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Generation of Einstein-Podolsky-Rosen Pairs of Atoms

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Pairs of atoms have been prepared in an entangled state of the Einstein-Podolsky-Rosen (EPR) type. They were produced by the exchange of a single photon between the atoms in a high Q cavity. The atoms, entangled in a superposition involving two different circular Rydberg states, were separated by a distance of the order of 1 cm. At variance with most previous EPR experiments, this one involves massive particles. It can be generalized to three or more atoms and opens the way to new tests of nonlocality in mesoscopic quantum systems. [S0031-9007(97)03502-3]

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One of the most puzzling aspects of quantum mechanics, its nonseparability, is illustrated vividly by the famous Einstein-Podolsky-Rosen (EPR) paradox [1]. A pair of particles flying apart from each other is predicted by quantum mechanics to yield measurement results incompatible with our intuitive conceptions about locality and reality. Such a nonclassical behavior is expected from any system made of two parts whose wave function cannot be written, in any basis, as a direct product of independent substates. The system parts are then said to be entangled. The study of entanglement has been given a firm conceptual ground by Bell who derived inequalities that Nature should obey if locality and reality were respected and which are violated by quantum mechanics [2]. Many experiments since Bell's paper have demonstrated violations of these inequalities and have vindicated quantum theory [3–7].

In most EPR experiments so far [3,4,6,7], pairs of photons flying apart are created in a correlated state by a radiative process (spontaneous emission cascade in an atom or down-conversion in a nonlinear medium). Entangled protons have also been studied in an early experiment [5]. All these studies have dealt with very simple elementary particle systems, in which the entanglement mechanism is imposed by spontaneous processes.

Entangling more complex systems in a controlled way is a challenging goal, which has been discussed in many recent proposals. The generation of EPR pairs of massive atoms instead of massless photons has been considered [8–11]. Ideas to generalize entanglement to larger numbers of particles have also been analyzed [8,10,12].

The "manipulation" of entanglement is another important aspect of the new EPR experiment proposals. The idea is to apply a set of well-controlled interactions to the particles of the system in order to bring them into a "tailored" entangled state. In this context, the physics of entanglement meets the theory of quantum information processing. Teleportation of quantum states could in principle be achieved [13] as well as quantum cryptography [14]. Simple quantum computation steps could also be carried out. Particles can then be viewed as carriers of quantum bits of information and the realization of "engineered" entanglement is closely related to the building of gates acting on these bits [15].

We describe here an experiment in which we have entangled two initially independent atoms and analyzed their correlations. The entanglement procedure involves the resonant coupling, one by one, of the atoms to a high Q microwave superconducting cavity C. The atoms, prepared in circular Rydberg states [16], exchange a single photon in the cavity and become entangled by this indirect interaction. We have demonstrated the effect with pairs of atoms separated by centimetric distances and we have measured their correlations at a distance by a Ramsey interferometric method. This experiment can be generalized to atomic triplets or to larger numbers of

particles. It opens the way to a new class of entanglement experiments in mesoscopic systems.

Let us first describe the principle of the cavity induced entanglement in the ideal case of a perfect cavity having an infinite damping time [10]. Let us call e and g the two relevant Rydberg states of each atom and assume that the cavity, initially in its vacuum state, is exactly resonant with the atomic transition between these states (level e above level g). Two atoms enter successively the cavity. The first one is prepared in e and the second one in g. The initial state of the combined system is the uncorrelated tensor product $|\Psi\rangle = |e_1, g_2, 0\rangle$, where the last symbol in the ket refers to the photon number in C. Let us call Ω the vacuum Rabi frequency which defines the rate at which each atom and the cavity exchange a single photon. If the duration t_1 of the first atom interaction with C is such that $\Omega t_1 = \pi/2$, this atom has a probability $1/2$ of staying in e and leaving C empty and a probability $1/2$ of having emitted a photon and evolved into g. Between the passage of the two atoms across C, the combined system is described by the state

$$|\Psi'\rangle = \frac{1}{\sqrt{2}}\left(|e_1, g_2, 0\rangle - |g_1, g_2, 1\rangle\right), \qquad (1)$$

which corresponds to a maximum entanglement between the first atom and the cavity field.

The second atom, prepared in g, enters C after a delay T. Its interaction time with the field is set to the value $t_2 = 2t_1$, so that $\Omega t_2 = \pi$. If the first atom has left C empty, the second one stays in g without altering the field. If the first atom has emitted a photon, the second one absorbs it with unity probability and ends up in e. As a result, the combined system is left in the state

$$|\Psi_{\mathrm{EPR}}\rangle\,|0\rangle = \frac{1}{\sqrt{2}}\left(|e_1, g_2\rangle - |g_1, e_2\rangle\right)|0\rangle, \qquad (2)$$

which appears as a pair of atoms in a maximally entangled atomic state $|\Psi_{\mathrm{EPR}}\rangle$ in the presence of an empty cavity. The field, which starts and ends up in vacuum and remains at the end of the process decorrelated from the atoms, acts as a "catalyst" for the atomic entanglement.

A spin analogy describes the state of this EPR pair. The levels e and g can be seen as the "up" and "down" states of a fictitious spin $1/2$ quantized along an arbitrary Oz direction. The $|\Psi_{\mathrm{EPR}}\rangle$ state is the rotationally invariant "spin zero" state of the combined system. It can be written in the same way in another basis. For example, if the "spins" are quantized along a direction orthogonal to the initial one, the new spin eigenstates are of the form $|e\rangle \pm e^{i\phi}|g\rangle$, where ϕ is the angle of the new quantization axis in the xOy plane. We can rewrite the spin zero state, within an irrelevant overall phase factor, as

$$|\Psi_{\mathrm{EPR}}\rangle = \frac{1}{2\sqrt{2}}\left[\left(|e_1\rangle + e^{i\phi}|g_1\rangle\right)\left(|e_2\rangle - e^{i\phi}|g_2\rangle\right) - \left(|e_1\rangle - e^{i\phi}|g_1\rangle\right)\left(|e_2\rangle + e^{i\phi}|g_2\rangle\right)\right]. \qquad (3)$$

If the first particle is detected in the up state along the ϕ direction, the other one will certainly be found down along this direction and vice versa. The detection direction can be decided after the atoms have emerged from the cavity and ceased to interact with its field (delayed choice). This kind of perfect correlation, obtained whichever basis is chosen, cannot be explained in classical terms whatsoever. This is the essence of the EPR paradox.

The experimental setup, shown in Fig. 1, is a modified version of the one used in [17,18]. Rubidium atoms, effusing from an oven O and velocity selected in zone V, are prepared in box B in one of the two circular Rydberg states with principal quantum number 51 or 50 (respectively, e and g) before crossing the cavity C. The velocity selection is performed by emptying the $F = 3$ hyperfine ground state of Rubidium with a first optical pumping laser beam L_1 orthogonal to the atomic beam. This level is then repopulated with a second pulsed laser beam L_1' (duration 2 μs) whose direction makes a 55° angle with the atomic beam. Atoms having a well-defined velocity with a ± 30 m/s resolution are preselected, their mean velocity being determined by the frequency of the repumping laser (Doppler effect selection).

The circularization process [16] is a stepwise excitation which involves diode lasers L_2 exciting the previously velocity selected Rubidium atoms from the $F = 3$ ground state, followed by radio frequency transitions between Rydberg levels. This process is also pulsed, preparing at well-defined time (within a 2 μs window) about 0.13 circular atom on the average and adjusted to cut in the preselected atomic velocity distribution a very thin "slice" corresponding to an improved resolution of ± 0.4 m/s. From the knowledge of the pulse time and of the velocity, the position of each atom along its trajectory is determined at any time with a ± 1 mm precision, an essential feature which allows us to manipulate it at proper times when it flies across the apparatus.

An experimental sequence involves a pair of two circular atom pulses, leaving B in levels e and g, respectively (circular levels purity >95%), with a time interval T_0

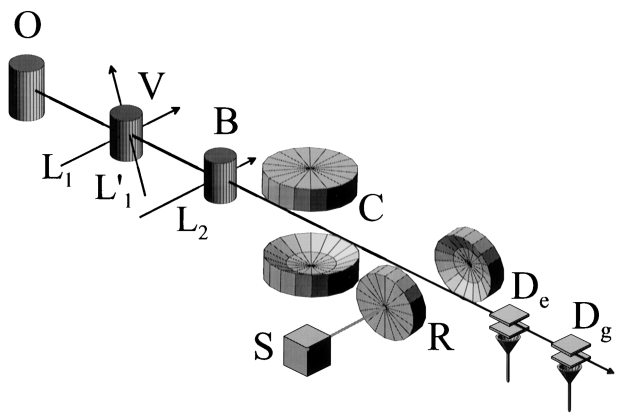

FIG. 1. Sketch of the experimental setup.

(0 to 100 μs) and velocities v_1 and v_2 fixed independently. The atoms of the pair cross the cavity one after the other, separated in C by a delay T determined by T_0, v_1, and v_2. We have checked experimentally that there are no Rydberg atoms outside the expected time and velocity windows. The whole sequence is repeated every 1.5 ms.

The superconducting microwave cavity C is made of two niobium mirrors in a Fabry Perot configuration (mirror separation 2.7 cm). It is cooled to 0.6 K. The mean blackbody photon number is negligible (it was measured to be only 0.05 at 0.8 K [17]). The relevant TEM_{900} cavity mode has a waist $w = 6$ mm and is slightly off resonant with the transition at 51.1 GHz between e and g (detuning 170 kHz). The cavity photon damping time is $T_{\rm cav} = 112$ μs, much shorter than the interval between two experimental sequences. Exact resonance between the atoms and the cavity is obtained by switching on a small electric field F_0 across the cavity mirrors while each atom is crossing C. The field F_0 tunes the Rydberg state transition in resonance by Stark effect. The Rabi frequency $\Omega/2\pi$ of the Rydberg atom transition resonant with the cavity mode is 48 kHz [17]. When F_0 is off, the atom-cavity coupling is negligible.

After leaving C, the atoms cross a low Q analyzing cavity R in which a $\pi/2$ classical microwave field Rabi pulse generated by a source S can be applied separately to each atom of each pair. Finally, the atoms reach the field ionization state selective detectors D_e and D_g for levels e and g, respectively, which determine their energy. The quantum efficiency is 35%. In 0.5% of the sequences, there is one atom detected in each of the two pulses ("useful events"), the probability of two atoms in a single pulse being very small ($<$1.5%). The pulse in R transforms an $(|e\rangle \pm e^{i\phi}|g\rangle)/\sqrt{2}$ state into $|e\rangle$ or $|g\rangle$, so that R followed by D can be viewed as a detector of the "spin state" of each atom in a direction of the xOy plane orthogonal to the initial Oz "quantization direction" (ϕ is the phase of the microwave pulse).

In a first calibration experiment, we fire only one atomic pulse in each sequence, in order to adjust the durations of the F_0 pulses corresponding to the $\pi/2$ and π Rabi pulses in C. We adjust t_2 by maximizing the probability of flipping an atom initially in level e to level g. The $\pi/2$ pulse duration is adjusted in a similar way by equalizing the transition probability in C to the value 1/2.

Once the Rabi pulses are calibrated, we perform the EPR correlation experiment. We fire pairs of atomic pulses and keep only the "useful events." We first detect the state of the atom when the microwave pulse in R is switched off, which is equivalent to measuring the up and down spin states of the EPR pair along the Oz direction. The chosen parameters are $T_0 = 100$ μs, $v_1 = 337$ m/s, and $v_2 = 432$ m/s. The second atom is then catching up to the first one, their separation in C being $T = 26$ μs (distance between B and C: 9.95 cm). Averaging over 1000 coincidences, we find the joint probabilities $P_{eg} = 0.44$, $P_{ge} = 0.27$, $P_{gg} = 0.23$, $P_{ee} = 0.06$, with statistical errors of the order of 0.03.

For a pure EPR pair, these probabilities should be $P_{eg} = P_{ge} = 1/2$, $P_{ee} = P_{gg} = 0$. Several experimental imperfections account for the difference. These ideal values assume that the photon stays in C without decaying during the time interval T between the two atoms. The probability of such an ideal photon loss-free event is $P_{\rm cav} = \exp(-T/T_{\rm cav})$. When photon decay occurs, the energy exchange between the $|e_1, g_2\rangle$ and $|g_1, e_2\rangle$ states cannot happen, resulting in a decrease of the weight of the $|g_1, e_2\rangle$ component in the final state of the system. The statistical effect of the random photon decay is to transform $|\Psi_{\rm EPR}\rangle$ into a density operator which can be expanded as the sum of an EPR part of the form $P_{\rm cav}|\Psi_{\rm EPR}\rangle\langle\Psi_{\rm EPR}|$ plus additional non EPR contributions. The joint probabilities then become $P_{eg} = 1/2$, $P_{ge} = P_{\rm cav}/2$, $P_{gg} = (1 - P_{\rm cav})/2$, $P_{ee} = 0$, where $P_{\rm cav} = 0.79$. Moreover, the π pulse in C for the second atom has been measured in an auxiliary experiment to transfer only $P_{\rm Rabi} = 80\%$ of the atoms. We have also to take into account the imperfections of the detectors. D_e detects erroneously 13% of the atoms in g, D_g detects 10% of the atoms in e. Note that events where an additional undetected atom is present in one of the pulses do not play a significant role since the mean number of atoms is very low. Including all these effects, we get $P_{eg} = 0.42$, $P_{ge} = 0.27$, $P_{gg} = 0.21$, $P_{ee} = 0.10$, in good agreement with the experimental values. This indicates that our cavity QED atomic "entangler" works as expected and that we understand well its present limitations. Out of all the observed coincidences, a fraction $P_{\rm cav}P_{\rm Rabi} = 0.63$ corresponds to genuine EPR events.

In a subsequent experiment, we apply to each atom of the pair a $\pi/2$ "analyzing" pulse in R with a frequency ν close to the $e \rightarrow g$ transition frequency ν_0. Figure 2

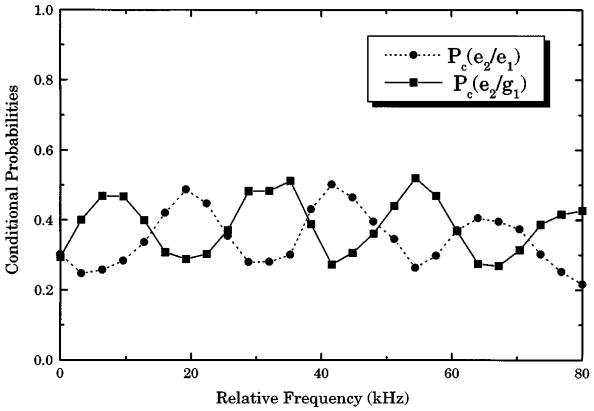

FIG. 2. Conditional probabilities $P_c(e_2/e_1)$ (circles) and $P_c(e_2/g_1)$ (squares) of measuring the second atom in level e when the first one has been found in e or g, respectively, plotted versus the frequency ν of the pulses in R. The lines connecting the experimental points have been added for visual convenience.

shows the detected conditional probabilities $P_c(e_2/e_1)$ and $P_c(e_2/g_1)$ of measuring the second atom in level e when the first one has been found in e or g, respectively. These probabilities are plotted versus the frequency ν of the R pulses. Statistics of 25 000 events are accumulated. The points are experimental and the curves connect them for visual aid. The following parameters have been chosen for these recordings: $T_0 = 30\ \mu$s, $v_1 = 413$ m/s, and $v_2 = 400$ m/s. The two atoms are spreading apart from each other, with a time interval $T = 37\ \mu$s in C and a maximum separation of 1.5 cm just before detection.

The observed signals are reminiscent of the Ramsey fringes [19] observed when two separated oscillatory fields are applied to a single atom, with the important difference that the two pulses are here applied to the different atoms of each pair. If the two atom state analyses occurred at the same time, we would again ideally expect, according to Eq. (3), an anticorrelation signal $P_{eg} = P_{ge} = 0.5$. The atoms reach R, however, at different times separated by an interval $T' = 42\ \mu$s. The detection of the first atom instantaneously determines "at a distance" the state of the second one which collapses into the state $|e\rangle - e^{i\phi}|g\rangle$ ($|e\rangle + e^{i\phi}|g\rangle$) if the first one has been detected in e (respectively, g) and then starts to precess at the Bohr frequency ν_0 until it is "caught up" by the pulse at frequency ν applied in R. The probability that this pulse brings the second atom in e or g depends upon the relative phase of the atomic precession with respect to that of the field in R at time T', resulting in a $\cos[2\pi(\nu - \nu_0)T']$ modulation of this probability. We find indeed an experimental period $\Delta\nu = 24$ kHz, very close to $1/T'$. The phase opposition between the $P_c(e_2/e_1)$ and $P_c(e_2/g_1)$ signals is also easy to understand. Detection of the first atom in e or g corresponds indeed to a collapse of the second atom state into two "transverse" spin states with opposite directions which precess π out of phase with respect to each other.

The correlation signals shown in Fig. 2 demonstrate the entanglement between the atoms. The modulation depth, 25% instead of the 100% ideal value, is understood by taking into account the various limitations described above, without forgetting the defects of the microwave analyzing pulses themselves (due to field inhomogeneities, the succession of two $\pi/2$ pulses in R flips the atom's state with a probability 0.6 instead of 1). We have checked that this modulation is a pure two-atom correlation effect (no modulation of the atomic populations when a single atomic pulse is sent in the setup).

We have shown that our Cavity QED setup can entangle with a "purity" larger than 0.63 two atoms separated by a macroscopic distance. The present limitations of the experiment can be improved by using a better cavity (values of $P_{\rm cav} > 0.98$ will be obtained with $T_{\rm cav} > 1$ ms, which is achievable with present technology) as well as by increasing the efficiency of our Rabi pulses. A "purity of entanglement" large enough to test Bell's inequalities with massive particles seems to be within reach. Preparation of atom triplets correlated in a Greenberger-Horne-Zeilinger configuration of the form $|e, e, e\rangle - |g, g, g\rangle$ [20] is also possible by simple generalization of our entanglement procedure involving a combination of resonant and dispersive atom-field couplings [12]. Applications to simple teleportation schemes involving two cavities have also been considered [13].

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