From Lamb Shift to Light Shifts: Vacuum and Subphoton Cavity Fields Measured by Atomic Phase Sensitive Detection

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We have measured by Ramsey interferometry the dispersive light shifts produced on circular Rydberg states by very weak nonresonant microwave fields in a single cavity mode. This experiment yields an absolute measurement of mean photon numbers with a sensitivity of 0.1. The vacuum induced Lamb shift, equal to the light shift of "half a photon," has been observed, providing a direct and absolute measurement of the zero-point field fluctuations in a cavity mode.

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The vacuum field plays a central role in quantum electrodynamics (QED), giving rise to the Lamb shift of atomic levels. Inside a cavity, the structure of the field is modified and atomic vacuum shift effects become strongly dependent on the boundary geometry [1]. When photons are stored in a cavity mode nonresonant with the atomic transition, a radiative shift adds up to the Lamb shift, which evolves into a light shift, proportional to field intensity [2]. We report here the measurement of energy shifts produced on a two-level atom by nonresonant subphoton microwave fields stored in a low order cavity mode. For the first time, we have been able to connect and compare directly the Lamb shift (produced by the "half photon" vacuum fluctuations) to light shifts due to very small numbers of photons added into a mode. This experiment, which singles out the effect produced by isolated cavity modes on the atomic levels, is very different from other nonresonant cavity QED studies where perturbative effects involving a very large number of modes have been observed [3,4] or are presently investigated [5]. In some respects, it is more closely connected to the recently performed "vacuum Rabi splitting" experiments [6], in which resonant effects of the vacuum in a cavity mode have been investigated. In both experiments, the atom coupled to the field can be viewed as a single quantum entity on which spectroscopy is performed. This study sets the stage for new kinds of quantum measurements, including a recently proposed quantum nondemolition (QND) method for photon number counting [7].

The experiment, which detects atomic wave function phase shifts, has been performed by Ramsey interferometry [8] on a beam of circular Rydberg atoms [9–11]. The setup is sketched in Fig. 1. A thermal beam of rubidium atoms effuses from an oven O. At left, in the cylindrical box CB, the atoms are prepared in the circular Rydberg state with principal quantum number $n=51$. In the center, they are subjected to the dispersive effect in the cavity C. This effect is probed in a Ramsey interferometer involving two separated oscillatory fields applied in the R_1 and R_2 cavities sandwiching C, 9 cm apart from each other. The atomic detection occurs at right (detector D). The apparatus is enclosed in a shield cooled at 1.45 K by a ^{4}He cryostat.

Circular atoms [9], which have the maximum value $m=n-1$ of the valence electron angular momentum projection along the quantization direction, are an essential ingredient for this experiment. In these atoms, the electron is confined near the classical circular orbit with radius a_0n^2 (a_0: Bohr radius). The matrix element between the circular levels n and $n+1$ of a linear projection of the electric dipole on the orbit plane has the very large value $d_n \simeq qa_0n^2/2$ (1250 a.u. for $n=50$). Circular atoms also have a very long radiative decay time $t_{\rm rad}$ (3×10^{-2} s for $n=50$), much longer than the transit time across the apparatus (600 μs). Moreover, since spontaneous transitions to other states can be neglected, a two-level atom model adequately describes an experiment involving a transition between two circular states.

Our circular atom preparation, described in detail in [11], produces up to 300 circular atoms per pulse in the $n=51$ state, at a rate of 1600 Hz. These atoms have a horizontal electron orbit. They experience in R_1 and R_2 two successive pulses of resonant excitation to the $n=50$ circular state (transition frequency $\nu_0=51.099$ GHz). R_1 and R_2 are identical low Q Fabry-Perot resonators, fed by a microwave source S_1 whose frequency ν_r can be swept around ν_0. The vertical cavity C is made of two super-

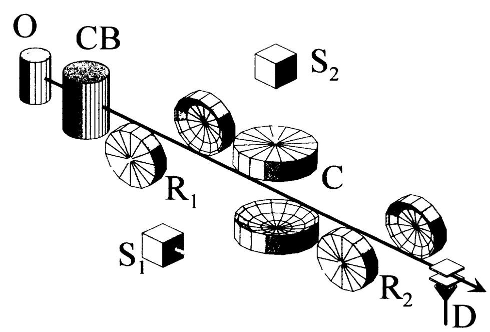

FIG. 1. General scheme of the circular Rydberg atom Ramsey interferometer (symbols defined in text).

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conducting niobium spherical mirrors (diameter 5 cm, curvature radius 4 cm) placed at $L=2.754$ cm from each other. It sustains in the ninth order the two TEM_{900} modes, with linear orthogonal polarizations and transverse Gaussian profiles (waist at center $w=5.96$ mm). The field is a standing wave with nine maxima between the mirrors and has a frequency close to ν_0. Because of a small mirror ellipticity, the mode degeneracy is slightly lifted (frequencies ν_{c1} and ν_{c2}, 146 kHz apart). The modes have a quality factor $Q=8\times10^5$ (bandwidth: 64 kHz). They can be tuned together by translating the mirrors with a piezostack (fine tuning) and a micrometer screw (gross tuning). The modes are controlled by measuring the cavity transmission with a network analyzer (AB Millimetre, Paris). A microwave source S_2 can be used to inject in C a coherent field whose amplitude is adjusted by calibrated attenuators.

The coupling of the circular atom to the cavity modes is defined by the vacuum Rabi frequency $\Omega(z,r) = d_n E_{\rm vac}(z,r)/\hbar$, where $E_{\rm vac}(z,r)$ is the rms vacuum field amplitude at the atom's location (cylindrical coordinates z,r) [1]. The spatial variation of the vacuum field is described by $E_{\rm vac}(z,r)=E_{\rm vac}(0)\exp(-r^2/w^2)\cos(2\pi\nu_0 z/c)$. The vacuum field amplitude $E_{\rm vac}(0)$ at antinodes is $(h\nu_0/2\epsilon_0 V)^{1/2}$ where ϵ_0 is the vacuum permittivity and V the effective cavity volume $\pi w^2 L/4$ (0.7 $\rm cm^3$). The maximum coupling at cavity center takes the value $\Omega(0,0)/2\pi=25$ kHz. However, the 1 mm diam atomic beam crosses the cavity at the measured height $z=0.7\pm0.2$ mm, resulting in a reduced rms coupling of the atoms on cavity axis $\overline{\Omega}/2\pi=17\pm3$ kHz. The atoms are coupled with an equal strength to the two modes.

The atoms are detected by ionization in an electric field E_i, the resulting electrons being accelerated by focusing lenses and counted by an electron multiplier. The field E_i is switched between the ionization thresholds of the $n=51$ and $n=50$ levels (136 and 148 V/cm, respectively). The populations of these levels are thus alternatively measured, and a fringe pattern is obtained by recording the population transfer rate versus ν_r. To improve the fringe visibility, the signal is recorded with monokinetic atoms. Since the excitation of the circular atoms is pulsed, gating the ionization signal at a fixed delay selects the atom velocity v with a precision $\Delta v/v$ of 1.5%. The field in R_1 and R_2 is also gated at the time the detected atoms cross these zones (field pulse duration 10 μs). The microwave amplitude in each zone is adjusted to maximize the fringe contrast.

A typical signal ($v=295$ m/s; $\nu_{c1}-\nu_0=2$ MHz) is shown in Fig. 2. The frequency ν_r is varied by 140 Hz increments and $\simeq3\times10^5$ atoms are recorded in 20 min. About 40 fringes are visible, with a 3.2 kHz spacing, equal to the inverse of the transit time between R_1 and R_2. The signal oscillates, around $\nu_r=\nu_0$, between 20% and 60% transfer rates. The fringes contrast is below 100%, partly due to microwave field inhomogeneities in

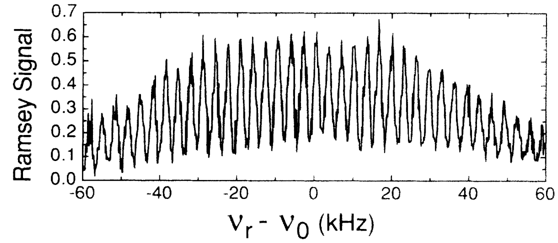

FIG. 2. Experimental Ramsey fringe signal observed on the $n=51\rightarrow n=50$ transfer rate versus $\nu_r-\nu_0$. The atom velocity is 295 m/s and $\nu_0-\nu_{c1}=2$ MHz.

R_1 and R_2. The observation of these fringes requires a precise control of the static fields in the apparatus. It is essential to apply along the atomic beam a small vertical dc electric field $\mathbf{E}_0$ ($\simeq0.3$ V/cm). By removing the degeneracy in the $n=50$ and 51 manifolds, this field prevents transitions to lower angular momentum levels [12] induced by stray fields due to patch effects and contact potentials. The field $\mathbf{E}_0$ also prevents the circular orbit from wobbling and keeps it horizontal. Sets of electrodes are used to apply $\mathbf{E}_0$ and to compensate the contact potential fields. The field $\mathbf{E}_0$ is created in C by applying 0.7 V between the mirrors. The magnetic field $\mathbf{B}_0$ in the apparatus is controlled by canceling the laboratory field and reducing its fluctuations with the help of a Mumetal cylinder around the cryostat and a superconducting indium coating of the 1.45 K thermal shield. The transverse fluctuations $\Delta\mathbf{E}_0$ and $\Delta\mathbf{B}_0$ of the fields on the section of the atomic beam as well as the temporal fluctuations of $\mathbf{B}_0$ are critical for fringe contrast and stability. The spatial fluctuations produce Stark and Zeeman inhomogeneous broadenings $2\alpha\mathbf{E}_0\Delta\mathbf{E}_0$ and $\mu_B\Delta\mathbf{B}_0$ [$\alpha=250$ kHz/(V/cm)^2 describes the quadratic Stark shift of the transition; $\mu_B=1.4$ MHz/G]. The observed fringe contrast yields an upper limit of 3 mV/cm and 400 μG, respectively, for $\Delta\mathbf{E}_0$ and $\Delta\mathbf{B}_0$. The temporal stability of the pattern (less than 25 Hz/day) sets the upper limit of the temporal magnetic field fluctuations (20 μG/day).

The phase shifts induced by C are measured by monitoring the translation of the central fringes of the spectrum while a small coherent field is injected in the ν_{c1} mode. The detuning $\nu_0-\nu_{c1}$ is set to a value $\delta_1/2\pi$ larger than $\overline{\Omega}/2\pi$ and than the cavity bandwidth. We operate in a low atomic flux regime (no more than about five atoms at a time in C). Collective effects are then negligible and the fringe pattern is checked to be independent of the atomic flux. The two signals shown in Fig. 3(a) correspond to $\delta_1/2\pi=150$ kHz and to injected fields with zero and one photon on average (the intensity calibration is discussed below). A fringe translation of $\simeq315$ Hz/photon is observed. The measurement of the phase of each fringe signal is obtained by fitting the experimental points to a sine function [thick solid lines in Fig. 3(a)]. The uncertainty of this fit, limited by the signal to noise ratio, is 25 Hz (0.05 radian phase shift). The linear

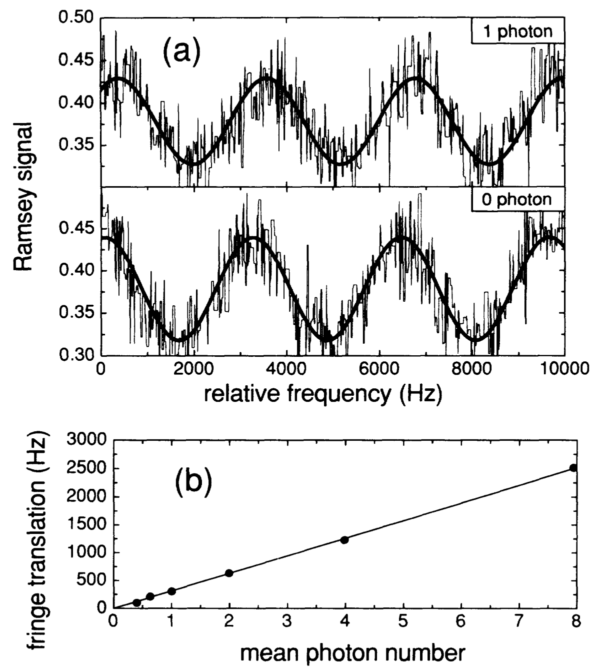

FIG. 3. (a) Central part of the fringe signal observed with zero (lower trace) and one photon on average (upper trace) injected in the cavity ($\delta_1/2\pi = 150$ kHz). The thick solid lines are best sine function fits to the data. (b) Fringe frequency translation versus injected mean photon number for same detuning.

translation of the fringes as a function of the field intensity is shown in Fig. 3(b). We have checked that this translation is, for a given field intensity, inversely proportional to δ_1, demonstrating the dispersive character of this effect. Note that similar Ramsey interferometry experiments have been performed recently in the optical domain, on macroscopic fields [13].

These light shift effects are now interpreted by a single mode perturbative QED calculation [1]. The atoms are prepared by the R_1 pulse in a linear superposition of the two $n=50$ and 51 levels. If the ν_{c1} cavity mode contains N photons, the combined atom-field system is described by the wave function $|\Psi\rangle = (|51;N\rangle + |50;N\rangle)/\sqrt{2}$, where the first number in each ket refers to the atom's state and the second to the field's. If there were no coupling between the atom and the field, this superposition would evolve between R_1 and R_2 at frequency ν_0. Because of the atom-cavity coupling, however, the states $|51;N\rangle$ and $|50;N\rangle$ undergo energy shifts while the atom crosses C. Neglecting very small effects due to strongly nonresonant transitions, these levels are only coupled, via nearly resonant virtual photon emission and absorption, to the states $|50;N+1\rangle$ and $|51;N-1\rangle$ (for $N>0$), respectively. The $n=51$ and $n=50$ states energy shifts are, to lowest order in Ω/δ_1, $\Delta_{51}(r,z) = \hbar(N+1)\Omega^2(r,z)/\delta_1$ and $\Delta_{50}(r,z) = -\hbar N\Omega^2(r,z)/\delta_1$. Note that the lower level does not undergo any appreciable vacuum shift.

These shifts translate into an accumulated phase shift $\Delta\varphi$ of the atomic superposition between R_1 and R_2, $\Delta\varphi = \int[\Delta_{51}(r,z) - \Delta_{50}(r,z)]dr/\hbar v$, whose average on the atomic beam section is

$$\Delta\varphi = \left(N+\frac{1}{2}\right)\frac{\overline{\Omega}^2}{\delta_1}\sqrt{2\pi}\frac{w}{v}. \qquad (1)$$

This formula is easily generalized to fields in a superposition of N states (such as coherent or thermal fields), provided the cavity relaxation time t_{cav} is smaller than the atom-cavity interaction time t_{int}, a condition largely fulfilled in this experiment ($t_{cav} = 2\ \mu$s; $t_{int} = 25\ \mu$s). In this case, the photon number randomly changes during t_{int} and the phase shift is obtained by replacing N by its average $\overline{N}$ in Eq. (1). An exact numerical calculation including the cavity field relaxation yields, for $\delta_1 > 80$ kHz, the same result as the perturbative approach of Eq. (1).

A residual phase shift is predicted by Eq. (1) for $N=0$. It comes from the vacuum cavity-induced "Lamb shift" of the upper $|51\rangle$ state. In order to observe it, we have recorded the fringes for various values of the atom-cavity detuning, with no injected field in C. We must then take into account the effects of the two modes, whose contributions to the vacuum shift are of comparable magnitude. We must also consider the presence of a residual thermal field in each of these modes with a mean photon number $\overline{N}_t$. The residual fringe phase shift is then given by $\Delta\varphi_0 = (\overline{N}_t + 1/2)\overline{\Omega}^2\sqrt{2\pi}(w/v)(1/\delta_1 + 1/\delta_2)$ with $\delta_1 = \nu_0 - \nu_{c1}$, $\delta_2 = \nu_0 - \nu_{c2}$. If the field were thermalized at the mirrors temperature ($T = 1.45$ K), $\overline{N}_t$ would be 0.23. We have determined directly $\overline{N}_t$ by measuring the transfer rate from $|51\rangle$ to $|50\rangle$ when the cavity modes are tuned to resonance. The atoms get in thermal equilibrium with the field during t_{int} and the relative populations of the two states provide an accurate measurement of $\overline{N}_t$, found to be 0.32 ± 0.02 (radiation temperature $T_r = 1.73$ K). We attribute the difference between T and T_r to radiation coupling inside C due to mirror surface scattering.

The measured residual fringe shift as a function of δ_1 ($\delta_2 = \delta_1 + 146$ kHz) is plotted in Fig. 4 (open circles) and compared to theory (dashed line). Achieving large detunings to record unshifted fringes requires one to move the micrometer screw (gross tuning), which changes the stray magnetic fields and randomly alters the fringe phase. We thus leave the phase of the fringes at infinite detuning as a free parameter in the fit. The coupling $\overline{\Omega}$ is also fitted. The agreement between experiment and theory is excellent. The best fit corresponds to $\overline{\Omega}/2\pi = 16.5 \pm 0.5$ kHz. The baseline uncertainty is ± 25 Hz. The fitted coupling is in good agreement with, and more precise than, its direct determination (17 ± 3 kHz). The phase shift variation per photon for a mode at $\delta_1/2\pi = 150$ kHz is then computed to be 0.62 ± 0.04 radian, a result used to calibrate the mean absolute photon number in the recordings of Fig. 3. According to this calibration, a 0.1 photon change corresponds to an observable 0.06 radian phase shift.

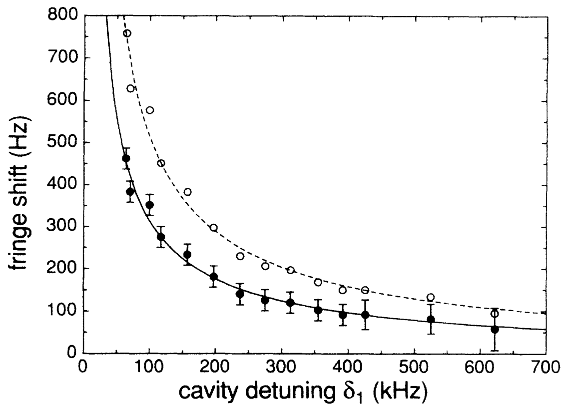

FIG. 4. Fringe frequency shifts as a function of atom-cavity detuning δ_1 with no injected field in C (experiment: open circles; theory: dashed line). The cavity Lamb shift, obtained by subtracting the thermal radiation-induced light shift, is shown by full circles (experiment) and solid line (theory).

Since the vacuum shift (1/2 term in $\Delta\varphi_0$) is a constant fraction of the total shift (proportional to $\bar{N}_t+1/2$), we can correct for the thermal effects by applying to the shifts the reduction factor $(1+2\bar{N}_t)^{-1}=0.62\pm0.02$. The extrapolated zero temperature cavity Lamb shifts measurements are shown by full circles and the QED prediction by the solid line in Fig. 4. The error bars are determined by the precision on the fringe position. This experiment clearly demonstrates the effect of the two cavity modes zero-point fluctuations on the upper atomic level.

A mechanical interpretation of these effects is also instructive [14]. The dispersive energy shifts, different for the $n=50$ and $n=51$ levels, correspond to forces acting on the atom crossing the cavity, which delay by different amounts the atomic wave packets associated with both levels. A phase difference of 0.05 radian corresponds to a differential spatial splitting equal to $\lambda_{dB}/40\pi$, where $\lambda_{dB}=15$ pm is the de Broglie wavelength of rubidium at 295 m/s. Our interferometric method thus demonstrates vacuum and subphoton induced forces in the cavity, producing a retardation of the atom as small as 125 fm.

We have shown the extreme sensitivity of Ramsey interferometry techniques using circular atoms for the measurement of very weak microwave fields, down to the vacuum, in a nonresonant regime. Subphoton shifts are observed with a detuning of the order of 10 times the atom-cavity coupling. With such detunings, no energy exchange can occur between the atom and the field. When we reach a regime where the photons survive long enough ($t_{cav}>t_{int}$ requires $Q>10^7$), this nonresonant feature will clearly open the way to QND measurement of very weak fields in a cavity [7].

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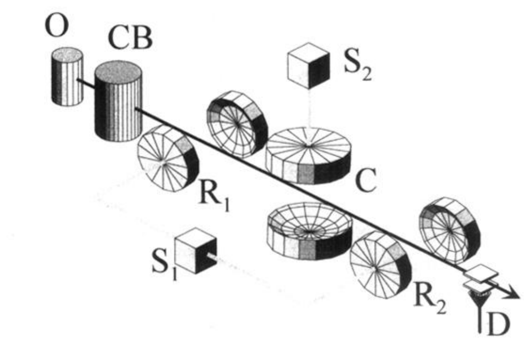

FIG. 1. General scheme of the circular Rydberg atom Ramsey interferometer (symbols defined in text).