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FEATURE

Quantum theory: still crazy after all these years

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The interpretation of quantum mechanics was once limited to the analysis of famous thought experiments. Now many of these are possible in the lab, but the subject remains as mysterious as ever

Quantum theory: still crazy after all these years

DANIEL GREENBERGER AND ANTON ZEILINGER

QUANTUM theory, the modern theory of atomic systems, is probably the most accurate and successful theory science has produced. It describes the structure of isolated atoms, the way they combine to form molecules, and the behaviour of all kinds of liquids and solids (including conductors, insulators, semiconductors and superconductors). Quantum theory is also widely used on smaller scales. It accurately predicts the structure and decay of nuclei, for example, while quantum field theory can be used to describe exotic elementary particles, such as quarks. Quantum effects are also important in the structure of massive objects, such as stars. Yet, in spite of this success, the interpretation of quantum theory has been subject to a continuous debate since its inception.

In the early days this debate seemed largely symbolic. Giants like Einstein and Bohr sparred over how to explain certain *gedanken* ("thought") experiments, each using very different versions of concepts such as causality. Most younger physicists held back from these discussions, partly to avoid being gobbled up by the giants, but mainly because the debate seemed to be largely philosophical and to have no experimental consequences. No-one disagreed on the likely outcome of these thought experiments, just on their interpretation.

For example, the intrinsic role of probability in quantum theory meant that individual atomic events could not, even in principle, be causally described, only statistically predicted. Previously, probability had merely played the role of describing our ignorance of what was happening at a deeper level. Now it seemed to imply that there was no deeper level – nature itself only determined what events could happen and the likelihood of each occurring. Einstein's discomfort with this notion was expressed in his famous saying: "God does not play dice with the universe". But it was the implied lack of causality, not the statistical nature of quantum theory, that most bothered him.

Spin up, spin down

A quick way to see Einstein's dilemma comes from examining the "spin" or intrinsic angular momentum of an elementary particle, such as an electron. The spin of an elementary particle is roughly analogous to the spin of the Earth. However, while we can easily imagine the Earth spinning at any rate and about any axis, the electron spin is more restricted. If one wants to measure the spin of the electron, one must do so about some chosen axis. One fixes this axis by setting up a magnetic field, which points in some direction, and asks: what is the component of the spin along this direction? The result is that the electron is always spinning around the axis in question, either counterclockwise from above or clockwise, but always with the same angular momentum. We say that the electron has spin $\frac{1}{2}$, (referred to a fundamental unit of angular momentum), and the result of our measurement is either $+\frac{1}{2}$ (spin up) or $-\frac{1}{2}$ (spin down).

Now, if an electron is spinning freely in space, can we say that it is spinning about some particular axis? We can measure its spin about any given axis, which will always tell us that it is now spinning about that axis, but what can we say about the electron before we made the measurement? Einstein said that it must have been spinning about some axis, but Bohr argued that only the probabilities of the electron having spin up or down along any axis are determined. In Bohr's "Copenhagen interpretation" the electron does not possess a definite spin component until the measurement is made. At this stage, there didn't seem to be any way to choose between these competing ideas, nor did it seem necessary.

However, in a famous paper in 1935, Einstein, Boris Podolsky and Nathan Rosen (EPR) pointed directly to the Achilles' heel of quantum theory. We will describe David Bohm's version of the "EPR paradox": a particle with no spin, while at rest, decays into two identical particles (labelled 1 and 2), each with spin $\frac{1}{2}$. Since momentum is conserved, the particles fly out in opposite directions. And since spin is conserved, the two spins must add up to zero. Therefore, if the spin of particle 1 is measured to be "up" along some specific direction, then the spin of particle 2

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must be "down" along that same direction. This fact was used by EPR to determine what they termed an "element of reality" in the system – a property that belongs to the system and is not an artefact of the measuring process. It is very hard in quantum theory to find such elements of reality, as quantum measurements tend to interfere strongly with the system being measured. We do not have the classical type of ability to observe the system "gently" without appreciably disturbing it.

EPR realized that there was a way round this quantum limitation: by measuring a property of particle 1, say its spin, we can determine the spin of particle 2 without ever touching it. If particle 1 is spin up about some axis, particle 2 must be spin down about the same axis. Furthermore, it must have been spin down since the original decay, because nothing has interacted with it since the decay. But quantum theory, argued EPR, denies this, and is unable to describe the spin before the measurement. Therefore, they concluded, it must be an incomplete theory.

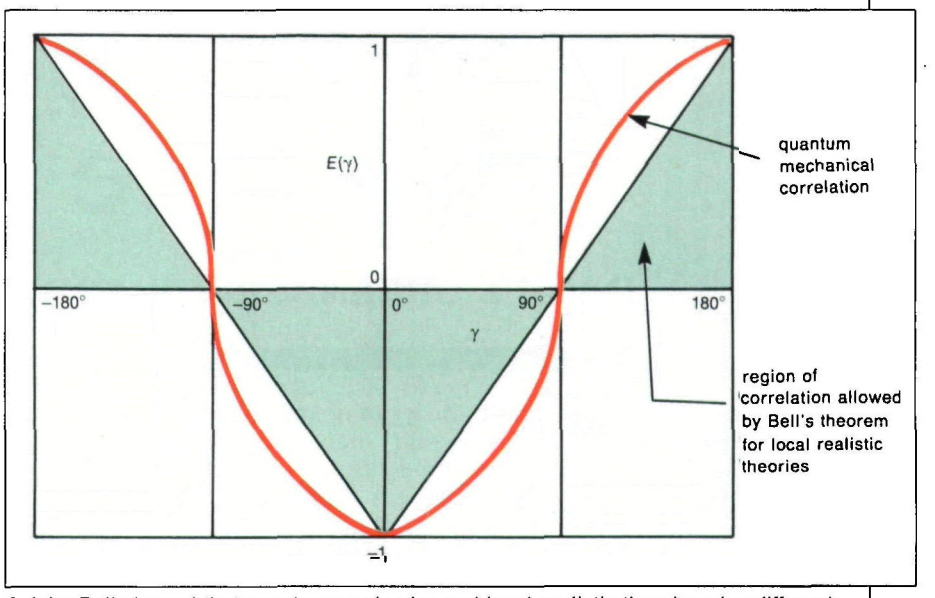
The power of this argument is its unassailable common sense. Yet Bohr's answer seems equally irrefutable. He pointed out that quantum measurements are not like classical measurements – their results depend on the complete experimental arrangement, which is not local in this case. Since we can measure the spin of particle 1 in any direction, and since particle 2 will always have exactly the opposite spin in this same direction, the spin of particle 2 is determined by the experiment on particle 1. How could particle 2 "know" in advance in which direction the experimenter was going to measure particle 1? Bohr argued that particle 2 could not have acquired a spin direction until particle 1 was measured. What existed before the measurement, he said, was a non-local correlation between the spins, but the value of the spin was not determined until the measurement was performed.

So here are two equally convincing arguments set out in 1935 with, it seemed, no way of deciding between them. Some famous physicists joined Einstein in refusing to believe in quantum theory as anything other than a calculational tool, but the younger generation started to prove how accurate and widely applicable the theory actually was. Moreover, it was considered bad taste to question the foundations of the subject by asking questions that could not be answered experimentally.

A new twist

The situation changed dramatically in the mid-1960s when John Bell showed that it was possible to distinguish between the interpretations of Einstein and Bohr in an experiment. Bell assumed, like EPR, that the two particles are emitted with definite spin directions, which are locally fixed at the decay. However, these directions might be unknown, or even unknowable, to the experimenter. He then showed that if we measure the spin of particle 1 along one direction, and the spin of particle 2 along another direction, the results will be correlated. For example, if we measure the spin of both particles along the same direction, particle 2 will always be spin down when particle 1 is spin up. They are thus perfectly correlated (or, rather, anti-correlated). However, if the spins are measured along different directions, the correlation will decrease. In other words, if particle 1 is spin up, particle 2 will sometimes be spin up and sometimes be spin down.

Quantum theory predicts that the correlation will be $E(\gamma)=-\cos\gamma$, where γ is the angle between the two spins. (If the measurement is repeated many times at the same angle, the correlation $E(\gamma)$ is the fraction of measurements for which the spins of the particles will agree with each other, minus the fraction of times they will disagree. They agree when both give the result "spin up" (or both "spin down") along their respective direction of measurement.) Bell applied the laws of probability to a theory in which the spin directions are determined by some unknown variables



1 John Bell showed that quantum mechanics and local realistic theories give different predictions for the correlation $E(\gamma)$ between the spin directions in an EPR experiment. For example, when the spin directions are measured at an angle of $\gamma=135°$ apart, quantum mechanics predicts a correlation of 0.71 while local realistic theories predict a maximum correlation of 0.5. Experiments have shown that quantum mechanics is correct.

at the time of decay. Such theories were known either as "hidden variable" or "local realistic" theories. He calculated an upper limit on the correlation that has become known as the Bell inequality.

At $\gamma=0°$ ($E=-1$) and $\gamma=\pm180°$ ($E=1$), the classical and quantum results must agree. However, at all other angles they disagree, with quantum theory giving higher levels of correlation (see figure 1 and Jack in Further reading). Bell thus set in motion a series of experiments to decide between quantum theory and the hidden variable or local realistic theories.

In order to perform these experiments, Bell's work had to be extended, since he had assumed perfect detectors and various other idealizations. These extensions had to make some "reasonable" assumptions of their own, such as that the detected particles represent a fair sampling of all the particles emitted. Otherwise, it is always possible to construct a demonic theory that will outwit the experimenter. When asked whether such theories stretch the bounds of the reasonable, their defenders tend to answer: "What could be more unreasonable than a breakdown of causality, as occurs in quantum theory?"

The first experimental test of Bell's theorem, by John Clauser and Stuart Freedman of the University of California at Berkeley, was performed in 1972, and the most famous experiment was carried out by Alain Aspect, Jean Dalibard and Gérard Roger at the Institute d'Optique in Paris in 1982. These, and most other EPR experiments, have been performed with the polarization of photons rather than the spin of particles. The 1982 experiment was

the first in which the measurements on the two particles were made so far apart that one could rule out the possibility of a signal passing between the particles at the speed of light, informing one particle of the result of the measurement on the other. Now many experiments have been done and, except for some of the very earliest, all the rest fully agree with the quantum mechanical results.

An ideal experiment would get round all of the loopholes caused by the "reasonable" assumptions made in the analysis by detecting (almost) all of the particles. For photons, detection efficiencies of more than about 80% are needed – a reachable but not imminent goal. Edward Fry of Texas A&M University is working on an experiment in which mercury atoms are used. Although only a few of the particles generated would meet the conditions of the experiment, almost 100% of those that did could, in theory, be detected. This experiment would be definitive.

However, in the absence of such perfection, the situation today is that quantum theory seems to be well supported experimentally. Einstein's views were not illogical, or even unreasonable – quite the contrary. Their very reasonableness is why the experiment has been done over and over. It is just that the EPR assumptions do not seem to be supported by nature. The Achilles' heel of quantum theory turned out not to be vulnerable. At some very fundamental level, nature is either acausal or non-local. In other words, events can be correlated in a way that cannot be traced back in time to some cause at a fixed point (like the point where the original particle decayed). The other possibility is that correlations can be carried between the particles at speeds exceeding that of light.

However, if Einstein's scepticism about quantum theory was misplaced, special relativity was not challenged. An intriguing aspect of these correlations is that they cannot, either in theory or experiment (so far), be used to communicate faster than the speed of light.

Entangled states

Within quantum theory, the behaviour of a particle in a given state is determined by a complex wave function, $\psi(x)$. The probability of finding the particle at x is given by $|\psi(x)|^2$. The wave function for a two-particle system in which the particles behave independently of each other is simply the product of two single-particle wave functions. However, if the particles are correlated in a non-classical, non-local way, the wave function is not a simple product of two single-particle wave functions. Schrödinger called such states "entangled states".

For example, if ψ represents a "spin up" state and φ a "spin down" state, then the wave function for the EPR state, $\Psi(x_1,x_2)$, would be proportional to $(\psi(x_1)\varphi(x_2) - \varphi(x_1)\psi(x_2))$. In this state, if particle 1 is spin up then particle 2 is spin down, and vice versa. (The minus sign is important, but not for our purposes.) It is such states, which cannot be factored into a simple product and which manifest purely quantum correlations, that cause all of the trouble for classical theories. Many new techniques have been developed to create such entangled states.

A radical improvement of the Bell theorem that involves entangled states of three or more particles was proposed by us and Michael Horne of Stonehill College, Massachusetts, in 1989. This is called the Greenberger–Horne–Zeilinger (GHZ) theorem, or the "Bell theorem without inequalities". In this case, we can imagine a particle of spin ½ that decays into three particles of spin ½. Now we can measure the spin of particle 1 along a direction in the plane perpendicular to its motion, given by an angle α, and similarly for particle 2 (angle β) and particle 3 (angle γ). We can arrange a situation such that the correlation between them will be given by $E=-\cos(\alpha+\beta+\gamma)$. Now, when $(\alpha+\beta+\gamma)=0°$ or $180°$, the particles will be perfectly correlated. If we measure the spin of two of them, we can predict with certainty the spin of the third, even if it is far away. But this time there is a freedom that did not exist for two particles. If one of the angles, say α, is fixed, then β can have any value so long as $\alpha+\beta+\gamma=0$; in the two particle case, if α is fixed then so is β. It is this extra freedom that makes it impossible to construct a local, deterministic theory that can explain all possible cases at once.

So far, no-one has constructed an entangled state of three particles to test that quantum theory will work for them, though a number of suggestions have been offered. However, since quantum theory works for three particles in many other cases, it would be amazing if it failed here.

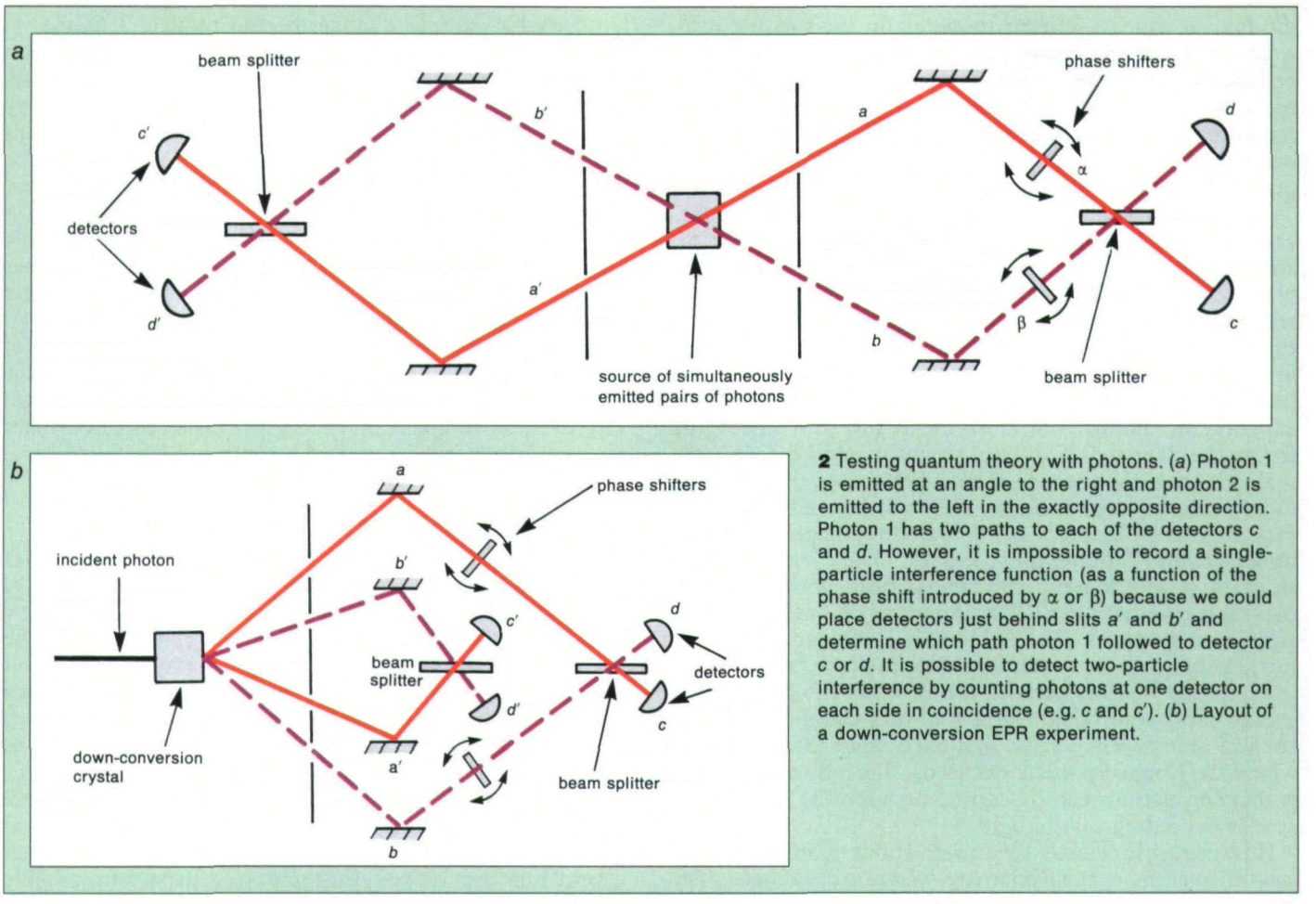
Gedanken no more

There is now a proliferation of experimental techniques that make it possible to probe the interpretation of quantum theory in the laboratory. Many of these new techniques are based on lasers. For example, lasers can be used to cool heavy ions trapped in magnetic fields to about 0.1 K. Indeed it is possible to trap and cool single atoms and ions. This allows the frequency of the radiation they emit to be measured very accurately. (In a gas, collisions with other particles and the particle's own kinetic energy "broaden" the emission line). This allows more accurate tests of quantum calculations of atomic energy levels and may also lead to improved frequency standards. When several ions are trapped, they tend to collapse into a stable geometric pattern (kept apart by their Coulomb repulsion), much like a phase transition.

Another new technology for testing quantum theory is the micromaser – a microwave cavity through which a beam of Rydberg atoms (relatively stable atoms with an electron excited into a high-lying near-circular state) is sent one atom at a time. Lasers can be used to prepare the atoms in special states before they enter the cavity, and to change their state again after they leave it but before they are detected. If the resonant frequency of the cavity is tuned to the frequency of a transition between two of these Rydberg states, single photons can be trapped in the cavity as the atom passes through. The next atom can be made to absorb this photon, or otherwise interact with the cavity, so both atoms will become correlated. It may be possible to make a multiparticle state and test the GHZ theorem by passing a succession of atoms through a micromaser.

When a single atom passes through a micromaser we have a system of entangled states (the atom is non-locally coupled with the photons in the cavity). Therefore we can probe the atom to find out how many photons are in the cavity, and vice versa. The number of photons in the cavity and their phase are related by the uncertainty principle. If there are a lot of photons in the cavity, the photon number becomes uncertain and the radiation becomes classical with a well-defined phase. This means that atoms (which have been prepared in a state that is not resonant with the cavity) maintain their phase when they travel through the cavity, and this can be measured in an interferometer.

However, if there are very few photons in the cavity and the atoms are resonant with the cavity, then the emission of absorption of a photon can be detected – but at the cost of losing information about the phase of the atom. These techniques, which have now been extended to optical wavelengths, allow us to perform very sophisticated



2 Testing quantum theory with photons. (*a*) Photon 1 is emitted at an angle to the right and photon 2 is emitted to the left in the exactly opposite direction. Photon 1 has two paths to each of the detectors *c* and *d*. However, it is impossible to record a single-particle interference function (as a function of the phase shift introduced by α or β) because we could place detectors just behind slits *a'* and *b'* and determine which path photon 1 followed to detector *c* or *d*. It is possible to detect two-particle interference by counting photons at one detector on each side in coincidence (e.g. *c* and *c'*). (*b*) Layout of a down-conversion EPR experiment.

experiments (e.g. see Gerhard Rempe 1995 "Single atoms light up in microlaser" *Physics World* April p31).

A pair of micromasers could be used to illustrate another fundamental principle of quantum theory – "wave-particle duality". This states that you cannot make a particle interfere with itself (i.e. exhibit wave-like behaviour) and still tell which path it took through the interferometer (particle-like behaviour). If we had two similar cavities side by side we could split the beam, so that the atom might pass through either of the cavities, and the beams would recombine before they reach the detector. If there were many photons in the cavities, one could have good phase knowledge for the recombined atom and create an interference pattern. However, if we could measure that a photon was absorbed or emitted in one cavity, we could use this to obtain path knowledge (i.e. to know which cavity the atom passed through), and this would wipe out any interference pattern between the beams.

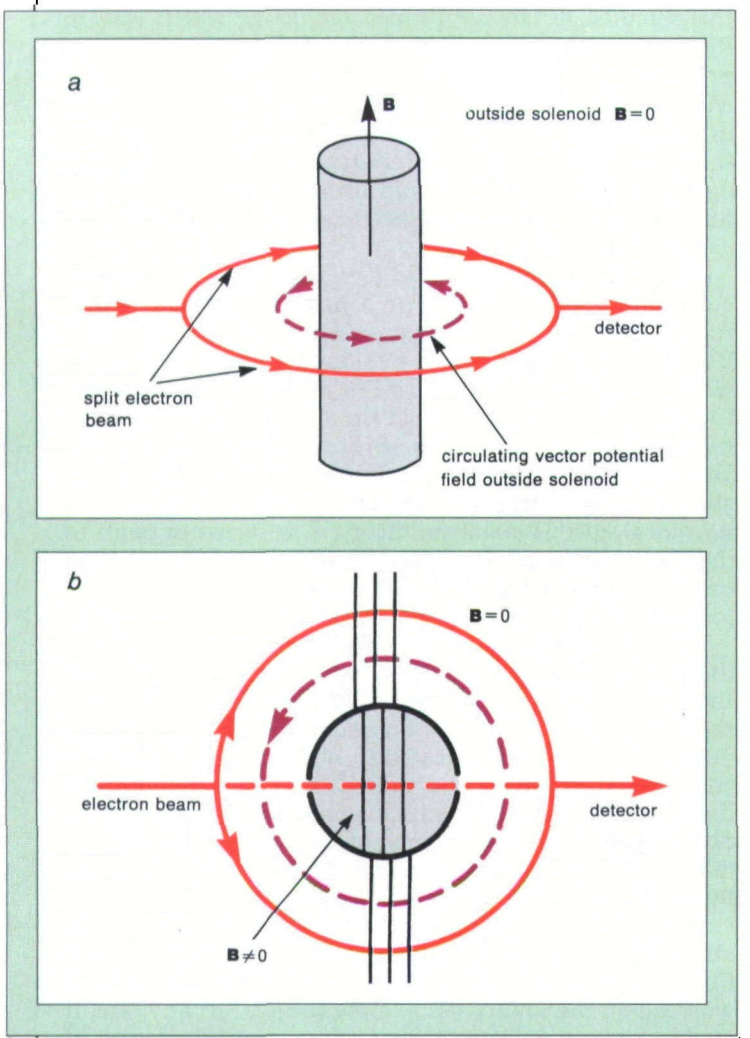
Another useful feature of these experiments is that they can be made to reveal pure quantum statistical effects. Classical radiation obeys Poisson statistics (the statistics of random fluctuations). However, photon correlations can be used to produce sub-Poisson statistics between the photons, proving their quantum nature. These features are very important in producing what are called "squeezed states". In an ordinary radiation field we cannot know perfectly both the amplitude and the phase of the electric field (or any other two complementary characteristics of the field), because of the uncertainty principle. The random fluctuations restrict them to a certain minimum uncertainty, and the product of the two is constrained by the uncertainty principle. But in a squeezed state, one of these characteristics can be well known, at the expense of large fluctuations in the other. The idea is to use the well known component to make a measurement of some physical quantity, which can then be determined much more accurately than if it were being measured by a randomly fluctuating field.

The detection of gravitational waves is one potential use for squeezed states. In such a device, squeezed light would be used to detect the minuscule vibrations induced in a large metal bar by a gravitational wave. However, such a detector is still beyond our best technology, and the use of squeezed states is even more problematic.

Interfering busy bodies

When Schrödinger was questioning quantum theory, he used the image of a cat in a box as a macroscopic device (Schrödinger's cat). The box contains a radioactive atom linked to a vial containing poison. When the atom decays, the poison is released and the cat dies. If the atom could be put into a coherent superposition of its initial state "a" and its decayed state "b", we could, in principle, create an entangled state, Ψ = (atom in state "a", poison not released, cat alive) + (atom in state "b", poison released, cat dead). When we opened the box, the cat would become either purely alive or purely dead – the wave function Ψ would be "reduced" by the measurement. But until the box was opened the cat would be in an entangled state, alive + dead.

Schrödinger thought that this example would be silly enough to convince people that quantum theory could not apply to macroscopic objects. The problem is that a cat has an incredible number of internal states, and it is nearly impossible to keep them all coherent so that they can manifest interference. But presumably quantum mechanics should apply to the system. It is only that we



3 Side (*a*) and top (*b*) view of an Aharonov–Bohm experiment in which a coherent electron beam is split into two components, which are passed round opposite sides of a solenoid before recombining. The recombined beam shows an interference pattern as a function of the magnetic field inside the solenoid, even though the electrons do not pass through the magnetic field at any stage. This highly non-local and purely quantum effect is caused by the magnetic vector potential, which can be non-zero in regions where there is no magnetic field. The top view shows the circular vector potential (dotted line). This causes the wave fronts on the right of the solenoid to lead those on the left.

cannot see any interference effects.

However, earlier this year Dave Pritchard's group at the Massachusetts Institute of Technology obtained an interference pattern for a beam of sodium molecules using microfabricated diffraction gratings (see Chapman *et al.* in Further reading). If molecules with their complicated internal states have wave-like properties that we can see, what size of macroscopic body can we truly be limited by?

A molecule is no cat, but it is also a far cry from an electron. This is a crucial problem in quantum theory. Indeed molecules can be prepared in states in which the de Broglie wavelength is much smaller than the size of the molecules. This has the effect of extending the applicability of quantum theory up to fairly large particles.

Another technique for bringing thought experiments to life in the laboratory is parametric down-conversion – a process in which a nonlinear crystal converts a single ultraviolet photon into two red photons (see Greenberger, Horne and Zeilinger in Further reading). The crystal ensures that energy and momentum are conserved. In a co-ordinate system in which the photons have equal and opposite momenta, we can place slits so that photon 1 can be in one of two states, a or b, and photon 2 is either in state a' or b'. Since we cannot tell which state the photon will be created in, we have an entangled state, $\Psi \propto [\psi_1(a)\psi_2(a')+\psi_1(b)\psi_2(b')]$. The wave function reflects the fact that if photon 1, say, is in state a, photon 2 will be in state a', and similarly for b and b' (figure 2). Photons in states a and b pass through phase-shifters α and β, interfere in a beam splitter and are detected at c and d; photons in states a' and b' interfere in a separate beam splitter and are detected at c' and d'.

We might expect to be able to record an interference pattern in c or d simply by plotting the number of photons detected in a fixed time as a function of the phase shift (changed by simply rotating a plate of glass to change the optical path length) in one of the beams. However, we cannot – the two paths a and b leading to the beam splitter do not interfere. That is, there is no single-particle interference in this set-up. (This lack of single-particle interference also prevents faster-than-light communication.) This is because we could put counters in paths a' and b' – if photon 2 triggered counter a', we would know that photon 1 took path a. This means that the laws of quantum mechanics forbid interference between two paths if we can tell which path the beams take. Indeed the very possibility of being able to tell which path the photon took prevents the beams from interfering. The only interference one can get is by counting coincidences between the two photons, one on each side, when both beam splitters are present. For example, if we only count photons in c, which are detected in coincidence with photons in, say, c', then we will record a two-particle interference pattern. A range of fundamental experiments can be performed with this set-up (see Rarity in Further reading).

Going through a phase

Besides the non-locality shown by the entangled states of many particles, quantum mechanics also possesses non-locality for single-particle states. The most important manifestation of this is the Aharonov–Bohm effect, predicted in 1958 and confirmed experimentally many times since (see Tonomura in Further reading). The effect can produce an interference pattern between two beams, even when neither passes through a force field.

In both quantum theory and classical theory, electromagnetic fields are produced by potentials. For instance the magnetic field, **B**, is produced by the vector potential **A** and it is possible for **A** to be non-zero in a region where there is no magnetic field. In classical physics the potentials are bookkeeping devices, with no physical effects. A particle with no forces on it will feel no effect of any kind. However, in quantum theory these potentials change the phase of the wave function, even when the fields themselves, and hence the forces, vanish.

The classic Aharonov–Bohm experiment involves splitting a coherent electron beam, passing the components around either side of a solenoid and then recombining the beam. Although there is no magnetic field outside the solenoid, there is a circular potential that advances the wave front of one electron beam and retards the other (figure 3*a*). When the two recombine, there will be a phase shift between them that depends on the magnetic flux through the closed path formed by the electron beams.

The potential keeps track of the phase of the electron beam everywhere in space so that it can bend the beam if it encounters a real magnetic field. In the figure there is a real field inside the solenoid. If a small hole were drilled through the solenoid, the magnetic field would bend the

electron as it passed through the solenoid. Therefore the phase on one side of the solenoid must be ahead of the phase on the other side – just in case you decide to direct your beam right through the solenoid.

However, even if you decide to set up a experiment that avoids the solenoid, the geometry of what happens between the beams must be recorded by the potential (figure 3*b*). It records the fact that if you wanted to bring one of the beams continuously from one side of the solenoid to the other, you would have to encounter this bending in the middle. The accompanying phase shift along the way must be taken account of, so the potential keeps track of the continuity of everything that could happen throughout space, and affects the wave function accordingly. This is a truly non-local effect.

There is an electric potential equivalent for the Aharonov–Bohm effect. It involves passing one of the electron beams through an electric potential that is spatially homogeneous but varying in time (a capacitor with a time-dependent voltage for example). This will produce a potential but not a force. There is an equivalent effect for any time-dependent potential. This effect has recently been produced in a neutron interferometer by a collaboration between Anthony Klein's group at the University of Melbourne and Sam Werner at the University of Missouri–Columbia. In this device the neutron beam can be split by centimetres and coherently recombined. The homogeneous potential was produced by the interaction of the neutron magnetic moment with a magnetic field in one of the split beams, which produced a phase shift between the two amplitudes when the beams were recombined. In other words we have a coherent microscopic system separated by macroscopic distances.

Another analogue of the Aharonov–Bohm effect, the Aharonov–Casher effect, has also been seen in the Melbourne–Missouri neutron interferometer. Here the solenoid in the centre is replaced by a line of electric charge. As the split neutron beam passes it, the neutron sees an induced magnetic field, which again produces a force-free interaction with its magnetic moment, producing a measurable phase shift between the beams.

All of these effects have a topological significance, and are a special case of a much more comprehensive phase effect discovered by Michael Berry of Bristol University in the UK. If a particle is subject to an external force that changes slowly, but in such a way that it returns to its initial value, the particle will slowly change its orientation to follow the external field. At the end, the particle will be left in its original state, but multiplied by a phase factor. Part of this phase factor merely keeps track of the time evolution of the particle, but there will be an extra contribution that is topological in origin and records the geometry of the slowly changing external field. This is the Berry phase, which has been observed in many different experiments. There have been many experimental manifestations of this effect (see Shapere and Wilczek in Further reading), but an interferometer is especially advantageous, since a slowly varying field can be introduced into one arm of the interferometer and the phase difference between the beams will be the total integrated effect of this field. (That is, the time evolution can be subtracted out.)

Beyond Copenhagen

There is also an ongoing discussion concerning the interpretation of the wave function in quantum theory. The Copenhagen interpretation is strongly dependent on the outcome of laboratory measurements, which lead to the "collapse" of the wave function. But the measurement process itself cannot be described by this interpretation. Many people would like to have a self-consistent interpretation of quantum theory that is independent of measurements. The major motivation for this is cosmology, since cosmologists would like to discuss "the wave-function of the universe", which cannot be subject to some external measuring device.

An alternative approach is to replace the Schrödinger equation, which is linear, by a nonlinear equation that reproduces all of the standard effects of quantum theory. This strategy, championed by, among others, Giancarlo Ghirardi of the University of Trieste, Italy, also attempts to accomplish everything that the "collapse" of the wave function can. Another interpretation, due to the late David Bohm, replaces the entire statistical quantum apparatus by a deterministic one. However, it is highly non-local, just as quantum theory is. It seems to point to the possibility that probability could be less important to quantum theory than most of us believe, but that non-locality is here to stay.

We have only been able to scratch the surface of some of the new techniques and ideas that are affecting quantum theory. (The proceedings of a recent meeting on fundamental problems in quantum theory run to over 900 pages – see Further reading.) But the lesson is that the subject is no longer one that is confined to old men discussing views that have no experimental consequences. Some amazing new experimental techniques have been developed, and the experimenters are interested in the fundamental interpretation of the theory.

At the same time, new theoretical ideas are being advanced that will free the theory from the limitations of the standard interpretation. It is an exciting time to be working on the foundations of the subject. At any rate, it is clear that we will never go back to a classical view of the world. When quantum theory does finally break down, as all theories inevitably must, it will be because – in spite of all the strange phenomena it successfully embraces – it will not be sufficiently weird to encompass all natural phenomena. Nature itself is even weirder than quantum theory, and that is sure to be the theory's ultimate undoing.

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