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Mesoscopic Coherences in Cavity QED (*).

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Summary. — The principles of cavity QED experiments are described, in which fields exhibiting coherences between different mesoscopic states are generated and studied. These experiments, based on the Ramsey method of atomic interferometry, are presently under way at Ecole Normale Supérieure, Paris. They will constitute tests of the quantum measurement theory and could open the way to interesting applications in quantum computing and cryptology.

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1. – Introduction: «Schrödinger cats» and macroscopic coherences in physics.

Professor Cini, who has always shown a great interest in the fundamental aspects of Quantum Theory, has explored in several papers the paradox of the measurement process in microphysics. This paper, which discusses some aspects of this paradox and suggests experiments to illustrate them, was presented at the Conference organized in his honour in Rome in February 1994.

The interference of probability amplitudes is at the heart of Quantum Theory. The reason why it is very hard to «understand» quantum mechanics comes from the fact that our classical intuition is based on the observation of nature at a macroscopic level, where probability of events merely adds up, without exhibiting interferences. We have thus developed an intuition of the world where interferences have no real place, making it for some people very hard to be at ease with the tricks of Nature at the microscopic scale. Quantum interference implies many puzzling concepts such as «non-locality» (a particle can be at the same time at different places) or non-local

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entanglement (manifestations of the so-called EPR paradox). Some of these effects can be very involved, but, as noticed once by Feynman, the difficulty of understanding quantum mechanics can always be reduced, *in fine*, to the basic interference problem encountered in the Young double-slit experiment.

Schrödinger has illustrated the difficulty of connecting the classical to the quantum worlds in his famous «cat paradox» [1], which can be described in very simple terms. According to quantum mechanics, microscopic systems may exist in superposition states, with the possibility of interference for the corresponding probability amplitudes. For example, a decaying particle is described, before any measurement is performed, as being in a superposition of the excited state and of the decaying product states. Furthermore, a microscopic event can trigger a macroscopic phenomenon in an avalanche process (detection of a single photon, for example). There is thus a direct connection, via the detection mechanism, between the micro- and the macro-worlds. This connection opens the possibility to copy, at the macroscopic scale, the superposition states of the micro-world. For instance, the photon emitted by a single microscopic decay event could be used to trigger a gun and kill a cat trapped in a closed box. Since there is at any given time an amplitude that the photon has been emitted and an amplitude that the microscopic system is still excited, does it mean that the cat is, before being observed (*i.e.* before the box is opened), in a linear superposition of the dead and alive states? The meaning of this statement may be discussed at various levels (physical, or philosophical). At the physical level, the only one relevant here, it is possible to give it a very simple and operational sense: if the cat is in a superposition state, it should be possible to design an experiment whose result would be sensitive to the interference between the «cat alive» and «dead cat» states. In other words, the physics of the cat in the box should be different from the classical situation where one knows that the cat is dead with a given probability or alive with the complementary probability, without interference between these two possibilities.

The cat paradox is important because it is directly connected to the theory of measurement in quantum physics [2]. In short, one may say that the cat is a macroscopic «meter» used to measure the photon emission process. The «dead cat» state corresponds to the position of the «meter» when the photon has been emitted, while the «cat alive» state corresponds to the position of the «meter» when the photon is not yet there. The fact that it is a complicated meter and a rather cruel measurement process is beyond the point (after all, canaries have been used to detect the level of carbon monoxyde in coal mines!). One could as well replace the cat by a «needle» with two positions and rephrase the discussion in similar terms. The real question is «why do we never observe interferences between the states of a macroscopic needle?» or «why does a needle sets instantaneously into one or the other position?» (why do we observe only dead or alive cats and never anything in between?). Stated in this way, the cat paradox is obviously related to the problem of the wave function collapse in quantum mechanics [2].

The measurement (or cat's) paradox has been discussed at length during the last six decades and many explanations have been given for the non-observation of quantum coherences at the macro-level. An interesting summary of this problem may be found in Leggett's *Les Houches Lectures* in 1986 [3]. One line of explanation, proposed among others by Cini [4], says that the large size of the measuring device makes it impossible to distinguish, for all practical observables, between the pure state vector of the total «object + apparatus» system and a statistical and essentially classical description in terms of a density matrix. Another line of explanation invokes the irreversible damping of the macroscopic coherences, due to the unavoidable coupling of the system to its large-size environment [5]. This environment might be, for example, the radiation field, the emission of a single photon by the system being enough to destroy the macroscopic quantum coherence. An important parameter in all these discussions is the size of the apparatus, in short the size of the «needle». Since the quantum coherence does exist at the microscale of small systems and disappears at the large scale of macroscopic objects, there should be an intermediate «mesoscopic» scale at which the decoherence process should be experimentally accessible.

2. – From «Gedanken» to real experiments in mesoscopic coherence studies: the principle of the cavity QED experiments.

Up to recently, the study of quantum coherence at the mesoscopic level was utopic and all the discussions of Schrödinger cat situations belonged to the realm of «Gedankenexperiments». Owing to many technological progresses, this is no longer the case now. At least two experimental domains, the physics of superconducting junctions [3, 6] and quantum optics [7-14], offer real possibilities to prepare in the laboratory superpositions of states with macroscopic, or more precisely «mesoscopic» sizes and to witness their decoherence. In this article, the status of the quantum optics experiments performed at Ecole Normale Supérieure (ENS) will be presented. The interest of these experiments is to give a concrete illustration of the main ideas briefly discussed above and to relate, on a simple example, various intriguing concepts of quantum mechanics such as non-locality, entanglement, superpositions and interferences....

The new domain of Quantum Optics where such experiments have become possible is called «Cavity Quantum Electrodynamics» [9]. Cavity QED, as it is usually abbreviated, deals with individual atoms and a few photons coupled together in an electromagnetic resonator. Due to recent progresses in the technology of high-Q cavities and in atomic-beam manipulation, photons could now be continuously observed in a cavity and counted non-destructively, in a way quite similar to the counting and manipulation of material particles [10-14]. «Einstein-Podolsky-Rosen» (EPR) situations [15], involving atoms correlated at macroscopic distances via their interaction with a cavity field could be studied [16]. More to the point of our present discussion, non-classical fields could also be generated in high-Q cavities [11, 12, 14, 17, 18], which would display some of the properties discussed by Schrödinger in the cat paradox. Fields which are superpositions of states corresponding to different phases or amplitudes could be generated and studied. Fields occupying two or more cavities, with a quantum coherence between the states localized at different places could also be studied [18]. These fields could be made of a relatively large number of photons, up to a few tens likely, making the scale of these systems somewhat intermediate between the truly microscopic single-photon scale and the macroscopic dimension of large classical fields.

A simple Rydberg-atom–superconducting-cavity set-up, sketched in fig. 1, can be used to prepare and study these mesoscopic states. The principle of the system operation is quite simple. An atomic beam, emerging from an oven O, crosses the cavity C. The atoms are prepared, before entering C into a superposition of Rydberg

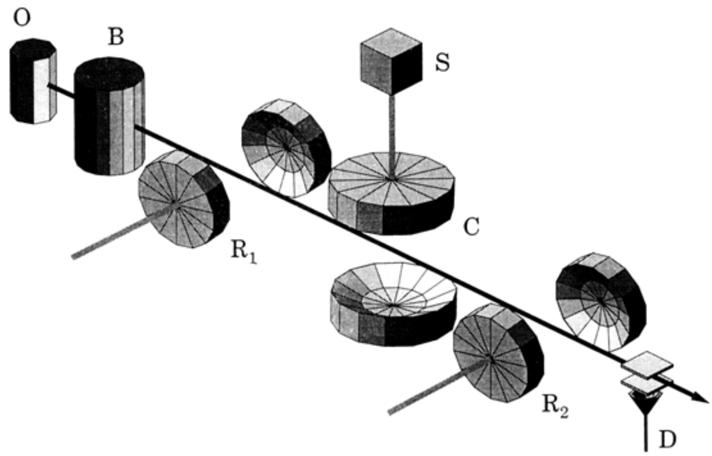

Fig. 1. – Sketch of the circular Rydberg-atom–superconducting-cavity set-up for mesoscopic field state studies.

states $|e\rangle$ and $|g\rangle$ of different energies. The preparation into state $|e\rangle$, which involves laser and radiofrequency excitation, takes place inside the preparation box B. A microwave cavity R_1 between B and C is then used to apply a resonant pulse on the atoms, admixing the intially prepared Rydberg state $|e\rangle$ with another state $|g\rangle$ of slightly different energy. In this way, an initial atomic state of the form $c_e|e\rangle + c_g|g\rangle$ is injected into C. The coefficients c_e and c_g can be adjusted at will by choosing the parameters of the microwave pulse applied in R_1. In the following discussion, we choose for the sake of simplicity $|c_e| = |c_g| = 1/\sqrt{2}$ (corresponding to a $\pi/2$ microwave pulse in R_1). The atoms then interact with the field in C while crossing it. The cavity, fed by the microwave source S, sustains a mode whose frequency is slightly off-resonant with the transition linking $|e\rangle$ to $|g\rangle$ so that no energy exchange but only phase alterations can occur on the atom and the field systems. After leaving C, the atoms cross a second microwave zone R_2 identical to R_1 and are detected downstream by field-ionizing them and counting the resulting ions in the detector D. By adjusting the ionizing electric field, this detection can be made energy-sensitive and one can thus count the atoms in $|e\rangle$ and $|g\rangle$ and determine how the probability of finding them in either level is affected by the coupling with R_1, C and R_2 [9].

Let us focus here on important orders of magnitude. The atom-field coupling is characterized by the angular frequency Ω, which represents the rate at which the atom and the empty cavity exchange a photon at resonance (vacuum Rabi frequency) [9]. Typically, $\Omega/2\pi$ is equal to 25 kHz in our system. The quantum correlations produced by the atom-field interaction are destroyed in a time of the order of the atom and field relaxation times T_{at} and T_{cav}. The experiments must thus be carried out within a time shorter than T_{at} and T_{cav} and the conditions $\Omega T_{\mathrm{at}} \gg 1$, $\Omega T_{\mathrm{cav}} \gg 1$ must be fulfilled. Atoms prepared in circular Rydberg states with principal quantum number n around 50 appear as ideal tools to perform such experiments [19]. Circular states are a special kind of Rydberg states, in which the valence electron precesses in an orbit corresponding to the maximum possible value of the angular-momentum projection along the quantization axis [20]. Not only these atoms correspond to huge electric dipoles associated with very large Ω values, but they also have extremely long damping times T_{at}, in the 10^{-2} s range for $n = 50$. The preparation of these atoms, which occurs in the box B (fig. 1) is described in detail in [19]. The resonant frequency between the n and $n-1$ circular states (the e and g states of our present discussion) falls in the 50 GHz range for $n = 50$ (wavelength of about 0.6 cm). The high-Q cavity C coupled to the atom has thus a centimetre size. The cavity is made of separated mirrors facing each other, such a resonator being easy to tune (by displacing the mirrors). Moreover, the cavity can sustain a static electric field across the mirrors, which is very useful to maintain the direction and the shape of the circular orbit while the atom crosses the apparatus [21]. The cavity C, made of superconducting niobium cooled at 1 K or below, and submitted to a proper surface treatment, has a damping time in the millisecond range ($Q \cong 10^8$). This is longer than the flight time of thermal-velocity atoms over a distance of the order of a few centimetres from C to D, a condition required to keep quantum coherences alive during the experiment.

This set-up is an interferometer quite similar to a Young double-slit apparatus. The first zone R_1 prepares atoms in a linear superposition of atomic states which undergo different «histories» while the atom crosses C, with a probability amplitude for each. The second zone R_2 admixes again the two parts of the atomic wave function, before detection occurs. The probability of detecting the atom in $|e\rangle$ or $|g\rangle$ may then exhibit an interference term, which oscillates between 0 and 1 when the frequency ν of the microwave field applied in R_1 and R_2 is varied. This modulation is known as a «Ramsey fringe» signal [22]. The spatial interference of the usual Young interferometer is here replaced by an interference in time, and there is a close analogy between Young and Ramsey fringes. The interaction of the atom with a field in C may affect differently the two probability amplitudes associated with levels $|e\rangle$ and $|g\rangle$, resulting in a shift of the Ramsey-fringe pattern whose measurement yields

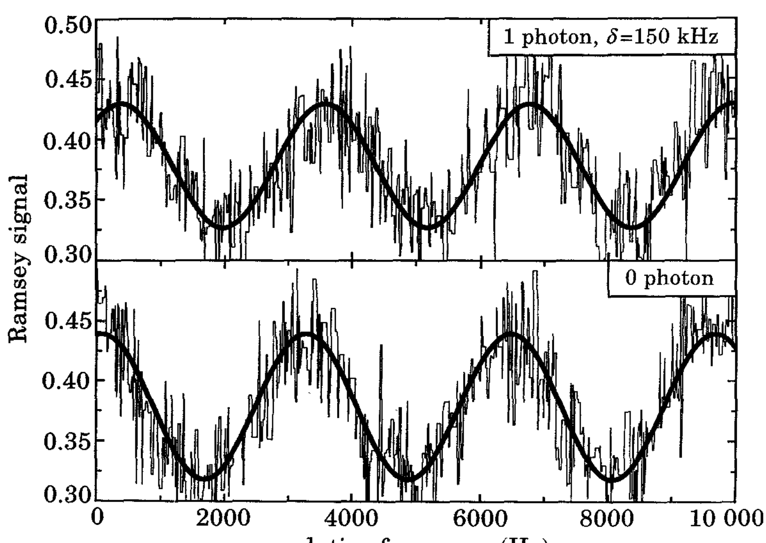

Fig. 2. – Population transfer signal between the circular Rydberg levels $|e\rangle$ ($n = 51$) and $|g\rangle$ ($n = 50$) as a function of the frequency ν applied in the microwave zones R_1 and R_2. The cavity (detuned by $\delta = 150$ kHz from the atomic transition) contains zero photons (lower trace) or one photon on average (upper trace). The translation of the Ramsey-fringe pattern reveals the dispersive light shift produced by subphoton fields (from ref. [23]).

a precious information about the atom-field interaction. Figure 2 shows as an example a typical recording of the fringes obtained with this Ramsey interferometer when the cavity is empty (lower trace) and when it contains on average one photon (upper trace). In this experiment, the atomic transition and the cavity mode are detuned by $\delta = 150$ kHz, the non-resonant atom-field interaction leading to small energy shifts of the levels $|e\rangle$ and $|g\rangle$. This experiment, described in detail in [23], demonstrates that our circular Rydberg-atom–cavity system has the sensitivity required to observe a single photon and to carry out the experiments discussed below.

Since the cavity and the atomic transition are slightly mistuned, with a frequency difference δ, any exchange of energy between atom and field is made impossible. The atom-field coupling is then purely dispersive and the atom can be viewed as a purely «measuring device» for the field initially stored in C [10, 11]. The interaction then produces a mere dephasing of the field (index effect of the atom crossing C) and also dephases the atom's wave function by an angle depending upon the number of photons in the cavity and of the quantum state of the atom. More precisely, if N photons are present in the cavity, the initial state of the «atom + field» system is $|\Psi_1\rangle = c_e|e, N\rangle + c_g|g, N\rangle$ and immediately after the atom has crossed C it becomes $|\Psi_2\rangle = c_e \exp[i\varepsilon(N+1)t]|e, N\rangle + c_g \exp[-i\varepsilon Nt]|g, N\rangle$, where t is the atom-cavity crossing time. The Bohr frequency of the atomic transition is shifted by $\varepsilon(2N+1)$, where the quantity $2\varepsilon = 2\overline{\Omega^2}/\delta$ is the frequency shift per photon of the atomic transition, averaged over the trajectory of the atom across the cavity. This shift is precisely the quantity measured in the experiment described above [23] (see fig. 2). Note that, in addition to the light shift effect (terms proportional to N in the argument of the exponentials appearing in the expression of $|\Psi_2\rangle$ above), there is even for $N = 0$ a shift of the upper Rydberg level $|e\rangle$ ($+1$ term in the argument of the first exponential in the expression of $|\Psi_2\rangle$). This is the «Lamb shift» produced by the vacuum field in the cavity [23].

Let us now study the effect produced by an atom on a coherent state of the field $|\alpha\rangle$ [24]. This state is characterized by its complex amplitude α and can be expressed as a superposition of different photon numbers states, $|\alpha\rangle = \sum_N C_N |N\rangle$ with $C_N = \exp[-|\alpha|^2/2][\alpha^N/\sqrt{N!}]$. It can be produced by coupling C to a classical source of current (S in fig. 1) which is switched off immediately before the atom is sent across the apparatus. After the atom has left the cavity, the state of the «atom + field» system is expressed as the superposition:

$$(1)\qquad |\Psi_3\rangle = c_e \exp[i\varepsilon t]|e\rangle\left\{\sum_N C_N \exp[i\varepsilon Nt]|N\rangle\right\} + c_g|g\rangle\left\{\sum_N C_N \exp[-i\varepsilon Nt]|g\rangle\right\} =$$

$$= c_e \exp[i\varepsilon t]|e, \alpha\exp[i\varepsilon t]\rangle + c_g|g, \alpha \exp[-i\varepsilon t]\rangle .$$

Clearly, an atom in $|e\rangle$ (respectively, in $|g\rangle$) dephases the field in the cavity by the angle $+\varepsilon t$ (respectively, $-\varepsilon t$). This is a mere index effect, obtained at the single-atom level. If the atom is in a linear superposition of the two levels, the phase shift results in an entanglement of the system after the interaction, the internal state of the atom being correlated to the phase of the field in the cavity. The number of photons in C cannot be changed by the atom-field interaction and the entanglement results from a purely dispersive phase shift distorsion of the wave function, different for each photon number and atomic state.

If the microwave zone R_2 is left inactive, measuring the atom's state in D results in the collapse of the field phase to a single value, leaving the field in either the state $|\alpha \exp[i\varepsilon t]\rangle$ or the state $|\alpha \exp[-i\varepsilon t]\rangle$. A very interesting situation arises when a $\pi/2$ microwave pulse mixing levels $|e\rangle$ and $|g\rangle$ is applied on the atoms in R_2. Then, the atom + field state immediately after the atom leaves R_2 becomes

$$(2)\qquad |\Psi_4\rangle = c_e(\exp[i\varepsilon t]/\sqrt{2})[|e, \alpha\exp[i\varepsilon t]\rangle + |g, \alpha\exp[i\varepsilon t]\rangle] + \\ +(c_g/\sqrt{2})[|g, \alpha\exp[-i\varepsilon t]\rangle - |e, \alpha\exp[-i\varepsilon t]\rangle$$

and the subsequent detection of the atom in level $|g\rangle$ or $|e\rangle$ results in the collapse of the field into one of the two states:

$$(3)\qquad |\Phi^{\pm}\rangle = c_e \exp[i\varepsilon t]|\alpha\exp[i\varepsilon t]\rangle \pm c_g|\alpha\exp[-i\varepsilon t]\rangle .$$

These are linear superposition of field states with different classical phases which, for obvious reasons, have been dubbed «Schrödinger cat states» of the field [7]. This scheme of «Schrödinger cat» state preparation involving the dispersive interaction of a single atom with a coherent field was described first in ref. [8] and its first discussion in the context of Ramsey experiments in cavity QED can be found in ref. [11].

The processes leading to the «cat states» are closely related to those involved in the EPR paradox [15]. The atom and the field in the cavity are entangled by their interaction. This entanglement survives the system separation. One subsystem (the field) collapses into a state which depends upon the result of the measurement performed on the other part (the atom), even if these two parts are far apart when this measurement is performed. The state into which this collapse occurs depends upon the kind of measurement one decides to perform (by adjusting the microwave parameters in R_2). This decision can even be made after the systems have ceased to interact (one can change these parameters while the atom is flying from C to R_2, thus realizing a «delayed choice» experiment). There is, however, a practical difference with the usual EPR situation which involves some correlation between the states of spin-like particles flying apart from each other. Here, we correlate a spin-like particle (the atom) to an harmonic-oscillator-like system (the field). Moreover, we know how to measure the «spin» (by the field ionization detection in D), but we do not have any convenient way of measuring directly the field stored in C. In fact, the only practical way to get information on the field is to couple it to atoms which are subsequently detected. We are thus naturally led to consider what happens if we send several atoms across the same cavity and perform correlated measurements on them.

3. – Witnessing the decoherence of the mesoscopic superposition (a proposal for an experiment in progress).

For the sake of definiteness, let us adjust the atom's parameters to the values $c_e = -i/\sqrt{2}$, $c_g = 1/\sqrt{2}$, $\varepsilon t = \pi/2$. Equation (3) then becomes

$$(4)\qquad |\phi^{\pm}_{\text{phase}}\rangle = (1/\sqrt{2})(|\beta\rangle \pm |-\beta\rangle)$$

with $\beta = i\alpha$. The field in the cavity is then prepared in a linear superposition of two coherent-field states with opposite phases. These particular superpositions are even (respectively, odd) photon number states when the sign in eq. (4) is + (respectively, $-$). These Schrödinger cat states have been studied extensively in theoretical papers [11, 25-28]. Cavity QED provides for the first time a practical means not only to generate, but also to detect them.

We have described elsewhere [17] a possible way of probing the coherent nature of the state superposition enabling us to distinguish between a field described by eq. (4) and a mere statistical mixture of the $|\beta\rangle$ and $|-\beta\rangle$ field states. The method consists in sending a second atom after the first one and to measure the conditional probability of detecting both atoms in the same or in different states. This probability presents an interference term between two probability amplitudes, one associated to each of the $|\beta\rangle$ and $|-\beta\rangle$ states. This interference is constructive for the probability of detecting the second atom in the same state as the first one, making this conditional probability equal to 1 and destructive for the probability of the second atom to be detected in a state different from the first one, making this conditional probability equal to zero. If the field in C is instead in a statistical mixture, the interference vanishes and both conditional probabilities level off to 1/2.

We have neglected in the analysis so far the relaxation of the field in the cavity [11]. Dissipative processes have a strong effect on these quantum superpositions. In a time of the order of $T_{cav}/\overline{N}$, where $\overline{N} = |\alpha|^2$ is the average number of photons in the coherent field, they evolve into a classical statistical mixture. The time $T_{cav}/\overline{N}$ appears indeed as the average time for the absorption of the first photon from the field in the cavity walls. As soon as this first photon has been lost, the quantum coherence has essentially vanished, a quite general feature of this kind of mesoscopic coherences. We thus expect the conditional probability of detecting the first and the second atom in the same (or in different) quantum state to be a function of the delay T between the two atomic detections. Figure 3 shows the predicted evolution of the conditional probability to detect the two atoms in different states as a function of T. For short delays ($T \ll T_{cav}/\overline{N}$), this probability should be close to 0. For large delays ($T_{cav}/\overline{N} \ll T \ll T_{cav}$), it should take the value 1/2. The continuous change of this probability from 0

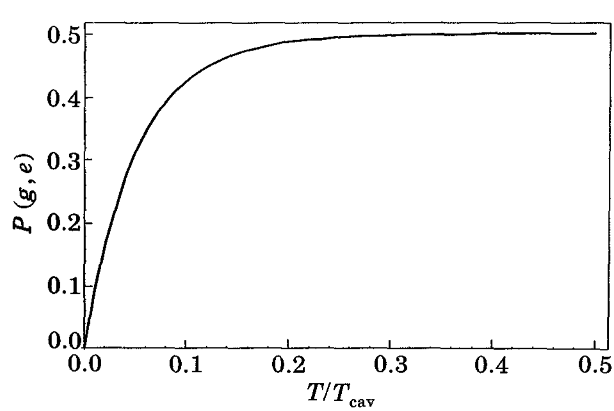

Fig. 3. – Probability $P(g, e)$ to detect the atom preparing the «cat state» and the subsequent probe atom in different levels (g and e, respectively), as a function of the delay T between the two atoms (10 photons on average in the cavity). The variation of this probability from 0 to 0.5 over a time of the order of $T_{cav}/10$ reveals the decay of the mesoscopic coherence in the cavity (from ref. [17]).

to 1/2 as T is increased should be a direct evidence of the «Schrödinger cat» decoherence.

As discussed in the introduction section, it is possible to interpret the phase of the field in C as a kind of «needle» pointing in two possible directions, each direction being correlated to one of the two Rydberg states $|e\rangle$ or $|g\rangle$ of the first atom crossing C (see eq. (1)). This «needle» remains for some time in a quantum superposition of its two possible classical positions, but in the end it chooses one or the other (when the quantum superposition has evolved, due to the field dissipative coupling to its environment, into a statistical mixture). For «small needles» ($N = |\alpha|^2 = 1$), this decoherence occurs in the relatively long time T_{cav}. For «mesoscopic needles» ($N = |\alpha|^2 = 10$ to 100), the decoherence becomes much faster, but should still be observable. Since we can adjust the intensity of the field initially present in the cavity from small to large values of N, such an experiment would enable us to explore the fuzzy boundary between the quantum world (where «small needles» are, at least for some time, quantum objects existing in several possible states susceptible to create interference effects), and the classical world (where «large needles» decohere into mutually exclusive states much faster than the velocity at which they can be observed).

We have discussed so far the preparation and study of «phase cats» of the field. Other kinds of cats can be generated with simple variants of this cavity QED set-up. Instead of preparing a coherent field inside the cavity prior to the first atom injection, it is possible to employ the atom itself as a kind of «quantum switch» governing the flow of the field inside the cavity [18]. The cavity must then be connected to a classical source slightly mistuned, so that, in the absence of an atom, it cannot feed any field inside C. The atomic parameters are then adjusted so that an atom crossing C in level $|e\rangle$ provides exactly the mode frequency shift required to tune it into resonance with the source. On the other hand, the atom in level $|g\rangle$ leaves the cavity and the source mistuned. We take again here advantage of the single-atom index effect, the atom behaving as a kind of dispersive «plunger» tuning C in and out of resonance with the source. Such a device allows us to prepare «amplitude cat

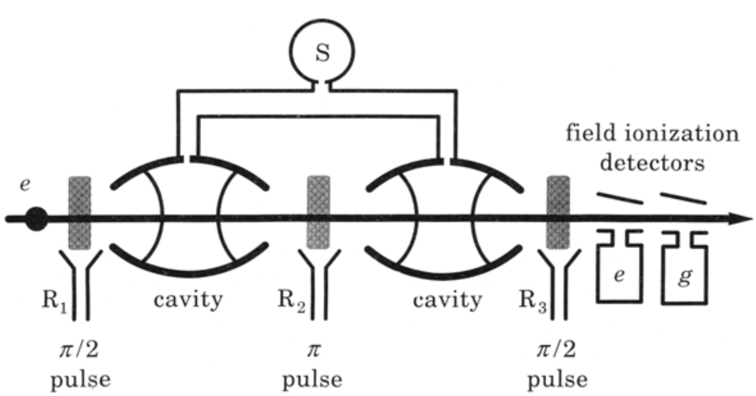

Fig. 4. – Set-up for the preparation of a field delocalized in two cavities (an experiment in project). The source S feeds both cavities through a T-shaped waveguide. An atom sent across both cavities acts as a switch. The state of the switch is controlled by the pulses applied in the zones R_1 and R_2. The non-local field is prepared when the atom is detected by the field ionization detectors, following a $\pi/2$ pulse applied in zone R_3 (adapted from ref. [18]).

states» of the form $|\phi^{\pm}_{\text{amplitude}}\rangle = (1/\sqrt{2})(|\alpha\rangle \pm |0\rangle)$, whose coherence can also be tested by sending a second atom across the system and measuring the conditional probability that both atoms end up being detected in the same or in different quantum states.

The quantum switch can also be used to generate non-local cat states in two identical cavities C_1 and C_2 [18] (see fig. 4). The two cavities are now coupled symmetrically to a slightly mistuned source and a single atom is sent across both cavities. A microwave zone R_1 in front of C_1 prepares again the atom in a linear symmetrical superposition of $|e\rangle$ and $|g\rangle$ states, realizing the quantum switch device. A π microwave pulse applied in zone R_2 turns $|e\rangle$ into $|g\rangle$ between C_1 and C_2 and exchanges the open and closed states of the switch. The two levels $|e\rangle$ and $|g\rangle$ are finally mixed again in the downstream zone R_3 before the atom is detected. In this way, one can generate the superposition state $|\phi^{\pm}_{\text{non-local}}\rangle = (1/\sqrt{2})(|\alpha; 0\rangle \pm |0; \alpha\rangle$, a non-local field with equal (or opposite) probability amplitudes for the coherent field to be in the first or in the second cavity (the first and the second symbol in each ket refer to the field in C_1 and C_2, respectively).

4. – Conclusion: feasibility and possible applications of these experiments.

We have presented the principles of cavity QED experiments aiming at generating and probing various mesoscopic «cat» states of the electromagnetic field. We have shown that all these experiments are exploiting the remarkable properties of a Ramsey atomic interferometer in which atoms are following two interfering paths across the cavity containing the field. This set-up is quite analoguous to a more familiar Young double-slit apparatus. In fact, we have analysed elsewhere [12] experiments with a Young design and shown that the strangeness of the «Schrödinger cat» is deeply related to the behaviour of a particle which follows two paths at the same time and is used to control the evolution of a macro- or meso-scopic system. In its Young version, the experiment is of the «Gedanken» type, since many orders of magnitude on several key parameters would have to be gained to make it feasible [12]. The Ramsey version is realistic, though, and we have already demonstrated the operation of an interferometer able to detect the phase shifts produced by less than one photon on average in the cavity [23], a key condition for the observation of the «cat states». We are left with the important task of demonstrating that this state can be protected well enough against relaxation. The cavity damping time T_{cav} must be long enough so that the quantum coherence can be observed over times T_{cav}/N longer than the atom-cavity transit time 10^{-5} to 10^{-4} s), with N of the order of 10 at least. Recent progresses in the technology of open superconducting cavities at ENS, in which cavity damping times of the order of 10^{-3} s have been achieved, show that this condition can be fulfilled and open encouraging perspectives for Schrödinger cat state experiments in the near future.

Beyond testing fundamental laws of quantum mechanics, these experiments could lead to interesting applications. Quantum switches [18] exhibiting coherence between their open and closed states would open the possibility of realizing new kinds of gates for computers, operating according to quantum logics, as opposed to the classical logic of usual computers. Such quantum computers, which would manipulate probability amplitudes instead of classical bits of information, are now being seriously considered and studied by mathematicians [29]. Cavity QED experiments of the kind discussed above seem very promising to demonstrate the feasibility of quantum logic gates [30]. Cryptography [31] and particle teleportation [32] are other possible domains of application of these experiments. Sharing EPR entangled particles between two observers wishing to exchange secretely information has been proposed as a way to produce unbreakable quantum cryptographic keys [31]. It has also been suggested that sharing EPR pairs of particles could be used in principle as a way of teleporting an unknown quantum state from one observer to the other [32]. Cavity QED experiments of the kind analysed above could be very useful to implement in practice these ideas. We have shown, for example, that a field delocalized between two cavities could be used instead of the EPR pair of particles to teleport the state of a Rydberg atom from one cavity to the other and to achieve in this way teleportation in a realistic experiment [33]. Clearly, many fascinating fields of quantum optics would be opened by the demonstration of the existence of mesoscopic coherences in cavity QED experiments.

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