tell enough because it does not know enough. There are aspects of the situation that we do not see, the famous "hidden variables." If we could know these hidden variables, the problems would drop away, and the quantum world would reveal itself to be as precise and objective as the classical world.

Bohr's response to this was that quantum mechanics is all the theory we are going to get, and we had better content ourselves with dealing on its terms.

Instead of looking for hidden variables directly — how do you look for something when you don't know what it is you are looking for? — Einstein and his followers devised challenges for quantum theory by which they hoped to drive it into paradox on its own terms. One problem here is that you have to be careful of your paradox. Quantum theory contains built-in paradoxes, which its supporters tend to accept as part of nature depending on their philosophical predilections, and if you present them with a certain paradox, they may say, "So what?"

In 1935 Einstein, with Boris Podolsky and Nathan Rosen, published a description of a hypothetical situation they thought would confound quantum mechanics. It is known as the Einstein-Podolsky-Rosen paradox. Now, on its 50th anniversary, the EPR paradox seems finally to have been "refuted," according to Mermin.

The EPR paradox takes off from the phenomenon of correlation. Suppose an atom emits two photons of light in a single process and they go off in opposite directions. These two photons are correlated with each other by the terms of their origin. Let's suppose their polarizations are opposite: If you measure the polarization of photon A to be left at any instant, photon B's has to be right at the same instant.

Can such a correlation maintain itself over long distances? If one set up detectors at opposite ends of the room (which from the atom's point of view is an astronomical distance), would the measurements show it? It might seem obvious to many people that they should, but many physicists would question that. To them it looks like "action at a distance," and action at a distance has been uncomfortable for physicists since Isaac Newton: They don't like the idea of one thing influencing another without some physical connection between them, a string, a light beam, a radio wave. Here, as the photons are each traveling at the speed of light, nothing physically known can go between them.

In quantum theory this kind of correlated beginning means that there is one wave equation that describes the states of both photons for all time and space, no matter how far they get from one another. If quantum mechanical waves have a connection with physical reality — and the arguments on that question are also various, there being a number of positions between categorical yes and no — the correlation ought to hold.

The EPR point then becomes: If I measure the polarization of photon A at one end of the room, I automatically know the polarization of photon B at the other end, and a measurement there should confirm it. But I knew the state of B without measuring it. That means the attributes of B are objective and belong to B without reference to the act of measurement. Otherwise you have to suppose that the act of measurement that brings into actuality the particular polarization of photon A instantaneously affects matters at the other end of the room and brings into actuality a corresponding polarization for B.

The first choice would agree with Einstein and imply that quantum theory had to be reworked, presumably via hidden variables, into a theory that would provide for the objectivity conceded to the attributes of photon B. The second choice provides physics with what Einstein called "spooky actions at a distance" *(spukhafte Fernwirkungen)*. Einstein was betting that if the Copenhagen school picked it, and the choice came out explicitly, it would alienate the majority of physicists.

In fact that is what the Copenhagen school chose. As Max Born pointed out in a letter to Einstein, if you believe in the reality of correlations, there's no problem. Bohr's response was that there is a wholeness to a quantum event that persists over time and space and makes such linkages possible. In spite of that, physicists did not desert quantum mechanics; it calculates the results of experiments too well.

The philosophical problem of the bases and conceptual credibility of the theory remained, however, and physicists wondered whether experiment could really say anything about it. Such an experiment would use a large number of such two-photon emissions. Polarizers might be set up at opposite ends of the room. Their settings would be changed randomly and independently between shots. In this circumstance, for a given shot, polarizer A might be aligned with the polarization of photon A. Photon A would enter, and the apparatus would click. If at the same time polarizer B were aligned with photon B, a click would be heard from there. Depending on the polarizations and any correlation between them, sometimes there would be double clicks, sometimes single clicks, sometimes no clicks. Can the statistics of such an experiment tell anything about the philosophical dispute?

In 1964 John S. Bell of the CERN laboratory in Geneva showed that they can. *Regardless of one's philosophical presumptions,* he found that the mathematics of quantum mechanics allows the calculation of numbers, correlation rates, that can distinguish between the reality of quantum mechanical correlations and the nonreality. A simple case of one number or the other.

Over the last few years Alain Aspect of the University of Paris-South at Orsay and his co-workers, particularly Philippe Grangier of the University of Paris-South and Jacques Vigue of the Ecole Normale Supérieure in Paris, have done a series of experiments, variations of this and other long-suggested EPR experiments. The results have consistently been, as Aspect stated at the Bohr centennial symposium, what Bell's calculation expects for the reality of quantum correlations.

Various qualified observers are judging this as the final word on the EPR paradox. They say it means that hidden variables are not there, that quantum mechanics is what it is, and we have to live with it. The spooks seem to be loose in physics. Or, as Bohr said: "We must still be prepared for new surprises." □