Experiment and the foundations of quantum physics

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Instead of having to rely on gedanken (thought) experiments, it is possible to base this discussion of the foundations of quantum physics on actually performed experiments because of the enormous experimental progress in recent years. For reasons of space, the author discusses mainly experiments related to the Einstein-Podolsky-Rosen paradox and Bell's theorem, that is, to quantum entanglement. Not only have such fundamental experiments realized many historic proposals, they also helped to sharpen our quantum intuition. This recently led to the development of a new field, quantum information, where quantum teleportation and quantum computation are some of the most fascinating topics. Finally the author ventures into a discussion of future prospects in experiment and theory. [S0034-6861(99)03602-8]

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I. THE BACKGROUND

Quantum physics, a child of the early 20th century, is probably the most successful description of nature ever invented by man. The range of phenomena it has been applied to is enormous. It covers phenomena from the elementary-particle level all the way to the physics of the early universe. Many modern technologies would be impossible without quantum physics—witness, for example, that all information technologies are based on a quantum understanding of solids, particularly of semiconductors, or that the operation of lasers is based on a quantum understanding of atomic and molecular phenomena.

So, where is the problem? The problem arises when one realizes that quantum physics implies a number of very counterintuitive concepts and notions. This has led, for example, R. P. Feynman to remark, "I think I can safely say that nobody today understands quantum physics," or Roger Penrose (1986) to comment that the theory "makes absolutely no sense."

From the beginning, gedanken (thought) experiments were used to discuss fundamental issues in quantum physics. At that time, Heisenberg invented his gedanken gamma-ray microscope to demonstrate the uncertainty principle while Niels Bohr and Albert Einstein in their famous dialogue on epistemological problems in what was then called atomic physics made extensive use of gedanken experiments to make their points.

Now, at the end of the 20th century, the situation has changed dramatically. Real experiments on the foundations of quantum physics abound. This has not only given dramatic support to the early views, it has also helped to sharpen our intuition with respect to quantum phenomena. Most recently, experimentation is already applying some of the fundamental phenomena in completely novel ways. For example, quantum cryptography is a direct application of quantum uncertainty and both quantum teleportation and quantum computation are direct applications of quantum entanglement, the concept underlying quantum nonlocality (Schrödinger, 1935).

I will discuss a number of fundamental concepts in quantum physics with direct reference to experiments. For the sake of the consistency of the discussion and because I know them best I will mainly present experiments performed by my group. In view of the limited space available my aim can neither be completeness, nor a historical overview. Rather, I will focus on those issues I consider most fundamental.

II. A DOUBLE SLIT AND ONE PARTICLE

Feynman (1965) has said that the double-slit "has in it the heart of quantum mechanics. In reality, it contains the only mystery." As we shall see, entangled states of two or more particles imply that there are further mysteries (Silverman, 1995). Nevertheless, the two-slit experiment merits our attention, and we show the results of a typical two-slit experiment done with neutrons in Fig. 1 (Zeilinger *et al.*, 1988). The measured distribution of the neutrons has two remarkable features. First, the observed interference pattern showing the expected fringes agrees perfectly well with theoretical prediction (solid line), taking into account all features of the experimental setup. Assuming symmetric illumination the neutron state at the double slit can be symbolized as

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\text{passage through slit } a\rangle + |\text{passage through slit } b\rangle). \tag{1}$$

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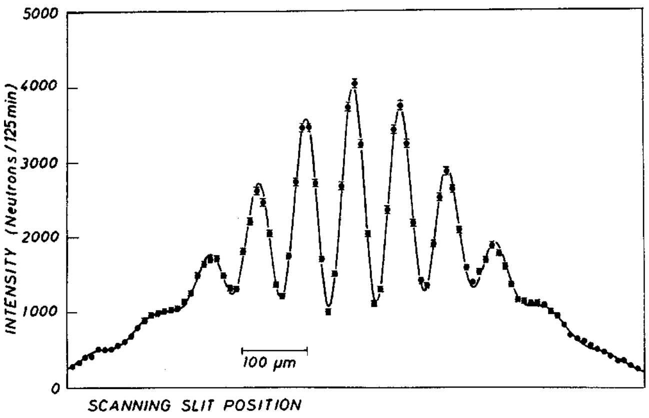

FIG. 1. A double-slit diffraction pattern measured with very cold neutrons with a wavelength of 2 nm corresponding to a velocity of 200 ms^{-1}. The two slits were 22 μm and 23 μm wide, respectively, separated by a distance of 104 μm. The resulting diffraction angles were only of the order of 10 μrad, hence the observation plane was located 5 m downstream from the double slit in order to resolve the interference pattern. (For experimental details see Zeilinger *et al.*, 1988.) The solid line represents first-principles prediction from quantum mechanics, including all features of the experimental apparatus. For example, the fact that the modulation of the interference pattern was not perfect can fully be understood on the basis that a broad wavelength band had to be used for intensity reasons and the experiment was not operated in the Fraunhofer regime.

The interference pattern is then obtained as the superposition of two probability amplitudes. The particle could have arrived at a given observation point $\vec{r}$ either via slit 1 with probability amplitude $a(\vec{r})$ or via slit 2 with probability amplitude $b(\vec{r})$. The total probability density to find the particle at point $\vec{r}$ is then simply given as

$$p(\vec{r})=|a(\vec{r})+b(\vec{r})|^2. \tag{2}$$

This picture suggests that the pattern be interpreted as a wave phenomenon.

Yet, second, we note that the maximum observed intensity is of the order of one neutron every two seconds. This means that, while one neutron is being registered, the next one to be registered usually is still confined to its uranium nucleus inside the nuclear reactor, waiting for nuclear fission to release it to freedom!

This feature of very low-intensity interference is shared by all existing neutron interferometer experiments (Rauch and Werner, in press). These pioneering matter-wave experiments led to the realization of a number of very basic experiments in quantum mechanics including the change of the sign of a spinor under a full rotation, the effect of gravity on the phase of a neutron wave, a number of experiments related to quantum complementarity, and many others.

Thus the interference pattern is really collected one by one and this suggests the particle nature. Then the famous question can be posed: through which of the two slits did the particle actually pass on its way from source to detector? The well-known answer according to standard quantum physics is that such a question only makes sense when the experiment is such that the path taken can actually be determined for each particle. In other words, the superposition of amplitudes in Eq. (1) is only valid if there is no way to know, even in principle, which path the particle took. It is important to realize that this does not imply that an observer actually takes note of what happens. It is sufficient to destroy the interference pattern, if the path information is accessible in principle from the experiment or even if it is dispersed in the environment and beyond any technical possibility to be recovered, but in principle still "out there." The absence of any such information is *the essential criterion* for quantum interference to appear. For a parallel discussion, see the accompanying article by Mandel (1999) in this volume.

To emphasize this point, let us consider now a gedanken experiment where a second, probe, particle is scattered by the neutron while it passes through the double slit. Then the state will be

$$|\psi\rangle=\frac{1}{\sqrt{2}}\begin{pmatrix}|\text{passage through slit } a\rangle_1|\text{scattered in region } a\rangle_2\\ +|\text{passage through slit } b\rangle_1|\text{scattered in region } b\rangle_2\end{pmatrix}. \tag{3}$$

There the subscripts 1 and 2 refer to the neutron and the probe particle, respectively. The state (3) is entangled and if the two states for particle 2 are orthogonal, no interference for particle 1 can arise. Yet, if particle 2 is measured such that this measurement is not able, *even in principle*, to reveal any information about the slit particle 1 passes, then particle 1 will show interference. Obviously, there is a continuous transition between these two extreme situations.

We thus have seen that one can either observe a wavelike feature (the interference pattern) or a particle feature (the path a particle takes through the apparatus) depending on which experiment one chooses. Yet one could still have a naive picture in one's mind essentially assuming waves propagating through the apparatus which can only be observed in quanta. That such a picture is not possible is demonstrated by two-particle interferences, as we will discuss now.

III. A DOUBLE SLIT AND TWO PARTICLES

The situation is strikingly illustrated if one employs pairs of particles which are strongly correlated ("en-

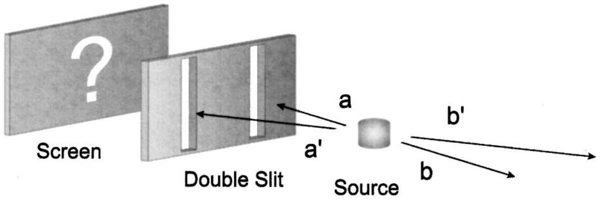

FIG. 2. A source emits pairs of particles with total zero momentum. Particle 1 is either emitted into beams a or a' and particle 2 into beams b or b' with perfect correlations between a and b and a' and b', respectively. The beams of particle 1 then pass a double-slit assembly. Because of the perfect correlation between the two particles, particle 2 can serve to find out which slit particle 1 passed and therefore no interference pattern arises.

tangled") such that either particle carries information about the other (Horne and Zeilinger, 1985; Greenberger, Horne, and Zeilinger, 1993). Consider a setup where a source emits two particles with antiparallel momenta (Fig. 2). Then, whenever particle 1 is found in beam a, particle 2 is found in beam b and whenever particle 1 is found in beam a', particle 2 is found in beam b'. The quantum state is

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|a\rangle_1|b\rangle_2 + |a'\rangle_1|b'\rangle_2). \tag{4}$$

Will we now observe an interference pattern for particle 1 behind its double slit? The answer has again to be negative because by simply placing detectors in the beams b and b' of particle 2 we can determine which path particle 1 took. Formally speaking, the states $|a\rangle_1$ and $|a'\rangle_1$ again cannot be coherently superposed because they are entangled with the two orthogonal states $|b'\rangle_2$ and $|b'\rangle_2$.

Obviously, the interference pattern can be obtained if one applies a so-called quantum eraser which completely erases the path information carried by particle 2. That is, one has to measure particle 2 in such a way that it is not possible, even in principle, to know from the measurement which path it took, a' or b'.

A recent experiment (Dopfer, 1998) used the so-called process of parametric down conversion to create entangled pairs of photons (Fig. 3) where a UV beam entering a nonlinear optical crystal spontaneously creates pairs of photons such that the sum of their linear momenta is constant. In type-I parametric down conversion, the two photons carry equal polarization. Parametric down conversion is discussed in somewhat more detail below. Although the experimental situations are different, conceptually this is equivalent to the case discussed above. In this experiment, photon 2 passes a double slit while the other, photon 1, can be observed by a detector placed at various distances behind the Heisenberg lens which plays exactly the same role as the lens in the gamma-ray microscope discussed by Heisenberg (1928) and extended by Weizsächer (1931). If the detector is placed at the focal plane of the lens, then registration of a photon there provides information about its direction, i.e., momentum, before entering the lens. Thus, because of the strict momentum correlation, the momentum of the other photon incident on the double slit and registered in coincidence is also well defined. A momentum eigenstate cannot carry any position information, i.e., no information about which slit the particle passes through. Therefore, a double-slit interference pattern for photon 2 is registered conditioned on registration of photon 1 in the focal plane of the lens. It is important to note that it is actually necessary to register photon 1 at the focal plane because without registration one could always, at least in principle, reconstruct the state in front of the lens. Most strikingly, therefore, one can find out the slit photon 2 passed by placing the detector for photon 1 into the imaging plane of the lens. The imaging plane is simply obtained by taking the object distance as the sum of the distances from the lens to the crystal and from the crystal to the double slit. Then, as has also been demonstrated in the experiment, a one-to-one relationship exists between positions in the plane of the double slit and in the imaging plane and thus, the slit particle 2 passes through can readily be determined by observing photon 1 in the imaging plane. Only after registration of photon 1 in the

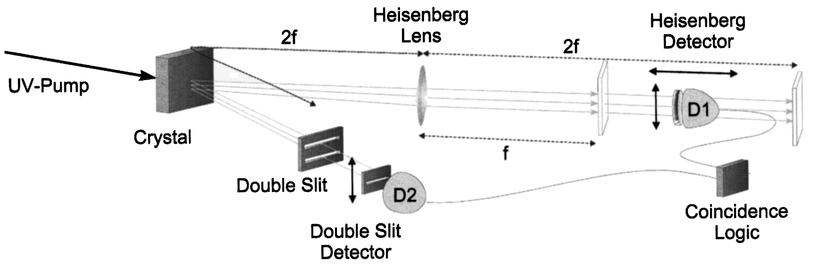

FIG. 3. Two photons and one double slit. A pair of momentum-entangled photons is created by type-I parametric down conversion. Photon 2 enters a double-slit assembly and photon 1 is registered by the Heisenberg detector arranged behind the Heisenberg lens. If the Heisenberg detector is placed in the focal plane of the lens, it projects the state of the second photon into a momentum eigenstate which cannot reveal any position information and hence no information about slit passage. Therefore, in coincidence with a registration of photon 1 in the focal plane, photon 2 exhibits an interference pattern. On the other hand, if the Heisenberg detector is placed in the imaging plane at $2f$, it can reveal the path the second photon takes through the slit assembly which therefore connot show the interference pattern (Dopfer, 1998).

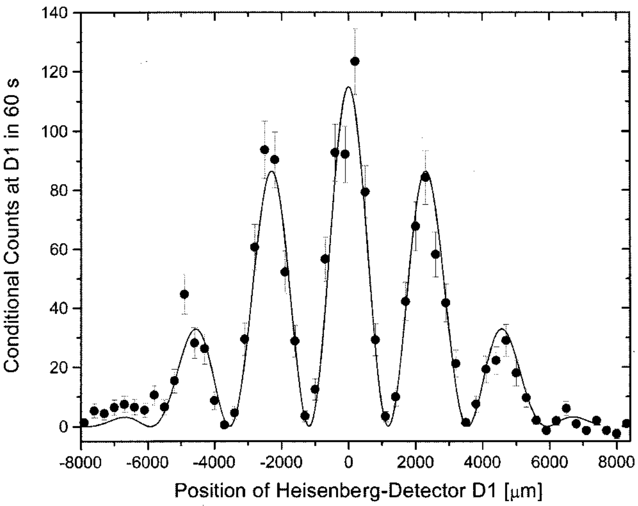

FIG. 4. Double-slit pattern registered by the Heisenberg detector of photon 1 (Fig. 3). The graph shows the counts registered by that detector as a function of its lateral position, if that detector is arranged in the focal plane of the lens. The counts are conditioned on registration of the second photon behind its double slit. Note that the photons registered in detector $D1$ exhibit a double-slit pattern even though they never pass through a double-slit assembly. Note also the low intensity which indicates that the interference pattern is collected photon by photon.

focal plane of the lens is any possibility to obtain any path information from photon 1 irrecoverably destroyed.

We note that the distribution of photons behind the double slit without registration of the other photon is just an incoherent sum of probabilities having passed through either slit and, as shown in the experiment, no interference pattern arises if one does not look at the other photon. This is again a result of the fact that, indeed, path information is still present and can easily be extracted by placing the detector of photon 1 into the imaging plane of the lens.

Likewise, registration of photon 2 behind its double slit destroys any path information it may carry and thus, by symmetry, a Fraunhofer double-slit pattern is obtained for the distribution of photon 1 in the focal plane behind its lens, even though that photon never passed a double slit (Fig. 4)! This experiment can be understood intuitively if we carefully analyze what registration of a photon behind a double slit implies. It simply means that the state incident on the double slit is collapsed into a wave packet with the appropriate momentum distribution such that the wave packet peaks at both slits. By virtue of the strong momentum entanglement at the source, the other wave packet then has a related momentum distribution which actually is, according to an argument put forward by Klyshko (1988), the time reversal of the other wave packet. Thus, photon 1 appears to originate backwards from the double slit assembly and is then considered to be reflected by the wave fronts of the pump beam into the beam towards the lens which then simply realizes the standard Fraunhofer observation conditions.

One might still be tempted to assume a picture that the source emits a statistical mixture of pairwise correlated waves where measurement of one photon just selects a certain, already existing, wavelet for the other photon. It is easy to see that any such picture cannot lead to the perfect interference modulation observed. The most sensible position, according to quantum mechanics, is to assume that no such waves preexist before any measurement.

IV. QUANTUM COMPLEMENTARITY

The observation that particle path and interference pattern mutually exclude each other is one specific manifestation of the general concept of complementary in quantum physics. Other examples are position and linear momentum as highlighted in Heisenberg's uncertainty relation, or the different components of angular momentum. It is often said that complementarity is due to an unavoidable disturbance during observation. This is suggested if, as in our example in Sec. II, we consider determining the path a particle takes through the double-slit assembly by scattering some other particle from it. That this is too limited a view is brought out by the experiment discussed in the preceding section.

The absence of the interference pattern for photon 2 if no measurement is performed on photon 1, is not due to it being disturbed by observation; rather, it can be understood if we consider the complete set of possible statements which can be made about the experiment as a whole (Bohr, 1935) including the other photon.

As long as no observation whatsoever is made on the complete quantum system comprised of both photons our description of the situation has to encompass all possible experimental results. The quantum state is exactly that representation of our knowledge of the complete situation which enables the maximal set of (probabilistic) predictions for any possible future observation. What comes new in quantum mechanics is that, instead of just listing the various experimental possibilities with the individual probabilities, we have to represent our knowledge of the situation by the quantum state using complex amplitudes. If we accept that the quantum state is no more than a representation of the information we have, then the spontaneous change of the state upon observation, the so-called collapse or reduction of the wave packet, is just a very natural consequence of the fact that, upon observation, our information changes and therefore we have to change our representation of the information, that is, the quantum state. From that position, the so-called measurement problem (Wigner, 1970) is not a problem but a consequence of the more fundamental role information plays in quantum physics as compared to classical physics (Zeilinger, 1999).

Quantum complementarity then is simply an expression of the fact that in order to measure two complementary quantities, we would have to use apparatuses which mutually exclude each other. In the example of our experiment, interference pattern and path information for photon 2 are mutually exclusive, i.e., complementary, because it is not possible to position the detector for photon 1 simultaneously in the focal plane and in the image plane of the lens. Yet the complete quantum state encompasses both possible experiments.

We finally note two corollaries of our analysis. First, it is clearly possible to have a concept of continuous complementarity. In our case, placing the detector of photon 1 somewhere in between the two extreme positions mentioned will reveal partial path information and thus an interference pattern of reduced visibility. And second, the choice whether or not path information or the interference pattern become manifest for photon 2 can be delayed to arbitrary times after that photon has been registered. In the experiment discussed, the choice where detector D_1 is placed can be delayed until after photon 2 has been detected behind its double slit. While we note that in the experiment, the lens was already arranged at a larger distance from the crystal than the double slit, a future experiment will actually employ a rapidly switched mirror sending photon 1 either to a detector placed in the focal plane of the lens or to a detector placed in the imaging plane.

This possibility of deciding long after registration of the photon whether a wave feature or a particle feature manifests itself is another warning that one should not have any realistic pictures in one's mind when considering a quantum phenomenon. Any detailed picture of what goes on in a specific individual observation of one photon has to take into account the whole experimental apparatus of the complete quantum system consisting of both photons and it can only make sense after the fact, i.e., after all information concerning complementary variables has irrecoverably been erased.

V. EINSTEIN-PODOLSKY-ROSEN AND BELL'S INEQUALITY

In 1935 Einstein, Podolsky, and Rosen (EPR) studied entangled states of the general type used in the two-photon experiment discussed above. They realized that in many such states, when measuring either linear momentum or position of one of the two particles, one can infer precisely either momentum or position of the other. As the two particles might be widely separated, it is natural to assume validity of the locality condition suggested by EPR: "Since at the time of measurement the two systems no longer interact, no real change can take place in the second system in consequence of anything that may be done to the first system." Then, whether or not momentum or position can be assigned to particle (system) 2 must be independent of what measurement is performed on particle 1 or even whether any measurement is performed on it at all. The question therefore arises whether the specific results obtained for either particle can be understood without reference to which measurement is actually performed on the other particle. Such a picture would imply a theory, underlying quantum physics, which provides a more detailed account of individual measurements. Specifically, following Bell, it might explain "why events happen" (Bell, 1990; Gottfried, 1991).

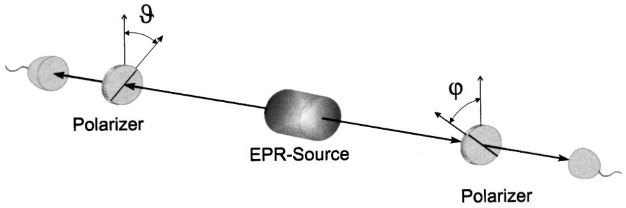

FIG. 5. Typical experimental arrangement to test Bell's inequality. A source emits, say, polarization-entangled pairs of photons. Each photon is sent through a polarizer whose orientation can be varied. Finally behind each polarizer, the transmitted photons are registered. Quantum mechanics predicts a sinusoidal variation of the coincidence count rate as a function of the relative angular orientation of the polarizers. Any such variation violates local realism as expressed in Bell's inequality.

In the sixties, two different developments started, which nicely complement each other. First, it was initially argued by Specker (1960) for Hibbert spaces of dimension larger than two that quantum mechanics cannot be supplemented by additional variables. Later it was shown by Kochen and Specker (1967) and by Bell (1966; for a review see Mermin, 1993), that for the specific case of a spin-1 particle, it is not possible to assign in a consistent way measurement values to the squares of any three orthogonal spin projections, despite the fact that the three measurements commute with each other. This is a purely geometric argument which only makes use of some very basic geometric considerations. The conclusion here is very important. The quantum system cannot be assigned properties independent of the context of the complete experimental arrangement. This is just in the spirit of Bohr's interpretation. This so-called contextuality of quantum physics is another central and subtle feature of quantum mechanics.

Second, a most important development was due to John Bell (1964) who continued the EPR line of reasoning and demonstrated that a contradiction arises between the EPR assumptions and quantum physics. The most essential assumptions are realism and locality. This contradiction is called Bell's theorem.

To be specific, and in anticipation of experiments we will discuss below, let us assume we have a pair of photons in the state:

$$|\psi\rangle=\frac{1}{\sqrt{2}}(|H\rangle_1|V\rangle_2-|V\rangle_1|H\rangle_2). \tag{5}$$

This polarization-entangled state implies that whenever (Fig. 5) photon 1 is measured and found to have horizontal (H) polarization, the polarization of photon 2 will be vertical (V) and vice versa. Actually, the state of Eq. (5) has the same form in any basis. This means whichever state photon 1 will be found in, photon 2 can definitely be predicted to be found in the orthogonal state if measured.

Following EPR one can apply their famous reality criterion, "If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity." This would imply that to any possible polarization measurement on any one of our photons we can assign such an element of physical reality on the basis of a corresponding measurement on the other photon of any given pair.

The next step then is to assume the two photons (systems) to be widely separated so that we can invoke EPR's locality assumption as given above. Within this line of reasoning, whether or not we can assign an element of reality to a specific polarization of one of the systems must be independent of which measurement we actually perform on the other system and even independent of whether we care to perform any measurement at all on that system. To put it dramatically, one experiment could be performed here on earth and the other on a planet of another star a couple of light years away. It is this very independence of a measurement result on one side from what may be done on the other side, as assumed by EPR, which is at variance with quantum mechanics. Indeed, this assumption implies that certain combinations of expectation values have definite bounds. The mathematical expression of that bound is called Bell's inequality, of which many variants exist. For example, a version given by Clauser, Horne, Shimony, and Holt (1969) is

$$|E(\alpha,\beta)-E(\alpha',\beta)|+|E(\alpha,\beta')+E(\alpha',\beta')|\leq 2, \tag{6}$$

where

$$E(\alpha,\beta)=\frac{1}{N}[C_{++}(\alpha,\beta)+C_{--}(\alpha,\beta)-C_{+-}(\alpha,\beta)-C_{-+}(\alpha,\beta)]. \tag{7}$$

Here we assume that each photon is subject to a measurement of linear polarization with a two-channel polarizer whose outputs are + and −. Then, e.g., $C_{++}(\alpha,\beta)$ is the number of coincidences between the + output port of the polarizer measuring photon 1 along α and the + output port of the polarizer measuring photon 2 along β. Maximal violation occurs for $\alpha=0°$, $\beta=22.5°$, $\alpha'=45°$, $\beta'=67.5°$. Then the left-hand side of Eq. (6) will be $2\sqrt{2}$ in clear violation of the inequality. Thus Bell discovered that the assumption of local realism is in conflict with quantum physics itself and it became a matter of experiment to find out which of the two world views is correct.

Interestingly, at the time of Bell's discovery no experimental evidence existed which was able to decide between quantum physics and local realism as defined in Bell's derivation. An earlier experiment by Wu and Shaknov (1950) had demonstrated the existence of spatially separated entangled states, yet failed to give data for nonorthogonal measurement directions. After the realization that the polarization entangled state of photons emitted in atomic cascades can be used to test Bell's inequalities, the first experiment was performed by Freedman and Clauser in 1972 (Fig. 6). By now, there exists a large number of such experiments. The ones showing the largest violation of a Bell-type inequality have for a long time been the experiments by Aspect, Grangier, and Roger (1981, 1982) in the early eighties. Aside from two early experiments, all agreed with the predictions of quantum mechanics and violated inequalities derived from Bell's original version using certain additional assumptions. Actually, while the experimental evidence strongly favors quantum mechanics, there remained two possible mechanisms for which a local realistic view could still be maintained.

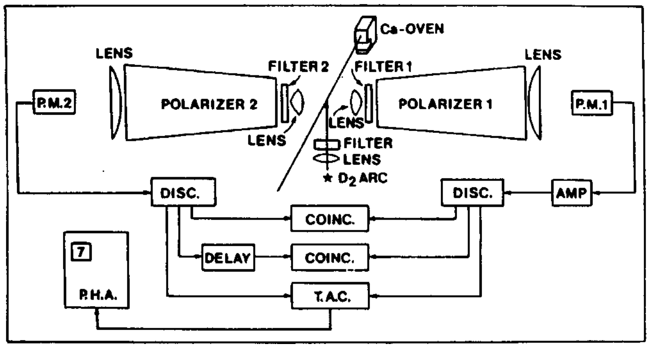

FIG. 6. Sketch of the experimental setup used in the first experiment demonstrating a violation of Bell's inequality (Freedman and Clauser, 1972). The two photons emitted in an atomic cascade in Ca are collected with lenses and, after passage through adjustable polarizers, coincidences are registered using photomultiplier detectors and suitable discriminators and coincidence logic. The observed coincidence counts violate an inequality derived from Bell's inequality under the fair sampling assumption.

One problem in all experimental situations thus far is due to technical insufficiencies, namely that only a small fraction of all pairs emitted by the source is registered. This is a standard problem in experimental work and experimentalists take great care to ensure that it is reasonable to assume that the detected pairs are a faithful representative of all pairs emitted. Yet, at least in principle, it is certainly thinkable that this is not the case and that, should we once be able to detect all pairs, a violation of quantum mechanics and data in agreement with local realism would be observed. While this is in principle possible, I would agree with Bell's judgment (1981) that "although there is an escape route there, it is hard for me to believe that quantum mechanics works so nicely for inefficient practical set-ups, and is yet going to fail badly when sufficient refinements are made. Of more importance, in my opinion, is the complete absence of the vital *time* factor in existing experiments. The analyzers are not rotated during the flight of the particles. Even if one is obliged to admit some long-range influence, it need not travel faster than light—and so would be much less indigestible." Until recently, there has been only one experiment where the time factor played a role. In that experiment (Aspect, Dalibard,

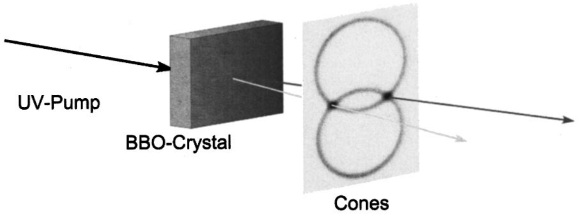

FIG. 7. Principle of type-II parametric down conversion to produce directed beams of polarization entangled photons (Kwiat *et al.*, 1995). An incident pump photon can spontaneously decay into two photons which are entangled in momentum and energy. Each photon can be emitted along a cone in such a way that two photons of a pair are found opposite to each other on the respective cones. The two photons are orthogonally polarized. Along the directions where the two cones overlap, one obtains polarization-entangled pairs. In the figure, it is assumed that a filter already selects those photons which have exactly half the energy of a pump photon.

and Roger, 1982) each of the two photons could be switched between two different polarizers on a time scale which was small compared to the flight time of the photons. Due to technical limitations at the time of the experiment and because this switching back and forth between two different polarizations was periodic, the experiment does not completely fulfill Bell's desideratum, but it is an important step.

Experimental development in the last decade is marked by two new features. First, it was realized initially by Horne and Zeilinger (1985, 1988) for momentum and position, and then by Franson (1989) for time and energy, that situations can arise where Bell's inequality is violated not just for internal variables, like spin, but also for external ones. This observation put Bell's theorem in a much broader perspective than before. Second, a new type of source was employed (Burnham and Weinberg, 1970), based on the process of spontaneous parametric down conversion. The first to use such a source in a Bell-inequality experiment were Alley and Shih in 1986. In such experiments, a nonlinear optical crystal is pumped by a sufficiently strong laser beam. Then, with a certain very small probability, a photon in the laser beam can spontaneously decay into two photons. The propagation directions of the photons and the polarization are determined by the dispersion surfaces inside the medium. The so-called phase-matching conditions of quantum optics, which for sufficiently large crystals are practically equivalent to energy and momentum conservation, imply that the momenta and the energies of the two created photons have to sum up to the corresponding value of the original pump photon inside the crystal. In effect, a very rich entangled state results. The two emerging photons are entangled both in energy and in momentum. In type-I down conversion, these two photons have the same polarization while in type-II down conversion, they have different polarization.

A recent experiment utilized type-II down conversion (Figs. 7 and 8) such that the two emerging photons having orthogonal polarizations effectively emerge in a polarization-entangled state as discussed above [see Eq. (5)]. In the experiment (Weihs *et al.*, 1998), the photons were coupled into long glass fibers and the polarization correlations over a distance of the order of 400 m was measured. The important feature of that experiment is that the polarization of the photons could be rotated in the last instant, thus effectively realizing the rotatable polarizers suggested by Bell. The decision whether or not to rotate the polarization was made by a physical random-number generator on a time scale short compared to the flight time of the photons. Figure 9 shows the principle of the experimental setup. Due to technological progress it is possible now in such experiments to violate Bell's inequality by many standard deviations in a very short time: in this experiment by about 100 standard deviations in measurement times of the order of a minute. In a related experiment (Tittel *et al.*, 1998), en-

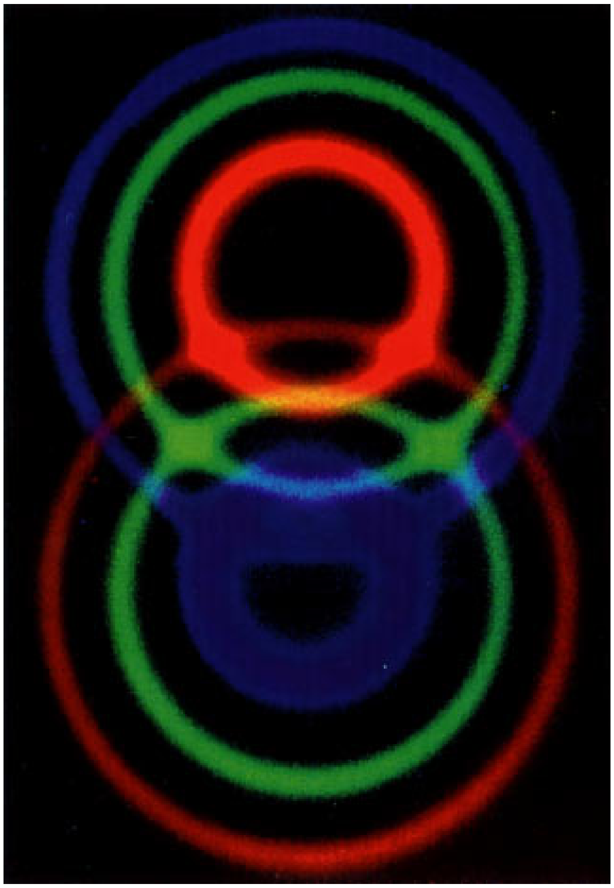

FIG. 8. (Color) A more complete representation of the radiation produced in type-II parametric down-conversion (photo: Paul Kwiat and Michael Reck). Three photographs taken with different color filters have been superposed here. The colors are actually false colors for clarity of presentation. The photons emitted from the source are momentum and energy entangled in such a way that each photon can be emitted with a variety of different momenta and frequencies, each frequency defining a cone of emission for each photon. The whole quantum state is then a superposition of many different pairs. For example, if measurement reveals a photon to be found somewhere on the red small circle in the figure, its brother photon is found exactly opposite on the blue small circle. The green circles represent the case where the two colors are identical.

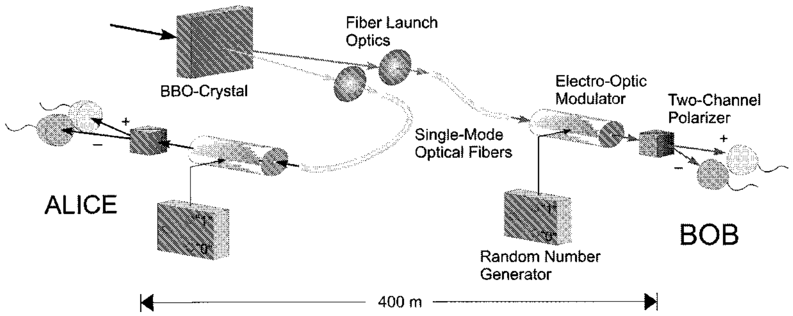

FIG. 9. Long-distance Bell-inequality experiment with independent observers (Weihs *et al.*, 1998). The two entangled photons are individually launched into optical fibers and sent to the measurement stations of the experimenters Alice and Bob which are separated from each other by a distance of 400 m. At each of the measurement stations, an independent, very fast, random-number generator decides, while the photons are really in flight, the direction along which the polarization will be measured. Finally, events are registered independently on both sides and coincidences are only identified long after the experiment is finished.

tanglement could be demonstrated over distances of more than 10 km but without random switching.

A few points deserve consideration regarding future experiments. On the one hand experiments must be improved to high enough pair-collection efficiencies in order to finally prove that the fair sampling hypothesis used in all existing experiments was justified. On the other hand, and more interesting from a fundamental point of view, one could still assume that both random-number generators are influenced by joint events in their common past. This suggests a final experiment in which two experimenters exercise their free will and choose independently the measurement directions. Such an experiment would require distances of order of a few light seconds and thus can only be performed in outer space.

Another future direction of research will certainly be directed at quantum entanglement employing more systems, or at larger, specifically more massive, systems. A first experiment in Paris was able to demonstrate entanglement between atoms (Hagley *et al.*, 1997).

VI. QUANTUM INFORMATION AND ENTANGLEMENT

While most work on the foundations of quantum physics was initially motivated by curiosity and even by philosophical considerations, this has recently led to the emergence of novel ideas in information science. A significant result is already a new perspective on information itself. Eventually, applications might include quantum communication, quantum cryptography, possibly even quantum computation.

Some of the basic novel features are contained in quantum teleportation involving two distant experimenters, conventionally called Alice and Bob (Fig. 10). Here, Alice initially has a single particle in the quantum state $|\psi\rangle$ (the "teleportee"). The state may be unknown to her or possibly even undefined. The aim is that the distant experimenter Bob obtains an exact replica of that particle. It is evident that no measurement whatsoever Alice might perform on the particle could reveal all necessary information to enable Bob to reconstruct its state. The quantum teleportation protocol (Bennett *et al.*, 1993) proceeds by Alice and Bob agreeing to share initially an entangled pair of "ancillary" photons. Alice then performs a joint Bell-state measurement on the teleportee and her ancillary photon, and obtains one of the four possible Bell results. The four possible Bell states (Braunstein *et al.*, 1992) are

$$|\psi^{\pm}\rangle=\frac{1}{\sqrt{2}}(|H\rangle_1|V\rangle_2\pm|V\rangle_1|H\rangle_2),$$

$$|\phi^{\pm}\rangle=\frac{1}{\sqrt{2}}(|H\rangle_1|H\rangle_2\pm|V\rangle_1|V\rangle_2). \tag{8}$$

They form a maximally entangled basis for the two-photon four-dimensional spin Hilbert space. These Bell states are essential in many quantum information scenarios. Alice's measurement also projects Bob's ancillary photon into a well-defined quantum state. Alice then transmits her result as a classical two-bit message to Bob, who performs one of four unitary operations, independent of the state $|\psi\rangle$, to obtain the original state. In the experiment (Bouwmeester *et al.*, 1997), femtosecond pulse technology had to be used in order to obtain the necessary nontrivial coherence conditions for the Bell-state measurements.

While teleportation presently might sound like a strange name conjuring up futuristic images, it is appropriate. The reader should be reminded of the strange connotations of the notion of magnetism before its clear definition by physicists. Quantum teleportation actually demonstrates some of the salient features of entanglement and quantum information. It also raises deep questions about the nature of reality in the quantum world.

Most important for the understanding of the quantum teleportation scheme is the realization that maximally entangled states such as the Bell basis are characterized by the fact that none of the individual members of the entangled state, in our case, the two photons, carries any information on its own. All information is only encoded in joint properties. Thus, an entangled state is a repre-

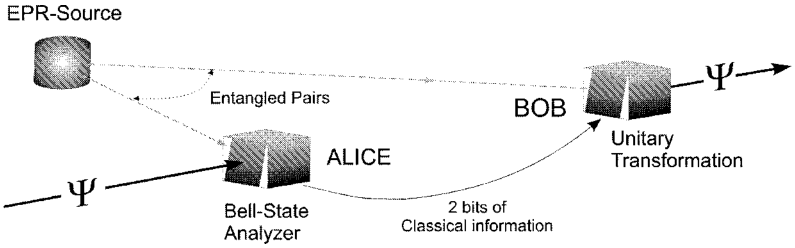

FIG. 10. Principle of quantum teleportation (Bennett *et al.*, 1993). In order to teleport her, possibly even unknown, quantum state $|\psi\rangle$ to Bob, Alice shares with him initially an entangled pair. She then performs a Bell-state analysis and, after receipt of Alice's measurement result, Bob can turn his member of the entangled pair into the original state by applying a unitary transformation which only depends on the specific Bell state result obtained by Alice and is independent of any properties of the teleportee state $|\psi\rangle$.

sentation of the relations between two possible measurements on the two members of the entangled pair. In the most simple case, the state $|\psi^-\rangle$ is a representation of the prediction that in any basis whatsoever, the two photons will be found to have orthogonal states with none of the photons having any well-defined state before measurement. The teleportation scheme then simply means that Alice's Bell-state measurement results in a well-defined relational statement between the original $|\psi\rangle$ and one of the two photons emerging from the EPR source. The specific entangled state emitted by the source then implies another relational statement with Bob's photon, and thus, by this line of reasoning, we have a clear relational statement connecting his photon with Alice's original. That statement is independent of the properties of $|\psi\rangle$, and Bob just has to apply the proper unitary transformation defined by the specific one of the four Bell states Alice happened to obtain randomly. In the most simple case, suppose Alice's Bell-state measurement happens to give the same result as the state emitted by the source. Then, Bob's particle is immediately identical to the original, and his unitary transformation is the identity. Even more striking is the possibility to teleport a quantum state which itself is entangled to another particle. Then, the teleported state is not just unknown but undefined. This possibility results in entanglement swapping (Zukowski *et al.*, 1993; Pan *et al.*, 1998), that is, in entangling two particles which were created completely independently and which never interacted.

The essential feature in all these schemes is again entanglement. Information can be shared by two photons in a way where none of the individuals carries any information on its own.

As a most striking example consider entangled superpositions of three quanta, e.g.,

$$|\psi\rangle=\frac{1}{\sqrt{2}}\left(|H\rangle|H\rangle|H\rangle+|V\rangle|V\rangle|V\rangle\right). \qquad (9)$$

Such states, usually called Greenberger-Horne-Zeilinger states (Greenberger *et al.*, 1989; Greenberger *et al.*, 1990), exhibit very rich perfect correlations. For such states, these perfect correlations lead to a dramatic conflict with local realism on an event-by-event basis and not just on a statistical basis as in experiments testing Bell's inequality. Such states and their multiquanta generalizations are essential ingredients in many quantum communication and quantum computation schemes (*Physics World*, 1998).

VII. FINAL REMARKS AND OUTLOOK

I hope that the reader can sympathize now with my viewpoint that quantum physics goes beyond Wittgenstein, who starts his Tractatus Logico-Philosophicus with the sentence, "The world is everything that is the case." This is a classical viewpoint, a quantum state goes beyond. It represents all possibilities of everything that could be the case.

In any case, it will be interesting in the future to see more and more quantum experiments realized with increasingly larger objects. Another very promising future avenue of development is to realize entanglements of increasing complexity, either by entangling more and more systems with each other, or by entangling systems with a larger number of degrees of freedom. Eventually, all these developments will push the realm of quantum physics well into the macroscopic world. I expect that they will further elucidate Bohr's viewpoint that over a very large range the classical-quantum boundary is at the whim of the experimenter. Which parts we can talk about using our classical language and which parts are the quantum system depends on the specific experimental setup.

In the present brief overview I avoided all discussion of various alternative interpretations of quantum physics. I also did not venture into analyzing possible suggested alternatives to quantum mechanics. All these topics are quite important, interesting and in lively development. I hope my omissions are justified by the lack of space. It is my personal expectation that new insight and any progress in the interpretive discussion of quantum mechanics will bring along fundamentally new assessment of our humble role in the Universe.

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REFERENCES

As impossible as it is to do justice to all the work done in the field, it is equally impossible to attempt to quote even a minute fraction only of the relevant papers published. The general references below should help the reader to delve deeper into the subject:

Bell, J. S., 1987, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge University, Cambridge).

Feynman, R. P., R. B. Leighton, and M. Sands, 1965, *The Feynman Lectures of Physics*, Vol. III, Quantum Mechanics (Addison-Wesley, Reading).

Greenberger, D. M., and A. Zeilinger, 1995, Eds., *Fundamental Problems in Quantum Theory* (Annals of the New York Academy of Sciences, Vol. 755, New York).

Greenstein, G. and A. G. Zajonc, 1997, *The Quantum Challenge: Modern Research on the Foundations of Quantum Mechanics* (Jones and Bartlett, New York).

Klyshko D., 1988, *Photons and Nonlinear Optics* (Gordon and Breech, New York).

Quantum Information, 1998, Phys. World **11** (3).

Rauch, H., and S. A. Werner, *Neutron Interferometry. Lessons in Experimental Quantum Mechanics* (Oxford University, Oxford) (in press).

Silverman, M. P., 1995, *More than One Mystery: Explorations in Quantum Interference* (Springer, Berlin).

Wheeler J. A., and W. H. Zurek, 1983, Eds. *Quantum Theory and Measurement* (Princeton University Princeton).

Specific papers quoted in the present paper are:

Alley, C. O., and Y. H. Shih, 1986, in *Proceedings of the Second International Symposium on Foundations of Quantum Mechanics in the Light of New Technology*, Tokyo, 1986, edited by M. Namiki *et al.* (Physical Society of Japan), p. 47.

Aspect, A., J. Dalibard, and G. Roger, 1982, Phys. Rev. Lett. **49**, 1804.

Aspect, A., P. Grangier, and G. Roger, 1981, Phys. Rev. Lett. **47**, 460.

Aspect, A., P. Grangier, and G. Roger, 1982, Phys. Rev. Lett. **49**, 91.

Bell, J. S., 1964, Physics (Long Island City, N.Y.) **1**, reprinted in J. S. Bell, 1987, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge University, Cambridge).

Bell, J. S., 1966, Rev. Mod. Phys. **38**, 447.

Bell, J. S., 1981, J. Phys. C2 **42**, 41, reprinted in J. S. Bell, 1987, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge University, Cambridge).

Bell, J. S., 1990, Phys. World **3**(August), 33.

Bennett, C. H., G. Brassard, C. Crépeau, R. Josza, A. Peres, and W. K. Wootters, 1993, Phys. Rev. Lett. **70**, 1895.

Bohr, N., 1935, Phys. Rev. **48**, 696.

Bouwmeester, D., J. W. Pan, K. Mattle, M. Eibl, H. Weinfurter, and A. Zeilinger, 1997, Nature (London) **390**, 575.

Braunstein, S. L., A. Mann, and M. Revzen, 1992, Phys. Rev. Lett. **68**, 3259.

Burnham, D. C., and D. L. Weinberg, 1970, Phys. Rev. Lett. **25**, 84.

Clauser, J. F., M. A. Horne, A. Shimony, and R. A. Holt, 1969, Phys. Rev. Lett. **23**, 880.

Dopfer, B., 1998, Ph.D. thesis (University of Innsbruck).

Einstein, A., B. Podolsky, and N. Rosen, 1935, Phys. Rev. **47**, 777.

Franson, J. D., 1989, Phys. Rev. Lett. **62**, 2205.

Freedman, S. J., and J. S. Clauser, 1972, Phys. Rev. Lett. **28**, 938.

Gottfried, K., 1991, Phys. World **4**(October), 41.

Greenberger, D. M., M. A. Horne, and A. Zeilinger, 1993, Phys. Today (8), 22.

Greenberger, D. M., M. A. Horne, and A. Zeilinger, 1989, in *Bell's Theorem, Quantum Theory, and Conceptions of the Universe*, edited by M. Kafatos (Kluwer, Dordrecht), p. 74.

Greenberger, D. M., M. A. Horne, A. Shimony, and A. Zeilinger, 1990, Am. J. Phys. **58**, 1131.

Hagley, E., X. Maître, G. Nogues, C. Wunderlich, M. Brune, J. M. Raimond, and S. Haroche, 1997, Phys. Rev. Lett. **79**, .

Heisenberg, W., 1927, Z. Phys. (Leipzig) **43**, 172, reprinted in English in Wheeler and Zurek (above).

Horne, M. A., and A. Zeilinger, 1985, in *Proceedings of the Symposium Foundations of Modern Physics*, edited by P. Lahti and P. Mittelstaedt (World Scientific, Singapore), p. 435.

Horne, M. A., and A. Zeilinger, 1988, in *Microphysical Reality and Quantum Formalism*, edited by A. van der Merwe, F. Seller, and G. Tarozzi (Kluwer, Dordrecht), p. 401.

Kochen, S. and E. Specker, 1967, J. Math. Mech. **17**, 59.

Kwiat, P., H. Weinfurter, T. Herzog, and A. Zeilinger, 1995, Phys. Rev. Lett. **74**, 4763.

Mandel, L., 1999, Rev. Mod. Phys. **71** (this issue).

Mermin, N. D., 1993, Rev. Mod. Phys. **65**, 803.

Pan, J. W., D. Bouwmeester, H. Weinfurter, and A. Zeilinger, 1998, Phys. Rev. Lett. **80**, 3891.

Penrose, R., 1986, in *Quantum Concepts in Space and Time*, edited by R. Penrose and C. J. Isham (Clarendon Press, Oxford), p. 139.

Schrödinger, E., 1935, Naturwissenschaften **23**, English translation in *Proceedings of the American Philosophical Society*, 124 (1980) reprinted in Wheeler & Zurek, above.

Specker, F., 1960, Dialectica **14**, 239.

Tittel, W., J. Brendel, B. Gisin, T. Herzog, H. Zbinden, and N. Gisin, 1998, Phys. Rev. A **57**, 3229.

Weihs, G., T. Jenewein, C. Simon, H. Weinfurter, and A. Zeilinger, 1998, Phys. Rev. Lett **81**, 5039.

Weizsächer, K. F., 1931, Z. Phys. **40**, 114.

Wigner, E. P., 1970, Am. J. Phys. **38**, 1005.

Wu, C. S., and I. Shaknov, 1950, Phys. Rev. **77**, 136.

Zeilinger, A., 1999, Found. Phys. (in press).

Zeilinger, A., R. Gähler, C. G. Shull, W. Treimer, and W. Hampe, 1988, Rev. Mod. Phys. **60**, 1067.

Zukowski, M., A. Zeilinger, M. A. Horne, and A. K. Ekert, 1993, Phys. Rev. Lett. **71**, 4287.