Entanglement, Decoherence and the Quantum/Classical Boundary

Schrödinger intended his gedanken experiment of a hapless cat mortally entangled with a quantum trigger as a *reductio ad absurdum*. But nowadays such experiments are being realized in laboratories—without offending the antivivisectionists

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Quantum mechanics is very puzzling. A particle can be delocalized, it can be simultaneously in several energy states and it can even have several different identities at once. This schizophrenic behavior is encoded in its wavefunction, which can always be written as a superposition of quantum states, each characterized by a complex probability amplitude. Interferences between these amplitudes occur when the particle can follow several indistinguishable paths. Any attempt to determine which trajectory it "actually takes" destroys these interferences. This is a manifestation of wave–particle complementarity, which has recently been illustrated in textbook fashion by several beautiful experiments.[1]

Nonlocality in quantum systems consisting of spatially separated parts is even more puzzling, as Albert Einstein and collaborators Boris Podolsky and Nathan Rosen pointed out in the famous "EPR" paper of 1935.[2] Recent decades have witnessed a rash of EPR experiments, designed to test whether nature really does exhibit this implausible nonlocality.[3] In such experiments, the wavefunction of a pair of particles flying apart from each other is entangled into a non-separable superposition of states. The quantum formalism asserts that detecting one of the particles has an immediate effect on the other, even if they are very far apart. The experimenter can even delay deciding on the kind of measurement to be performed on the particles until after they are out of interaction range. Nonetheless, these experiments clearly demonstrate that the state of one particle is always correlated to the result of the measurement performed on the other, in just the strange way predicted by quantum mechanics.

The results of all these experiments are counterintuitive. Such things are never observed in our macroscopic world. Nobody has ever seen a billard ball going through two holes at once, or two of them spinning away from each other after a collision in a quantum superposition of anticorrelated states!

Schrödinger's cat

Nonetheless, macroscopic objects are made of atoms that individually obey quantum mechanics. There's the paradox. Erwin Schrödinger famously illustrated this conundrum with his provocative cat gedanken experiment.[4] He described a diabolical contraption in which a feline would become entangled with a single atom. The system would be described by a wavefunction representing at the same time the cat alive with the atom excited and the cat dead with the atom back in its ground state after its decay emission has triggered a lethal device. Quantum experts will object that a cat is a complex and open system which cannot, even at the initial time of this cruel experiment, be described by a wavefunction. The metaphor, nevertheless raises an important question: Why and how does quantum weirdness disappear in large systems?

Explanations for this "decoherence" phenomenon can be traced back to discussions by the founding fathers of quantum mechanics, and to 50-year-old developments in the theory of relaxation phenomena. But only in the last 15 years have entirely solvable models of decoherence in large systems been discussed, notably by Anthony Leggett, Eric Joos, Roland Omnès, Dieter Zeh and Wojciech Zurek.[5] (See also the article by Zurek in PHYSICS TODAY, October 1991, page 36.) These models are based on the distinction in large objects between a few relevant macroscopic observables like the position or momentum of the object, and an "environment" described by a huge number of variables, such as positions and velocities of air molecules, number of blackbody-radiation photons and the like.

When the system is brought into a superposition of different macroscopic states, information about this superposition is unavoidably and irreversibly leaking into the environment at a rate that increases with the separation between the parts, thus efficiently randomizing their quantum coherence. The link with complementarity is striking. As Zurek put it, the environment is watching the path followed by the system, and thus suppressing interference effects and quantum weirdness. The strong dependence of the decoherence rate on the system's size and the separation of its parts is the trademark of this phenomenon, which makes it different from other manifestations of relaxation.

In macroscopic systems, this process is so efficient that we see only its final result: the classical world around us. Could one prepare *meso*scopic systems—somewhere between the macro- and microscopic—in which decoherence would occur, but slowly enough to be ob-

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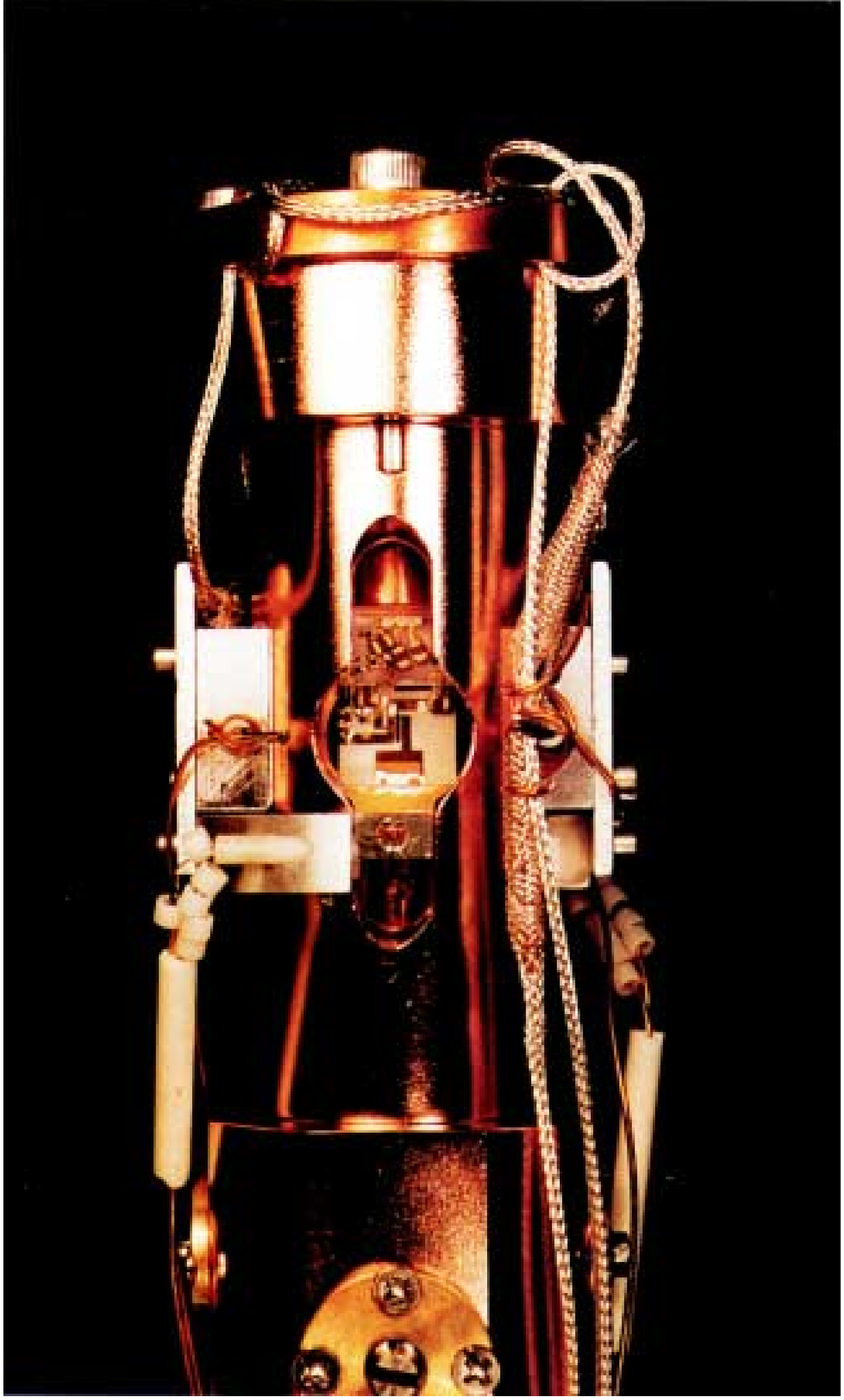

FIGURE 1. ION TRAP electrode structure used by the NIST group in Boulder, Colorado.[9] Single beryllium ions are confined along the vertical axis in the middle of the tiny 0.2-mm-wide notch at the center by potentials on the gold-plated electrodes. Through this notch, laser pulses can be directed at the oscillating ion. (Photo courtesy of C. Myatt, NIST.)

served? Until recently, such a thing could be imagined only as a gedanken experiment. But technological advances have now made such experiments real, and they have opened this field to practical investigation.

Various condensed matter systems have been considered as possible candidates for such studies. The possibility of using Josephson junctions and SQUID technology to prepare and study quantum coherences involving mesoscopic superconducting currents has been discussed by Leggett,[5] and interesting quantum tunneling experiments have been realized in this context. But they have not yet directly addressed the decoherence issue quantitatively.

Entangling experiments

In the last two years, great progress has been made in creating entangled quantum states of ions in traps or atoms in high-Q cavities. These two kinds of quantum optics experiments, very disparate in their techniques, have a striking similarity. They both realize a simple situation in which a two-level atom is coupled to a quantized harmonic oscillator. The Hamiltonian of this system, first studied by Edwin Jaynes and Frederick Cummings in 1963, has been a favorite of the theorists ever since. In spite of its simplicity, the system describes a great variety of interesting situations.[7]

There have been many proposals over the last 15 years to realize embodiments of Schrödinger's cat with such a system.[8] The feline role would be played by an excited harmonic oscillator. These experiments have now come of age. By taming small laboratory versions of Schrödinger's cat experiment in which the number of quanta can be progressively increased, we are learning more about decoherence and the elusive quantum/classical boundary.

In the ion trap experiment done by David Wineland, Chistopher Monroe and coworkers at the National Institute of Standards and Technology (NIST) laboratory in Boulder, Colorado, a single beryllium ion is monitored.[9] The trap is created in ultrahigh vacuum by a combination of static and oscillating electric fields applied to tiny metallic electrodes (See figure 1.) The ion is manipulated and detected in an exquisitely refined way by sequences of carefully tailored laser pulses. The ion oscillates in the trap along one direction at a frequency of 11.2 MHz. It has two relevant internal energy levels, which we call, for simplicity, $|+\rangle$ and $|-\rangle$. They are two hyperfine sublevels of the ion's ground state. The transition frequency between them is 12 GHz. The $|+\rangle$ state can be selectively detected by applying a polarized detection laser (L_d) beam tuned to a transition that couples this state to an excited level. As the ion subsequently decays back to its ground state, it emits fluorescence photons. Many photons are scattered when the ion is cycling under laser excitation. The $|-\rangle$ state, which does not interact with the tuned L_d beam, announces itself by the absence of light scattering—a null measurement.

At the beginning of the NIST experiment, cooling laser beams bring the ion down to its vibrational ground state. Its motional wavefunction is then a Gaussian wave packet localized at the trap's center. The packet's width, a few nanometers, is due to the zero-point quantum fluctua-

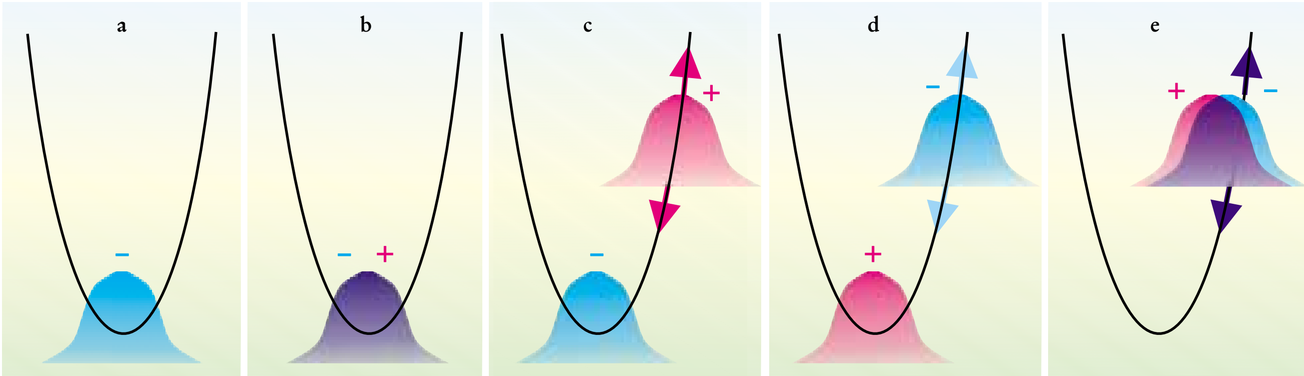

FIGURE 2. SCHRÖDINGER'S CAT in the Boulder ion trap. **a:** An ion in its lower hyperfine state $|-\rangle$ sits motionless at the bottom of the potential well. **b:** The internal state $|-\rangle$ is transformed into a still motionless superposition of $|+\rangle$ and $|-\rangle$ by a $\pi/2$ laser pulse L_1L_1'. **c:** A kicking laser pulse L_2L_2' starts only the $|+\rangle$ component oscillating macroscopically. **d:** The ion's internal states are swapped by a π pulse from L_1L_1'. **e:** A second L_2L_2' pulse launches the motionless $|+\rangle$ and recombines the two hyperfine components. The resulting wave-packet overlap depends on the relative phase of kicks **c** and **e**. After a final mixing of the hyperfine states by an L_1L_1' pulse, the detecting laser L_d reveals the hyperfine state by fluorescence. (Adapted from ref. 9.)

tions of the ion oscillator. The cold ion is initially in the hyperfine state $|-\rangle$. A pair of laser pulses, L_1 and L'_1, whose frequencies differ by the 12 Ghz hyperfine frequency, are then used to coherently mix the states $|+\rangle$ and $|-\rangle$, without affecting the ion's motion. These lasers exchange pairs of photons whose energy difference is fed into the ion's internal energy. In the language of classical optics, we would say that the ion is responding to the beat frequency. By adjusting the pulse duration, one can obtain any desired superposition of the two internal ion states. In this first stage of the experiment, the pulse is adjusted to prepare the two hyperfine states with equal weights—a so-called $\pi/2$ pulse.

A second pair of excitation kicking laser pulses, L_2 and L'_2, is then applied to set the ion in motion. Their frequency difference is now the 11.2 MHz vibration frequency of the trapped ion. The coherent interaction of the ion with this second pair of pulsed laser beams feeds energy into the ion's vibrational state, without affecting its internal hyperfine state. The second pair of beams is polarized in a direction such that the ion interacts with them only when it's in the $|+\rangle$ state; they have no effect on the $|-\rangle$ state. As a result, the ion wavefunction splits into two wave packets: One, correlated to the $|+\rangle$ hyperfine state, swings back and forth in the potential well. The other, correlated to $|-\rangle$, remains at rest at the center of the trap. The situation is obviously reminiscent of Schrödinger's cat.

The ion's state is analyzed by recombining the two wave packets and looking for interferences. The two internal states of the ion are switched by an $L_1L'_1$ pulse lasting twice as long as the first (a π pulse). Then a final $L_2L'_2$ kick launches the motionless part of the wavefunction (now correlated with the hyperfine state $|+\rangle$) into oscillation with an adjustable phase φ relative to the first oscillating state.

One gets maximum overlap if $\varphi = 0$. The two overlapping wave packets can still be distinguished by their different internal states. To observe interferences, one mixes these two states again by applying another $\pi/2$ pulse with $L_1L'_1$. Each of the two recombining wave packets then contains both hyperfine states. Finally the experimenters apply an L_d pulse from the detecting laser and collect the fluorescence for a small time interval. (See figure 2.)

Wineland and company repeat the experiment for different values of φ and observe interference fringes in the $|+\rangle$ fluorescence signal as φ is swept around zero (figure 3). The interference pattern clearly demonstrates the coherent superposition of the ion's two states of motion.

Before recombination, the separation of the two wave packets can reach a few tens of nanometers, several times the size of each individual packet. The ion's quantum state in each packet is a superposition of vibration states with relatively large quantum numbers, up to $n = 10$. In that sense, one may say that the system is mesoscopic.

Merely splitting a wave packet into two coherent parts is, of course, not new. All interferometry experiments do that routinely. The novel point here is that these packets remain Gaussian and do not disperse in time. These stable shapes provide a simple visualization of the system as a particle rolling in a bowl while it is simultaneously in two different states of motion. The ability to observe the oscillating ion for many periods, without dispersion, is potentially useful for decoherence studies. The decoherence one observes in these experiments, however, results from several sources of technical noise rather than from fundamental decay processes.

Feline decoherence

The study of Schrödinger cats and their decoherence has been pushed one step further in an experiment performed at the Ecole Normale Supérieure in Paris by a group that includes Jean-Michel Raimond, Michel Brune and myself.[10] The role of the cat in our experiment is played by a field oscillator consisting of a few photons stored in a

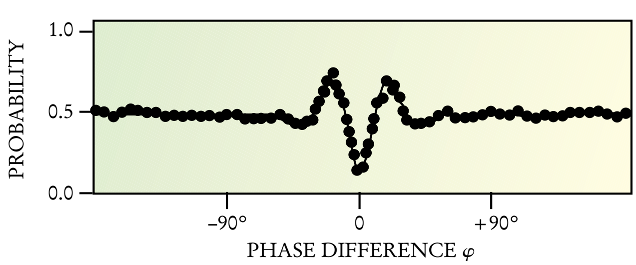

FIGURE 3. INTERFERENCE between the two ion wave packets in the Boulder experiment is seen in this plot of the phase-angle (φ) dependence of the probability of finding the ion in the internal hyperfine state $|+\rangle$ after recombining the two separated wave packets packets and mixing the two internal states. (Adapted from ref. 9.)

FIGURE 4. IN THE PARIS EXPERIMENT,[10] Schrödinger's cat is embodied by a few photons stored in the cavity C, whose mirrors are shown in the photo at right. A rubidium atom from oven O is prepared in box B in the Rydberg state $|+\rangle$. In the auxiliary cavity R_1, a microwave pulse turns it into a superposition of $|+\rangle$ and $|-\rangle$. Traversing C, the atom imparts to the cavity field two different phases at once. A second pulse in R_2 remixes the Rydberg states. The atomic state is measured in detectors D_+ and D_- by applying state-selective ionizing electric fields. A second atom, the "quantum mouse," tests the "cat" state prepared by the first atom. Statistical analysis of atomic energy correlations in many runs determines the quantum coherence of the cavity field. By varying the delay between the two atoms, one observes the cat's rapid decoherence.


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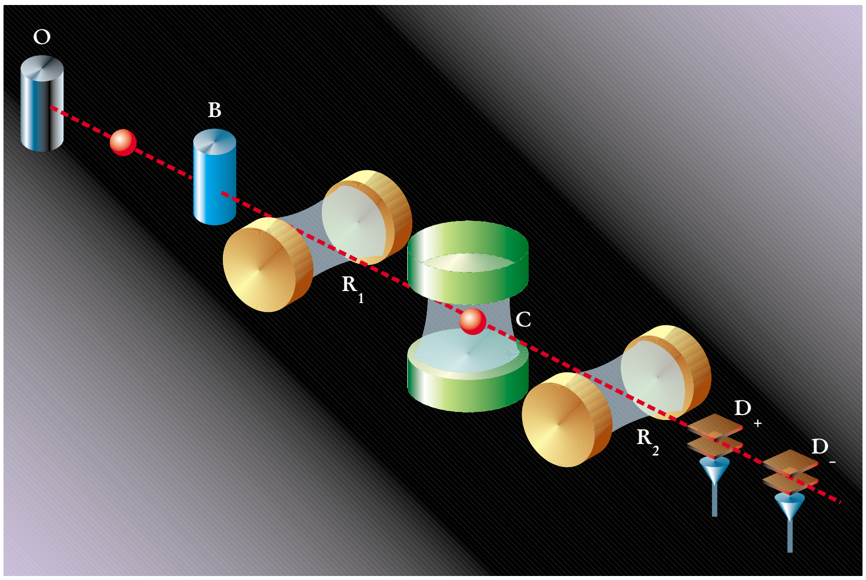


high-Q cavity. After interacting with a single atom, the field oscillates with two different phases at once—again a Schrödinger cat situation. The box in which the photonic cat is trapped is a cavity 3 cm long, consisting of two carefully polished niobium mirrors facing each other. (See the photo in figure 4.)

The photons are produced by a coherent millimeter-wave source coupled to the cavity by a waveguide. As soon as a few photons are stored, the source is switched off and the photons are left free to bounce back and forth between the mirrors. Coupling to the environment is minimized by cooling the setup to very low temperature (0.6 K), because blackbody radiation can cause unwanted, trivial relaxation effects. Furthermore, at this temperature the niobium is superconducting. The photons survive on average 160 microseconds before being scattered outside by mirror surface defects. One can tune the frequency of the field near 51 GHz by slightly moving the mirrors.

Once the radiation field is prepared, a single atom is sent across the cavity with an adjustable velocity (typically 400 m/s). This atom has a resonant frequency different from the field. Therefore it cannot absorb photons. The atom behaves like a small piece of transparent dielectric material with a refractive index slightly different from unity. It thus induces a small dispersive effect on the field, momentarily changing its frequency by a few kHz. The frequency resumes its initial value when the atom exits the cavity, after about 20 μs. But in the process the phase of the radiation field has been shifted.

Such an effect requires a special kind of atom. The refractive index corresponding to an ordinary atom in a volume of about 1 cm^3 differs from unity by only a few parts in 10^{22}. To get a much larger refractive index effect, we excited rubidium atoms from an atomic beam by laser and rf irradiation to a very high Rydberg state—with principal quantum number $n = 51$. By adjusting the laser intensity, we can reduce the flux of Rydberg atoms to the point where they cross the cavity one at a time.

A Rydberg level has a large degeneracy, corresponding to all possible values of the atomic angular momentum. The sublevel we prepare is the highest angular momentum state, with the excited electron moving around the nucleus in a very circular orbit. Although the radius of an ordinary atomic state is half an angstrom (0.05 nm), this state has a enormous orbital radius of 125 nm. The atom then behaves like a huge antenna strongly coupled to the radiation. It also has a very long radiative damping time, so that the loss of coherence due to spontaneous emission is negligible.

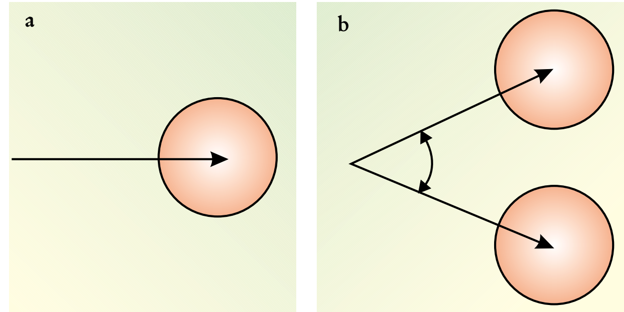
A single Rydberg atom in the 1 cm^3 cavity volume changes the refractive index by as much as a part in 10^7. That's 15 *orders of magnitude* more than one gets with an ordinary atom! The dephasing produced by such an atom on the field is on the order of a radian. Its value can be adjusted by controlling the atom's velocity and hence its transit time through the cavity, or by changing the frequency of the radiation field. (The refractive index is strongly frequency dependent.)

Introducing weirdness

We introduce quantum weirdness into these proceedings by subjecting the atom to an auxiliary microwave pulse before it enters the cavity. The pulse leaves the atom in a linear superposition of the two circular Rydberg states with principal quantum numbers 51 and 50. To stress the similarity with the ion experiment, we again label these states, respectively, $|+\rangle$ and $|-\rangle$. The cavity field is detuned slightly from the transition between these two states, which induces opposite refractive index changes in the cavity.

After the atom's traversal, the field thus acquires two distinct phases, each entangled with a different atomic state. One can think of a classical field as a vector in a plane, whose length is proportional to the field's amplitude and whose direction defines the field's phase. When there

FIGURE 5. ELECTROMAGNETIC CAVITY FIELD in the Paris experiment.[10] **a:** The initial coherent field can be described by a vector whose length gives its amplitude (square root of the mean photon population) and whose direction defines its phase. The uncertainty circle at the tip represents field quantum fluctuation. **b:** After interacting with a single atom prepared in a superposition of two Rydberg states corresponding to different refractive indices, the field becomes a superposition of two states with different phases. The field vector points in two different directions at once.



are only a few photons, the amplitude and phase exhibit relatively large quantum fluctuations. The field's state, called a coherent or Glauber state, is the analog of a Gaussian wave packet for a mechanical oscillator. The corresponding vector has a length equal to the square root of the average photon number, with a small uncertainty circle of radius unity at its tip.

The interaction with a single atom in the superposition state transforms the field into two vectors oriented along two different directions at once, symmetrical with respect to the initial field. (See figure 5.) The state of the atom-plus-field system can be written as:

$$|\psi\rangle = (|+, b\rangle + |-, c\rangle)/\sqrt{2}, \qquad (1)$$

where the field in each Dirac ket is represented by its vector.

Nonlocality

Here, as distinguished from the NIST ion experiment, the entanglement becomes *nonlocal* when the atom leaves the cavity. That imparts a distinctive EPR twist to our experiment. There is indeed no easy way to detect the field itself. The only practical way to get information is to detect the atom's energy and infer the field's state from it. The energy state is measured by selectively ionizing the atom in one of two detectors (D_+ or D_-) and collecting the resulting electrons. One gets the necessary energy selectivity by taking advantage of the fact that the threshold ionizing field is slightly different for the two Rydberg levels.

We must, however, take a final precaution if we want to preserve quantum weirdness. If we were to detect the atom directly after it leaves the cavity, we would find it in one or the other Rydberg state, and the field, in accordance with equation 1, would be projected into a well-defined Glauber state. The quantum ambiguity would be lost. To avoid this loss, we subject the atom, just before detection, to a second microwave pulse that remixes the two Rydberg states again. If the phase of this pulse is properly adjusted, $|+\rangle$ becomes $(|+\rangle + |-\rangle)/\sqrt{2}$ and $|-\rangle$ becomes $(|-\rangle - |+\rangle)/\sqrt{2}$. The cavity field is not affected.

The combined atom-plus-field system thus evolves into a new state:

$$|\Psi'\rangle = (+\rangle(|b\rangle - |c\rangle + |-\rangle(|b\rangle + (|c\rangle))/\sqrt{2} \qquad (2)$$

Each atomic state is now correlated to a superposition of coherent field states. We have the freedom to decide what kind of field state we will finally produce by choosing whether or not to apply the second microwave field pulse after the atom and the cavity have ceased to interact. A typical EPR paradox!

A quantum mouse

How can we detect the oscillator's quantum coherence? As in the ion trap experiment, we recombine the two state components and look for interference effects. The idea, first suggested in a paper we published in 1996 with Luis Davidovich from the Federal University of Rio de Janeiro,[11] is to send a second atom across the same apparatus after a delay. This second atom, identical to the first, plays the role of a quantum mouse probing the coherence of the cat state produced by the first atom. The probing atom is subjected to the same sequence of pulses. So, once again, it splits the phase of each field component in two. In this process, two parts of the system's wavefunction recombine with a unique final phase. When the first and second atoms traverse the cavity in different states, the second atom undoes the phase shift produced by the first.

This recombination leads to an interference term in the joint probability for finding the pair of atoms in any particular combination of the two Rydberg states. By repeating the experiment many times, we have reconstructed these joint probabilities and combined them to produce a two-atom correlation signal proportional to the interference term.

Repeating the experiment with increasing delays between the atoms, we found that the correlation, large at short times, vanishes as the delay increases. (See figure 6.) The loss of correlation is always faster than the damping of the field energy. It speeds up as the number of photons increases, becoming too fast to be observed when there are about 10. For a given field intensity, the decorrelation becomes faster when the angle between the field components increases.

These features are a direct demonstration of decoherence at work in a well-controlled situation. Because the part of the field scattered away by mirror defects is a smaller, entangled copy of the cavity field, it carries away crucial information about the field's phase. In principle, a leaking field with the intensity of only a single photon is large enough to yield information about its phase, provided that the two components are split by an angle on the order of one radian or more. At such an angle, the uncertainty disks of the two leaking field components are disjoint. If the splitting angle is small, extracting this phase information requires a somewhat larger leaking field. The mere fact that this information is available, even if it is not in fact read out, is enough to destroy, at a distance, the quantum coherence of the cavity field. Here, once again, complementarity manifests itself!

The time it takes for the first photon to escape is the average photon damping time divided by the mean photon number. This first-photon-escape time becomes shorter and shorter as the field energy stored in the cavity is increased. If the probe atom arrives after this first escape time, the cavity field has become an incoherent statistical mixture and all interference effects in the two-atom correlation are lost. This argument agrees well with our observations, as shown in figure 6 together with predictions calculated from decoherence theory.

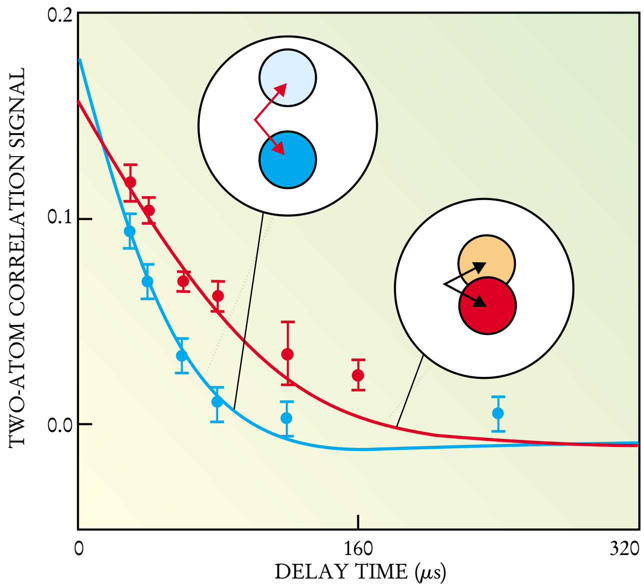


FIGURE 6. TWO-ATOM CORRELATION signal, which measures the coherence of the Schrödinger-cat cavity field produced by the first atom in the Paris experiment,[10] decreases with increasing time delay before sending the second atom. The two data sets correspond to two different dephasing angles between the cavity field "cat state" components. The field contains, on average, 3.3 photons. Decoherence is faster when the phase separation between cavity field components is larger. Then the decoherence time is about three times faster than the 160-μs field-energy decay time. The curves show decoherence theory predictions.

The fragility of coherence

The two-atom experiment gives us a visceral feeling for the extreme fragility of quantum coherences between macroscopically distinct states. The coherence vanishes as soon as a single quantum is lost to the environment. So we understand why real cats, or even much smaller objects made of enormous numbers of molecules, lose coherence immediately.

The experiment's connection with quantum measurement theory[12] is also striking. Consider, for the sake of argument, that it is the cavity field that's observing the atom, and not the other way around. The field can indeed be seen as a meter pointing in different directions according to the state of the atom, thus realizing a first step in an ideal atomic energy measurement. To complete the process, one would have to detect the field by amplifying it and then coupling it to a phase-sensitive radiation detector.

We recognize here the chain of operations, first described by John von Neumann, that connects by successive steps a microscopic object to the observer.[12] If all the instruments along this chain simply obeyed the linear evolution equations of quantum mechanics, they would get entangled into state superpositions of the kind described by equation 1, all the way up to the macroscopic level.

Collapsing the wavefunction

Such superpositions are, of course, never observed. One finds instead that the meter points randomly here or there. That's the state of affairs postulated by the orthodox Copenhagen interpretation of quantum mechanics, which enjoins us to disregard superpositions of apparatus states and to "collapse" them instantaneously to one of the possible meter states, the probability for any one of those meter readings being given by the absolute square of the corresponding wavefunction amplitude.

By contrast, the proponents of the modern decoherence theories prefer to view this wavefunction collapse as a real physical process caused by the coupling of the measuring apparatus to its environment. For all practical purposes, of course, the orthodox and decoherence points of view are equivalent, because the decoherence time is infinitesimal for any measurement that ultimately involves a macroscopic apparatus.

Our atom–cavity experiment, however, by isolating a first stage involving a mesoscopic meter in the measurement chain, has allowed us to catch the elusive moment when the meter loses its coherence. The choice of basis states in which decoherence occurs is also an important issue. Before decoherence, the entanglement between the microscopic system and the measuring apparatus describes possible correlations in all possible basis-state representations. (Compare equations 1 and 2.) The coupling to the environment, however, favors one basis of "robust" coherent states over other, very fragile superpositions. In that representation, all the weird EPR-like correlations that would otherwise introduce a fundamental ambiguity into the measurement process are destroyed.

In both the atom–cavity and ion trap experiments, quantum mechanics predicts a statistical distribution of outcomes over many repetitions of the experiments. Nothing more specific can be said *a priori* about the outcome of any one trial. Even when quantum coherence has vanished, we still have, in each run, two possible outcomes. The agency of choice remains mysterious. Attempts have been made to modify the quantum theory by adding subtle mechanisms that would "explain" quantum choice in systems with macroscopic components.[13] Whether such theories will be successful and lead to testable experimental predictions remains dubious.

Unless these unorthodox approaches are eventually vindicated, it seems, to paraphrase the disapproving Einstein, that God does indeed play dice. The atom–cavity Schrödinger's cat experiment does not address this ultimate mystery, but at least it offers us a glimpse at the process by which this dice game proceeds from the quantum mechanical (with the cat both dead *and* alive) to the classical realm (where the cat is either dead *or* alive).

These experiments are first steps along a challenging road. Entangling atoms and photons together in a controlled manner will open the way to fascinating applications. Two-level atoms and two-state vibration modes of quantum oscillators can be regarded as binary "quantum bits" in which information could be stored and manipulated in quantum computers by the promisingly permissive rules of quantum logic.[14] Following an idea of Ignazio Cirac and Peter Zoller at Innsbruck University, Wineland's group has already demonstrated with a single ion in a trap the elementary operation of a quantum gate.[15] Our group and Jeffrey Kimble and coworkers at Caltech have also shown that atom–cavity experiments can be turned into elementary quantum information processing machines.[16] (See PHYSICS TODAY, March 1996, page 21.) We have also recently achieved controlled entanglement of atoms crossing a cavity one at a time.[17] In a related area, quantum teleportation based on entanglement, proposed by Charles Bennett and coworkers 1992, has recently been demonstrated.[18] (See PHYSICS TODAY, February 1998, page 18, and the article by Bennett in the October 1995 issue, page 24.)

How big will Schrödinger cats eventually become, and how far can the quantum/classical boundary be pushed? These remain open questions. Decoherence becomes more and more efficient as the size of a system increases. It protects with a vengeance the classical character of our macroscopic world. That makes large-scale practical quantum computing a very distant dream, to say the least. (See the article by Haroche and Raimond in PHYSICS TODAY, August 1996, page 51.) In the meanwhile, experimenters will go on breeding all kinds of Schrödinger kittens made of a few particles, in the hope of learning more about the fascinating mysteries of quantum mechanics.

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