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Mind-boggling reality

David Bohm. Image from Library of Congress, New York — Telegram and Sun Collection, courtesy of AIP Emilio Segrè Visual Archives.

In 1935, Albert Einstein, Boris Podolsky and Nathan Rosen questioned whether quantum mechanics fully describes 'physical reality'. Their paper, which was intended to illustrate that quantum mechanics is incomplete, sparked discussions that go deep into the philosophical aspects of 'reality' and how physics can describe it. Later that year, Einstein confessed in a letter to Erwin Schrödinger that he felt that "the main point was, so to speak, buried by erudition", and began publishing his own versions of the 'incompleteness argument'. All of these accounts, and the original Einstein–Podolsky–Rosen paper, made their point using continuous variables — that is, position and momentum. However, the version that is most widely discussed in the modern literature, and also forms the basis of many experimental investigations, presents the argument in a simpler and clearer form, in terms of discrete spin variables. It was penned by David Bohm and appeared originally in his 1951 book *Quantum Theory*; he developed the argument further, in the context of experimental proofs, with Yakir Aharonov in 1957.

Bohm and Aharonov considered a molecule made of two atoms — each having one half-unit of spin — combined such that the total spin of the molecule is zero. When the two atoms are separated, and, for one of the spins, the spin component is measured along a given direction, the same component is immediately known for the other spin — it is exactly the opposite, as the total spin still has to be zero. At first sight, it might not seem surprising that information about the properties of the second particle of a composite system can be deduced without performing any measurement on it, and without any interaction between the two particles, if the initial condition restricts how the two particles behave with respect to each other.

For a quantum spin, however, the situation is more subtle. Quantum mechanics allows only one component of the spin to have a definite value. If, for instance, the x component of the spin is known, then the components along the y and z axes must be indeterminate; the component that is definite is determined by its measurement. Yet, in this case of two separated spin-1/2 particles, an experimenter can decide at the last minute — long after the two constituents have been separated — along which direction the first spin is measured. And this choice has immediate consequences on which component of the second, unobserved, spin is definite.

How can the second spin know what has been done to the first? Is there some kind of hidden interaction that quantum theory does not account for? Does quantum mechanics allow what Einstein famously called "spooky action at a distance" (an idea he did not like)? Einstein argued that if no action at a distance can instantaneously influence the second spin, then it must have had all its components well defined from the outset — hence, quantum mechanics must be incomplete.

A decisive step came in 1964 when John Bell, building on the Bohm–Aharonov formulation in spin variables, showed that quantum mechanics makes predictions that contradict the local-realistic world view of Einstein and do require action at a distance of some sort. Bell's theorem has been put to the test many times since, and although there is, as yet, no single experiment that closes all possible loopholes, the weight of evidence does still favour quantum mechanics.

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