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antisymmetric wave functions only one particle (without spin) may occupy a state; for symmetric wave functions, any number is possible. Based on this distinction, there are two separate distributions, the Fermi-Dirac distribution for systems described by antisymmetric wave functions and the Bose-Einstein distribution for systems described by symmetric wave functions.

In relativistic quantum theory it is shown that particles having integer spin necessarily obey Bose-Einstein statistics, while those having half-integer spin necessarily obey Fermi-Dirac statistics. (Particles obeying Bose-Einstein statistics are often called bosons; particles obeying Fermi-Dirac statistics, fermions.) For sufficiently high temperatures, both forms of distribution functions go over into the familiar Boltzmann distribution, although strictly speaking no system is correctly described by this distribution. In practice, of course, the Boltzmann distribution gives an exceedingly good description of the experiments, but there are situations, such as those involving the behavior of electrons in metals and liquid helium, where the quantum description is essential. *See* BOLTZMANN STATISTICS; BOSE-EINSTEIN STATISTICS; EXCLUSION PRINCIPLE; FERMI-DIRAC STATISTICS; KINETIC THEORY OF MATTER; NONRELATIVISTIC QUANTUM THEORY; QUANTUM MECHANICS; RELATIVISTIC QUANTUM THEORY; SPIN (QUANTUM MECHANICS); STATISTICAL MECHANICS. Max Dresden

Quantum teleportation

A way to transfer the state of a quantum system over large distances by employing entanglement. Entanglement is a nonclassical connection between objects that Albert Einstein called “spooky.”

To be able to travel from one place to another instantly and over arbitrary distances, or at least to move objects in this way, is an ancient dream. The concept of teleportation is frequently utilized in the literature of science fiction to overcome limitations imposed on space travel by the laws of physics.

In the standard science fiction approach, the sender, Alice, scans the object to be teleported in order to read out all the information needed to describe it. She then sends that information to the receiver, Bob, who uses this information to reconstitute the object, not necessarily from the same material as that of the original. However, according to quantum mechanics, it is impossible to succeed in this way. If only one individual object is at hand, it is impossible to determine its quantum state by measurement. The quantum state represents all that can be known about the object, that is, all possible (in general, probabilistic) predictions that can be made about future observations of the object.

In fact, it is quantum mechanics that comes to the rescue and makes quantum teleportation possible using a very deep feature of the theory, quantum entanglement. It is important to realize that there are significant differences between teleportation as portrayed in science fiction and quantum teleportation as realized in the laboratory. In the experiments, what is teleported is not the substance an object is made of but the information it represents.

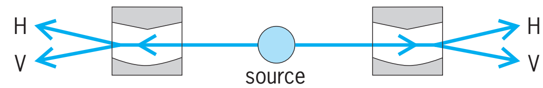

Fig. 1. **Principle of quantum entanglement for two photons emitted by a source. Each photon travels to its own two-channel polarizer, each of which can be rotated around the respective beam direction. Independent of the orientation of the polarizer, each detector (H or V) has the same probablility of registering a photon. If the two polarizers are oriented parallel, the two photons will always be registered in different detectors; that is, if one photon is registered in its H detector, the other is registered in its V detector, and vice versa. Yet neither photon carries any polarization before it is measured.**

Quantum entanglement. Entangled quantum states as used in teleportation were introduced into the discussion of the foundations of quantum mechanics by Einstein, Boris Podolsky, and Nathan Rosen in 1935. In the same year, Erwin Schrödinger introduced the notion of entanglement, which he called the essence of quantum mechanics.

In order to discuss entanglement, one specific case will be considered, and the possible experimental results will be examined (**Fig. 1**). There are many possible sources that can create many different sorts of entangled states. The source under consideration will be assumed to be the one used in the first teleportation experiments, which produced photons in a singlet polarization state. This means that neither photon enjoys a state of well-defined polarization; each one of the photons on its own is maximally unpolarized. Yet, when one of the two photons is subject to a polarization measurement, it assumes one specific polarization. That specific experimental outcome is completely random. As a consequence of the two photons being in the entangled singlet state, the other photon is instantly projected into a state orthogonal to that of the first photon. The fact that the measurement result on the second photon can be perfectly predicted on the basis of the measurement result of the first photon, even as neither one carries a well-defined quantum state, is known as the Einstein-Podolsky-Rosen paradox. In 1964 John Bell showed that these perfect correlations cannot be understood on the basis of properties that the entangled photons carry individually before the measurement. The resulting conflict between the philosophical position of local realism and the predictions of quantum mechanics, which have been confirmed beyond reasonable doubt in experiment, is known as Bell’s theorem. *See* HIDDEN VARIABLES; PHOTON; POLARIZATION OF WAVES.

From an information-theoretic point of view, the interesting feature of entanglement is that neither of the two photons carries any information on its own. All information is stored in joint properties.

Concept of quantum teleportation. It was first realized by Charles H. Bennett and his colleagues that entanglement can be utilized to make teleportation possible (**Fig. 2**). Alice, who is in possession of the

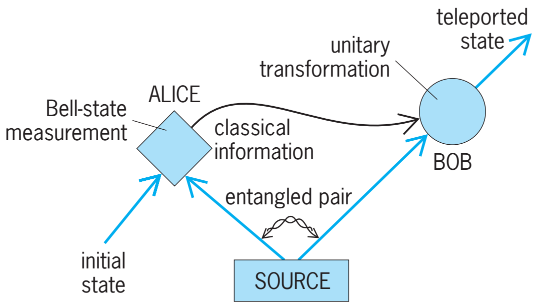

Fig. 2. Quantum teleportation procedure. Alice has an original particle in the initial state, and Alice and Bob also share an ancillary entangled pair. Alice then performs a Bell-state measurement and transmits the random result of that measurement in the form of two classical bits to Bob who, by a simple unitary transformation, can turn his ancillary photon into an exact replica of the original. (*After D. Bouwmeester et al., Experimental quantum teleportation, Nature, 390:575-579, 1997*)

original teleportee photon in a quantum state not known to her, and Bob initially share an ancillary pair of entangled photons, say in the singlet state described above. Alice then subjects her teleportee photon and her member of the ancillary pair to a Bell-state measurement. A Bell-state measurement is designed in such a way that it projects the two photons into an entangled state even if they were previously unentangled. This is a very tricky procedure both conceptually and experimentally. Conceptually, it means that the measurement must be performed in such a way that it is not possible, even in principle, to determine from the measurement result which photon was the teleportee and which was Alice's ancillary. They both have to lose their individuality. The result of the measurement must reveal only how the two photons relate to each other, and ignore individual properties. A Bell measurement has four possible results if the objects considered are defined in a two-dimensional Hilbert space just as is done to describe the photon's polarization. One of the four states is the singlet state discussed above. The other three states also define specific relations between the two photons, though different ones than those for the singlet state.

By the Bell-state measurement, Alice now knows how the unknown state of the teleportee photon relates to her ancillary one. She also knows in which entangled state the two ancillaries were produced, that is, how these two relate to each other. Thus she finally knows precisely how the teleportee relates to Bob's photon. More formally speaking, as a result of Alice's measurement Bob's photon is projected into a state which is uniquely related to the original state; the specific relationship is expressed by which of the four Bell states Alice obtained. Alice therefore informs Bob of her measurement result via a classical communication channel, and he, by applying a simple unitary transformation on his photon, changes it into the original state.

In one of the four cases, Alice obtains the information that her two photons have been projected into the singlet state, the same state in which the ancillaries were produced. Then, she knows that Bob's photon is instantly projected into the original state; the transformation that Bob has to apply is an identity transformation, that is, one that makes no change to his photon. That Bob's photon then instantly becomes an exact replica of the original seems to violate relativity. Yet, while Alice knows instantly that Bob's photon, no matter how far away, is already an exact replica, she has to inform Bob of the Bell measurement result such that he knows that his photon is already in the correct state. That classical information can arrive only at the speed of light. This requirement is also true for the other possible Bell-state measurement results. Bob has to know them in order to apply the correct transformation to his photon.

The result of the Bell measurement is not related at all to any properties that the original photon carries. Thus, that measurement does not reveal any information about its state. Therefore, the operation that Bob has to apply is also completely independent of any properties of the original photon. The reason that quantum measurement succeeds is that entanglement makes it possible to completely transfer the information that an object carries without measuring this information.

Experimental realization. An experiment therefore faces a number of challenges. They include (1) how to produce the entangled photon pairs and (2) how to perform a Bell measurement for independent photons. In the experimental realization by D. Bouwmeester and his colleagues in 1997, the entangled photons were produced in the process of spontaneous parametric downconversion. This is a second-order nonlinear process where a suitable crystal, in the experiment beta barium borate (BBO), is pumped with a beam of ultraviolet radiation. A photon from that beam has a very small probability to decay spontaneously into two photons, which then are polarization-entangled in just the way necessary for the experiment. The more tricky part is the Bell-state measurement because, in essence, it requires that the two photons are registered such that all information about which was the teleportee photon and which the ancillary is irrevocably erased. This is a nontrivial requirement since the two photons are coming from different directions, they might arrive at different times, and so forth. *See* NONLINEAR OPTICS; OPTICAL MATERIALS.

In the experiment, the Bell-state measurement was performed using a semireflecting mirror, which acted as a 50/50 beam splitter. Two photons were incident on the beam splitter, one from its front side and one from its back, and each one had the same probability of 50% to be either reflected or transmitted. If each of the two detectors in the two outgoing beams, again one in the front and one in the back, registered a photon simultaneously, then no information existed as to which incoming photon was registered in which detector, and the two were projected into the entangled singlet state. Narrow-bandwidth filters in front of the detectors further served to erase any time information which could also serve to identify the photons.

In this experiment, only one of the four possible Bell states could be identified, the singlet state. This certainly reduced the efficiency of the procedure, though in those cases in which the two detectors at the Bell-state analyzer registered, teleportation worked with a fidelity escaping all possible classical explanation.

In another experiment, also called entanglement swapping, it was even possible to teleport a photon that was still entangled to another one. That experiment started with two entangled pairs. A joint Bell-state measurement on one photon from each pair projected the other two photons onto an entangled state. In that way, two photons that neither came from the same source nor ever interacted with one another became entangled.

What all these experiments reveal is that the quantum state is really just a representation of the information that has been acquired. In the case of entanglement, it is only information on how objects relate to each other without any information on their individual properties. And in the case of teleportation, Alice's observation changes the quantum state that Bob observes. In other words, what can be said about the situation changes due to an observation by Alice. This gives very strong support to the Copenhagen interpretation of quantum mechanics. The first experiments were done with polarization-entangled photon pairs. Since then a number of experiments teleporting other properties such as continuous variables carried by the electromagnetic field of light, instead of the discrete ones discussed above, have been performed.

Prospects. While the teleportation distance in the first experiments was of the order of 1 m (3 ft), experiments in 2004 extended the distance to the order of 600 m (2000 ft), and there are plans to perform such experiments over much larger distances and even from a satellite down to laboratories on the ground. Other important experimental steps include the teleportation of quantum states of atoms (2004) and the teleportation of the quantum state of a photon onto that of an atomic cloud (2006).

Today quantum teleportation and entanglement swapping—the teleportation of an entangled state—are considered to be key building blocks of future quantum computer networks. At present there is intense research in the development of both quantum communication networks and quantum computers. Future quantum computers would use individual quantum states, for example those of atoms, to represent information in so-called quantum bits. They are expected to allow some algorithms to be performed with significantly higher speed than any existing computers. Quantum teleportation would allow the transfer of the quantum output of one quantum computer to the quantum input of another quantum computer. *See* NONRELATIVISTIC QUANTUM THEORY; QUANTUM COMPUTATION; QUANTUM MECHANICS; QUANTUM THEORY OF MEASUREMENT.

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Quantum theory of matter

The microscopic explanation of the properties of condensed matter, that is, solids and liquids, based on the fundamental laws of quantum mechanics. Without the quantum theory, some properties of matter, such as magnetism and superconductivity, have no explanation at all, while for others only a phenomenological description can be obtained. With the theory, it is at least possible to comprehend what is needed to approach a complete understanding.

The theoretical problem of condensed matter, that is, large aggregates of elementary particles with mutual interactions, is that of quantum-statistical mechanics, or the quantum-mechanical many-body problem: an enormous number, of order 10^{23}, of constituent particles in the presence of a heat bath and interacting with each other according to quantum-mechanical laws. What makes the quantum physics of matter different from the traditional quantum theory of elementary particles is that the fundamental constituents (electrons and ions) and their interactions (Coulomb interactions) are known but the solutions of the appropriate quantum-mechanical equations are not. This situation is not due to the lack of a sufficiently large computer, but is caused by the fact that totally new structures, such as crystals, magnets, ferroelectrics, superconductors, liquid crystals, and glasses, appear out of the complexity of the interactions among the many constituents. The consequence is that entirely new conceptual approaches are required to construct predictive theories of matter. *See* CRYSTAL STRUCTURE; FERROELECTRICS; GLASS; LIQUID CRYSTALS; SUPERCONDUCTIVITY.

The usual technique for approaching the quantum many-body problem for a condensed-matter system is to try to reduce the huge number of variables (degrees of freedom) to a number which is more manageable but still can describe the essential physics of the phenomena being studied. In general, the fundamental laws of quantum mechanics give little or no guidance for this task. For example, while it seems natural to describe a solid by a collection of ions and valence electrons, it is not apparent from the elementary equations of motion that this makes sense. Here, the ions consist of the nuclei and the more tightly bound electrons; the valence electrons are the more loosely bound ones which participate in the chemical bonding. The problem remains extraordinarily