Observation of Quantum Collapse and Revival in a One-Atom Maser

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The dynamics of the interaction of a single Rydberg atom with a single mode of an electromagnetic field in a superconducting cavity was investigated. Velocity-selected atoms were used and the evolution of the atomic inversion as atom and field exchange energy was observed. The quantum collapse and revival predicted by the Jaynes-Cummings model were demonstrated experimentally for the first time. The evaluation of the dynamic behavior of the atoms allows us to determine the statistics of the few photons in the cavity.

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Recent experiments with the one-atom maser[1] have demonstrated that it is possible to study the interaction of a single atom with a single mode of a resonant electromagnetic field in a cavity.[2,3] The atoms used in these experiments were Rydberg atoms with a very large principal quantum number n. The probability of induced transitions between closely adjacent states becomes very large and scales as n^4. Since the lifetime for spontaneous transitions is also very large, and scales proportionally to n^3 and n^5 for low- and high-angular-momentum states, respectively, the saturation power fluxes for transitions between neighboring states becomes extremely small. If this flux is expressed in terms of the number of photons per square of the transition wavelength λ and lifetime (the size λ^2 corresponding to the resonant cross section), one obtains (for $n \cong 30$) 10^2 and 1 for low- and high-angular-momentum states, respectively. This means that a few photons are able to saturate a transition.

Another important ingredient of the one-atom maser is the superconducting cavity: The quality factor is high enough for a periodic energy exchange between atom and cavity field to be observed; i.e., the relaxation time T_c of the cavity field is larger than the characteristic time of the atom-field interaction, which is given by the reciprocal of the Rabi frequency.

The situation realized in the one-atom maser approaches the idealized case of a two-level atom interacting with a single quantized mode of a radiation field as treated by Jaynes and Cummings many years ago.[4] It is therefore now possible to perform experiments on the dynamics of the atom-field interaction predicted in this theory. Some of the features are explicitly a consequence of the quantum nature of the electromagnetic field: The statistical and discrete nature of the photon field leads to new dynamic characteristics such as collapse and revivals in the Rabi nutation. The first experimental observation of the predicted effects are reported in this paper.

First we review the main results of the Jaynes-Cummings model with respect to the atomic dynamics. We consider a two-level atom in the excited state which enters a resonant cavity with a field of n photons. The probability $P_{e,n}$ of the atom to be in the excited state is then given by

$$P_{e,n}(t)=\tfrac{1}{2}\{1+\cos[2\Omega(n+1)^{1/2}t]\}, \qquad (1)$$

where Ω is the single-photon Rabi frequency. With a fluctuating number of photons initially present in the cavity, the quantum Rabi solution needs to be averaged over the probability distribution $p(n)$ of having n photons in the mode at $t=0$ [5,6]:

$$P_e(t)=\tfrac{1}{2}\sum_{n=0}^{\infty}p(n)\{1+\cos[2\Omega(n+1)^{1/2}t]\}. \qquad (2)$$

At a low atomic-beam flux, the cavity contains essentially thermal photons and their number is a random quantity conforming to Bose-Einstein statistics. In this case $p(n)$ is given by $P_{\mathrm{th}}(n)=\bar{n}_{\mathrm{th}}^{n}/(\bar{n}_{\mathrm{th}}+1)^{n+1}$, with the average number of thermal photons being $\bar{n}_{\mathrm{th}}=[\exp(h\nu/kT)-1]^{-1}$. The distribution of Rabi frequencies results in an apparent random oscillation $P_{e,\mathrm{th}}$. At higher atomic-beam fluxes the number of photons stored in the cavity increases and their statistics changes. If a coherent field is prepared in the cavity at $t=0$, the probability distribution $p(n)$ is given by a Poissonian: $p_c(n)=\exp(-\bar{n})\bar{n}^n/n!$. As first shown by Cummings, the Poisson spread in n gives a dephasing of the Rabi oscillations, and therefore $P_{e,c}(t)$ first exhibits a collapse.[5] This is described in the resonant case by the approximate envelope $\exp(-\Omega^2t^2/2)$ and is independent of the average photon number (this independence does not hold for nonresonant excitation). The collapse was also noted later in other work.[6] After the collapse there is a range of interaction times for which $P_{e,c}(t)$ is independent of time. Later $P_{e,c}(t)$ then exhibits recorrelations (revivals) and starts oscillating again in a very complex way. As has been shown by Eberly and co-workers the recurrences occur at times given by[7,8] $t=kT_R$ $(k=1,2,\ldots)$, with $T_R=2\pi(\bar{n})^{1/2}/\Omega$. Both collapse and revivals in the coherent state are purely quantum features and have no classical counterpart.

The inversion also collapses and revives in the case of a chaotic Bose-Einstein field.[9] Here the photon-number spread is far larger than for the coherent state and the collapse time is much shorter. In addition, the revivals completely overlap and interfere to produce a very irregular time evolution. A classical thermal field represented by an exponential distribution of the intensity also shows collapse, but no revivals. Therefore the revivals can be considered as a clear quantum feature, but the collapse is less clear-cut as a quantum effect.[9]

It is interesting to mention that in the case of two-photon processes the Rabi frequency turns out to be $2\Omega(n+1)$ rather than $2\Omega(n+1)^{1/2}$, enabling the sums over the photon numbers in $P_e(t)$ to be carried out in simple closed form. In this case the inversion revives perfectly with a completely periodic sequence.[10]

A highly collimated rubidium atomic beam (collimation ratio 1:2000) was used for the Rydberg-maser experiment.[1] The beam atoms pass through a Fizeau velocity selector (Fig. 1) consisting of 9 disks rotating with the same velocity. Each disk has 1486 radial slits close to the outer edge (width and distance 0.2 mm). The width of the velocity distribution of the atoms was 4%. Before entering the superconducting cavity, the atoms were excited into the upper maser level by means of the frequency-doubled light of a continuous-wave ring dye laser. The second harmonic was generated by a temperature-stabilized ammonium-dihydrogen-arsenate crystal. Linearly polarized light was used for the optical excitation; the vector of the electric field in the cavity was parallel to that of the optical excitation. In this way $\Delta m=0$ transitions are the only allowed transitions. The $5^2S_{1/2}, F=3 \rightarrow 63p_{3/2}$ line of the rubidium-85 isotope was excited for all the experiments. The maser cavity was manufactured from pure niobium rods (for details see Ref. 1). Two different resonators were available so that the transitions $63p_{3/2}$-$61d_{3/2}$ (21 506.5 MHz) and $63p_{3/2}$-$61d_{5/2}$ (21 456.0 MHz) could be investigated in the maser setup. The Rydberg atoms were detected by use of field ionization. The field strength was adjusted so that mainly atoms in the $63p_{3/2}$ level were ionized. Transitions to the lower maser level therefore led to a decrease of the ionization signal. In order to study the interaction of the $63p_{3/2}$ Rydberg atoms with the single-mode microwave field, the cavity was tuned by means of a piezoelectric transducer and the field-ionization signal was observed simultaneously. This procedure was repeated for different atomic velocities, i.e., different interaction times of the atoms with the cavity field. Only a single atom was present in the cavity at a time in all experiments.

At zero atomic flux the cavity contains the blackbody field. The average number of photons varies between $\bar{n}_{\text{th}}=3.8$ at 4.3 K and 1.5 at 2 K. When an atom in the upper maser level enters the resonant cavity, the probability of spontaneous decay is increased as a result of the enhanced vacuum field in the cavity. In addition, the

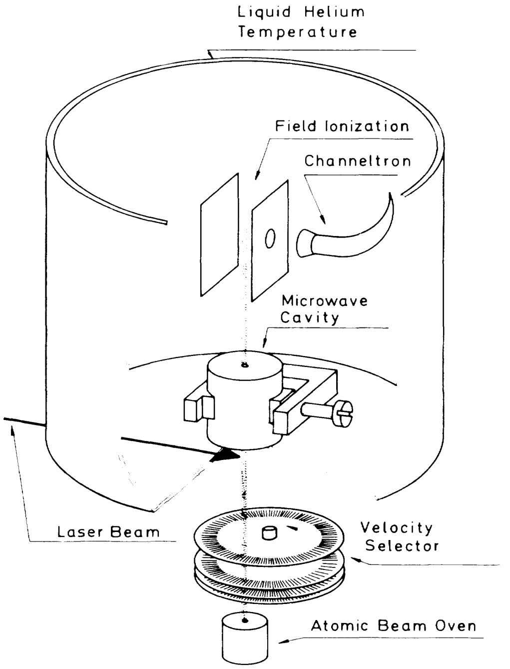

FIG. 1. Scheme of the experimental setup.

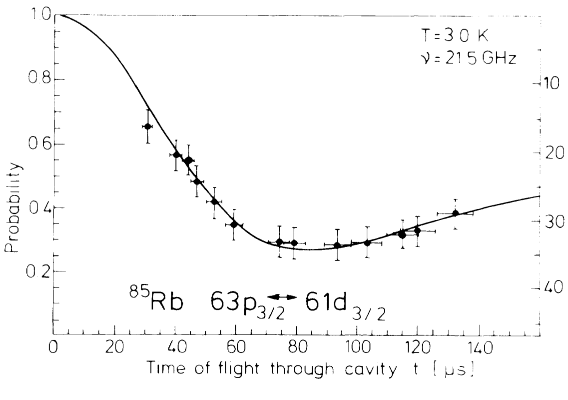

FIG. 2. The probability $P_e(t)$ of finding the atom in the upper maser level $63p_{3/2}$ for the cavity tuned to the $63p_{3/2} \leftrightarrow 61d_{3/2}$ transition of ^{85}Rb.

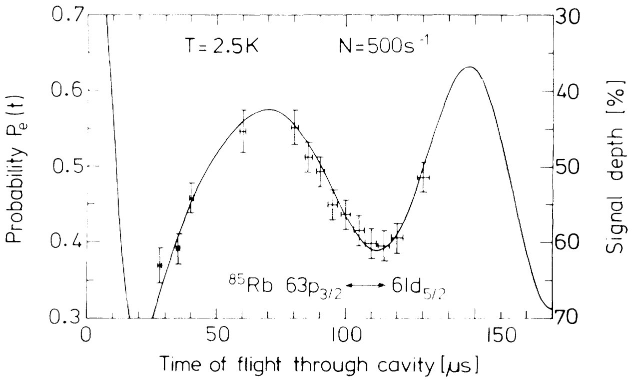

FIG. 3. The probability $P_e(t)$ of finding the atom in the upper maser level $63p_{3/2}$ for the cavity tuned to the $63p_{3/2} \leftrightarrow 61d_{5/2}$ transition of ^{85}Rb. The flux of Rydberg atoms is $N = 500\ \mathrm{s}^{-1}$.

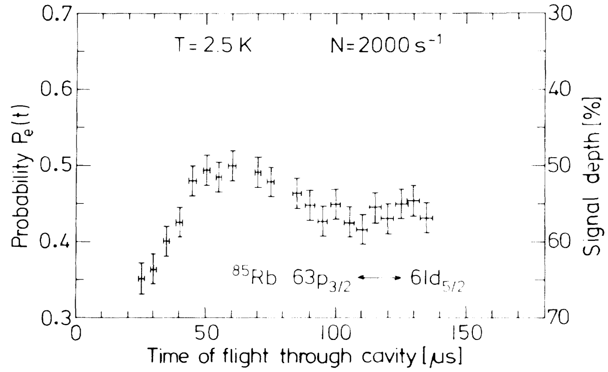

FIG. 4. Same as Fig. 3, but the flux of Rydberg atoms is $N = 2000\ \mathrm{s}^{-1}$.

emission is stimulated by the thermal radiation field. As a result of this emission the cavity field is increased by the emitted photon, and the atom, now in the lower maser level, can reabsorb a photon and return to the upper level. An increase of the atomic flux leads to a larger field in the cavity, and the average number of photons accumulated by the Rydberg atoms in the cavity is approximately given by $\bar{n}_m = T_c N/2$, where T_c is the characteristic decay time of the cavity and N the flux of Rydberg atoms. For the experiments N was varied between 500 and 3000 s^{-1}. With $T_c = 2$ ms, this means that $\bar{n}_m$ changes between 0.5 and 3 photons.

When the field-ionization signal is recorded in the experiment, the contribution of many atoms is averaged. Since the number of photons in the cavity changes as a result of statistics, the atoms passing through the cavity at different times experience different photon numbers, leading to the averaged time behavior of the inversion, as discussed above.

The experimental results obtained for the $63p_{3/2}$-$61d_{3/2}$ transition are shown in Fig. 2. In Fig. 2 the ratio between the field-ionization signals on and off resonance is plotted versus the interaction time of the atoms with the cavity field. The curve was calculated by use of the Jaynes-Cummings model. The total uncertainty in the velocity of the atoms is 10% in this measurement. The error in the signal follows from the statistics of the ionization signal and amounts to 4%. The measurement was made with the cavity at 3 K and $Q = 6 \times 10^7$ ($T_c = 500$ μs). There are on the average 2.5 thermal photons in the cavity. The number of maser photons is small compared with the number of blackbody photons. In order to observe the evolution of the excited state population over more periods, it is necessary to switch to a transition having a larger Rabi frequency Ω. The transition $63p_{3/2}$-$61d_{5/2}$ is suitable for this purpose.

The experimental results for this transition are shown in Figs. 3–5. The quality factor of the cavity was $Q = 2.7 \times 10^8$ ($T_c = 2$ ms) at a temperature of $T = 2.5$ K, which results in $\bar{n}_{\mathrm{th}} = 2$. The experimental results shown in Fig. 3 were obtained with very low atomic-beam flux ($N = 500\ \mathrm{s}^{-1}$). The curve represents the result of the Jaynes-Cummings model, and is in very good agreement with the experiment. When the atomic-beam flux is increased, more photons are piled up in the cavity. Measurements with $N = 2000$ and 3000 s^{-1} are shown in Figs. 4 and 5. The maximum of $P_e(t)$ at 70 μs flattens with increasing photon number, thus demonstrating the collapse of the Rabi nutation. Figures 4 and 5 show that for atom-field interaction times between 50 and about 130 μs, $P_e(t)$ is constant. Nevertheless, at about 150 μs $P_e(t)$ starts oscillating again (Fig. 5), thus showing a revival as predicted by the Jaynes-Cummings model. As pointed out by Eberly and co-workers,[7,8] the revival becomes more clearly observable at higher photon numbers; especially, the recurrences occur regularly, as discussed above. The results of Figs. 4 and 5 are in good agreement with the micromaser theory of Filipowicz,

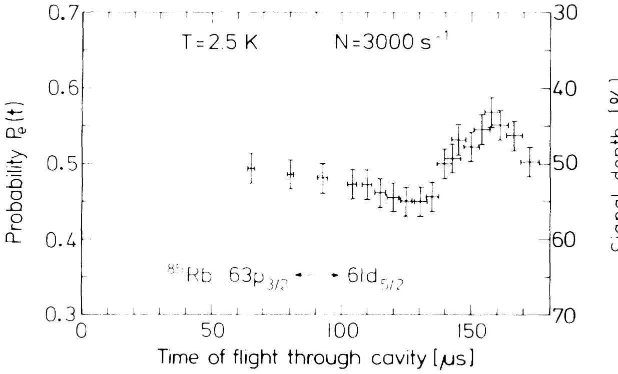

FIG. 5. Same as Fig. 3, but the flux of Rydberg atoms is $N = 3000\ \mathrm{s}^{-1}$.

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In order to measure the continuation of $P_e(t)$ to times longer than 130 μs it was necessary to increase the number of slow Rydberg atoms. The efficiency of the second-harmonic generation was therefore increased by a factor of 3 by the use of a $\mathrm{LiIO_3}$ crystal instead of an ammonium-dihydrogen-arsenate crystal. In this way 600 μW of radiation at 297 nm was produced. In order to study the atom-field evolution for times even longer than this, one has to prepare very slow atoms. This can be achieved by means of laser-cooling techniques. Experiments in this direction are in progress.

To summarize, the experimental results presented in this paper show clearly the collapse and revival predicted by the Jaynes-Cummings model. The variation of the Rabi nutation dynamics with increasing atomic-beam flux, and thus with increasing photon number in the cavity generated by stimulated emission, is obvious from Figs. 3-5. The results also demonstrate the change of the photon statistics starting with the chaotic Bose-Einstein field (Fig. 3). It is clear that a coherent field is not generated under all conditions; a sub-Poissonian photon-number distribution is also possible.[11] In addition, squeezing[12] and the generation of number states seems to be feasible.[13] In order to characterize the cavity field completely, the determination of the inversion of the atom behind the cavity is not sufficient: The phase of the field has to be measured also. This can be performed by means of an additional coherent and stable electromagnetic field which is applied before the atom enters the cavity.[14]

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