Sheet 1

The Bohr-Einstein debate and quantum entanglement tested experimentally

In quantum physics, the value of an observable[1] such as the position or velocity of a particle can generally only be predicted statistically, by the probability of finding a particular value. Niels Bohr, one of the founders of quantum mechanics, considered the probabilistic nature of the predictions of this theory to be fundamental. However, for Albert Einstein, the impossibility of predicting the results of measurements other than in probabilistic terms was, in his opinion, proof that quantum theory was "incomplete", and that it omitted to take into account certain aspects of reality. The debate had started.

To put the principles of quantum physics to the test, Albert Einstein, Boris Podolsky and Nathan Rosen suggested in 1935 a thought experiment (known as "EPR", after the authors' initials). The argument goes as follows: the laws of quantum mechanics allow the formation of pairs of "entangled" particles, which interacted in the past before becoming separated, and for which measuring the properties of one particle makes it possible to know the properties of the other one instantly, however far apart they may be. When a measurement is carried out on one of the entangled particles, it is as if its twin immediately felt this and adopted a physical state corresponding to that of its partner.

For Einstein, the discoverer of relativity which stipulates that no effect can travel faster than light, this description, which requires that change take place instantaneously at a distance, was unacceptable. He concluded that, if both particles had similar properties when measured, this was because they had acquired these properties during their initial interaction, and had kept them after being separated. This conclusion amounted to completing the formalism of quantum mechanics, and it was immediately contested by Niels Bohr. The debate between the two physicists lasted over 20 years until their death.

The experimental verdict

In 1964, John Bell, an Irish theorist working at CERN, the European particle physics laboratory in Geneva, showed that the respective positions of Niels Bohr and Albert Einstein led to different predictions. He wrote down inequalities which, if applied to the results of carefully chosen measurements carried out on entangled particles, would make it possible to settle the argument.

In 1975 at the Institut d'Optique at Orsay, Alain Aspect, building on pioneering work carried out in the United States, set out to build a source of pairs of entangled photons which was of unrivalled performance, thanks to the use of two-photon laser excitation, a method developed in Paris (Laboratoire Kastler Brossel – ENS Paris/CNRS/Université Paris VI) by Bernard Cagnac and his students. In 1982, this source enabled him, together with his co-workers Philippe Grangier, Jean Dalibard, and Gérard Roger, to test Bell's inequalities in situations closely similar to the ideal thought experiments on which the theorists based their reasoning. The results very clearly violate Bell's inequalities, and are in excellent agreement with the predictions of quantum theory. There is thus no model along the lines of Einstein's so-called "local realistic" ideas which describes *entangled particles.* They cannot be represented as two distinct systems having two identical copies of a set of parameters which

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[1] In quantum physics, an observable describes a measurable physical quantity. In order to define it, it is necessary to specify how the observation is made.

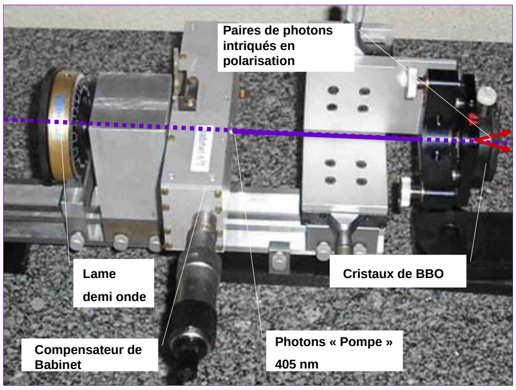
determine the whole set of physical properties: we have to accept that it is a single, "non-separable" system, described by an overall quantum state.

Properties at the heart of research into quantum computers

Thanks to this new source, Alain Aspect and Philippe Grangier were able, as early as 1985, to control the emission of single photons and to reveal the quantum properties (which have no equivalent in classical physics) of the light obtained in this way.

The quantum properties of pairs of entangled particles and of single photons are currently used to carry out operations involving secure data transmission by means of *quantum cryptography*. In these methods, the security of the transmission is guaranteed by the fundamental laws of quantum physics, rather than on the assumption underlying conventional methods of cryptography, namely that an adversary (the person who tries to decode the secret message) has a knowledge of mathematics or of information technology which does not go beyond the current state of the art. The phenomenon of entanglement also lies at the heart of research into *quantum computers*, whose processing power, if they are ever made, could be exponentially greater than that of conventional computers. This research into quantum information is likely to have a considerable impact on the field of secure data links, for instance on the Internet.

The experiment to test Bell's inequalities at Orsay (1982). The source of pairs of entangled photons consisted of several lasers, and a stream of atoms travelling into an atomic chamber which can be seen in the centre. Measurements were taken after they had travelled 6 meters in both directions from the source. © Groupe d'optique atomique /LCFIO



A modern source of pairs of entangled photons (2004). This source, developed at the Laboratoire de travaux pratiques at the Ecole Supérieure d'Optique, consists of a set of non-linear crystals excited by a violet semiconductor laser. It is only twenty centimeters long, and is far simpler than the source used in 1982. The entangled photons emitted by this type of source can be injected into optical fibers and travel for tens of kilometers, while remaining sufficiently correlated to violate Bell's inequalities. It is this kind of setup which is used in quantum cryptography systems. © Lionel Jacubowiez/Ecole supérieure d'optique