Observation of sub-Poisson Photon Statistics in the Cavity-QED Microlaser

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We have measured the second-order correlation function of the cavity-QED microlaser output and observed a transition from photon bunching to antibunching with increasing average number of intracavity atoms. The observed correlation times and the transition from super- to sub-Poisson photon statistics can be well described by gain-loss feedback or enhanced-reduced restoring action against fluctuations in photon number in the context of a quantum microlaser theory and a photon rate equation picture. However, the theory predicts a degree of antibunching several times larger than that observed, which may indicate the inadequacy of its treatment of atomic velocity distributions.

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Nonclassical light has attracted much attention in the context of overcoming the shot noise limit in precision measurements and creating single photon pulses for quantum information processing [1]. In quantum optics, one well-known source of antibunched light is in single-atom resonance fluorescence [2,3], where antibunching occurs due to a "dead time" delay between photon emission and atom reexcitation. The single-trapped-atom laser [4] and similar setups for delivering photons on demand [5,6] exhibit photon antibunching essentially due to a similar process. The microlaser, on the other hand, generates nonclassical light via a very different process involving active stabilization of photon number, and remarkably, as shown below, photon antibunching and sub-Poisson statistics can occur even when the number of intracavity atoms greatly exceeds unity.

The cavity-QED microlaser [7] is a novel laser in which an interaction between the gain medium and optical cavity is coherent. Well-defined atom-cavity coupling and interaction time lead to unusual behavior such as multiple thresholds and bistability [8,9]. The microlaser has been predicted to be a source of nonclassical radiation due to active stabilization of photon number at stable points. However, such predictions have generally been made on the basis of single-atom theory [10]. In this Letter we report the measurement of sub-Poisson photon statistics in the microlaser even with the number of intracavity atoms as large as 500.

The microlaser is the optical analogue of the micromaser [11], in which sub-Poisson photon statistics has been inferred from the measurement of atom state statistics [12]. The microlaser has the advantage of allowing *direct* measurement of statistical properties of its emitted field.

Our experimental setup (Fig. 1) is similar to that of Refs. [7–9]. The optical resonator is a symmetric near-planar Fabry-Perot cavity (radius of curvature $r_0 = 10$ cm, mirror separation $L \approx 0.94$ mm, finesse $F \approx 0.94 \times 10^6$ at $\lambda = 791$ nm, cavity linewidth $\Gamma_c/2\pi = 150$ kHz). Barium atoms in a supersonic beam traverse the TEM_{00} cavity mode (mode waist $w_m = 41$ μm) which is near resonance with the ${}^1S_0 \leftrightarrow {}^3P_1$ transition of ^{138}Ba ($\lambda = 791.1$ nm, linewidth $\Gamma_a/2\pi \approx 50$ kHz). Shortly before entering the cavity mode, atoms pass through a focused pump beam which excites them to the ${}^3P_1$ state via an adiabatic inversion process similar to that described in Refs. [7,13].

In order to ensure coherent atom-cavity interaction the variations in atom-cavity coupling constant and interaction time (or atomic velocity) have to be minimized. The sinusoidal spatial variation of the atom-cavity coupling constant $g(\mathbf{r})$ along the cavity axis due to the cavity standing wave is eliminated by employing a tilted atomic beam configuration [14,15]. The remaining transverse variation of g is minimized by restricting atoms to the center of the Gaussian cavity mode (i.e., close to the plane containing the atomic beam direction and cavity axis) via a 250 μm $\times$ 25 μm rectangular aperture oriented parallel to the cavity axis. The resulting variation in peak coupling g is about 10%. The aperture is placed 3 mm upstream of the cavity mode. The coupling at the center of the mode is $2g_0 = 2\pi \times 380$ kHz.

A supersonic beam oven similar to that of Ref. [16] was employed to generate a narrow-velocity atomic beam. At highest temperatures it can produce a beam with a velocity distribution of width $\Delta v/v_0 = 12\%$ with v_0 the most probable atom velocity and Δv the width of the distribu-

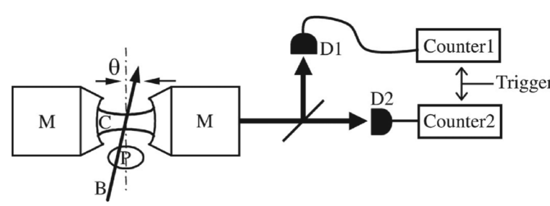

FIG. 1. Schematic of experimental setup. M: mirror, C: cavity mode, P: pump beam, θ: tilt angle, B: Ba atomic beam, D1, D2: start and stop detectors, Counter 1, 2: counter or timing boards.

tion (FWHM). However, under these conditions the oven lifetimes were impracticably short. Instead, we used a lower temperature oven, which results in a longer oven lifetime but a broader velocity distribution, $\Delta v/v_0 \simeq 45\%$ with $v_0 \simeq 750$ m/s. The atom-cavity interaction time $t_{\rm int}(=\sqrt{\pi}\omega_m/v_0)$ is about 0.10 μs.

In the tilted atomic beam configuration the microlaser exhibits two cavity resonances at $\omega_a \pm kv_0\theta$, corresponding to two Doppler-shifted traveling-wave modes [14,15]. The tilt angle $\theta \approx 15$ mrad corresponds to a separation of the two resonances by $2kv_0\theta \sim 30$ MHz, and thus the condition for traveling-wave-like interaction [15], $kv_0\theta \gg g$, is satisfied. The cavity spacing is adjusted by a cylindrical piezoactuator to lock to one of the two resonances with a use of a locking laser. In the experiment, cavity locking alternates with microlaser operation and data collection. During data collection, the microlaser output passes through a beam splitter and photons are detected by two avalanche photodiodes.

The dynamics of the microlaser result from an oscillatory gain function associated with coherent atom-cavity interaction. For a two-level atom prepared in its excited state and injected into a cavity, the ground state probability after the atom-cavity interaction time $t_{\rm int}$ is given by $\sum_n P_n \sin^2(\sqrt{n+1}gt_{\rm int})$, where P_n is the intracavity photon number distribution function. When the mean number of photons $\langle n\rangle$ in the cavity is much larger than unity (i.e., semiclassical limit), as in the present study, the time variation of the mean photon number can be obtained by means of a semiclassical rate equation [10,17] given by $d\langle n\rangle/dt = G(\langle n\rangle) - L(\langle n\rangle)$, where $G(n) \equiv \langle N\rangle \times \sin^2(\sqrt{n+1}gt_{\rm int})/t_{\rm int}$ the gain or emission rate of photons into the cavity mode and $L(n) = \Gamma_c n$ the loss with $\langle N\rangle$ the mean number of atoms in the cavity. The microlaser gain and loss are depicted in Fig. 2(a). For comparison, G and L for a conventional laser are shown in Fig. 2(b).

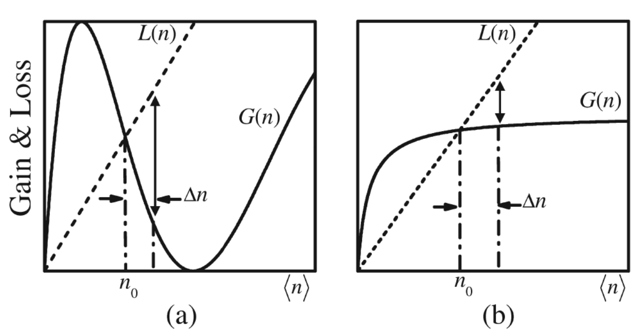

FIG. 2. Photon number stabilization. Solid line: gain $G(n)$; dashed line: loss $L(n)$. The restoring rate of the cavity-QED microlaser, shown in (a), for a momentary deviation Δn from a steady-state value n_0 is $\partial(L-G)/\partial n|_{n_0}$. (a) Cavity-QED microlaser has oscillatory $G(n)$. (b) Conventional laser: $G(n)$ approaches a constant value for large photon number and the restoring rate is $\partial L/\partial n = \Gamma_c$.

Photon number stabilization or suppression of photon number fluctuations occurs when the gain has negative slope. Consider a momentary deviation in the cavity photon number from a steady-state value n_0. The gain and loss provide feedback, acting to compensate for the deficiency or excess of photons, and restore the photon number to its steady-state value in a characteristic time τ_c, the correlation time. The tendency to stabilize the photon number is enhanced by the difference between the gain and loss as seen in Fig. 2.

Note that the rate to remove excessive photons or to supplement deficient photons is not just Γ_c as in the conventional laser, where the gain saturates to a constant value, but $\Gamma_c - \partial G/\partial n|_{n_0} > \Gamma_c$. The correlation time is then identified as $\tau_c = [\partial(L-G)/\partial n|_{n_0}]^{-1}$. This enhanced restoring rate is the source of suppression of photon number fluctuations below the shot noise level and thus of the sub-Poisson photon statistics. In the semiclassical limit ($\langle n\rangle \gg 1$), one can show that the Mandel Q parameter, defined as $Q = (\Delta n)^2/\langle n\rangle - 1$ with $(\Delta n)^2 = \langle n^2\rangle - \langle n\rangle^2$ the photon number variance [18], is approximately given by $Q \simeq G'(n_0)/[\Gamma_c - G'(n_0)]$ from the one-atom micromaser theory [1], assuming random arrival times of atoms with a monovelocity, with $G'(n_0) \equiv \partial G/\partial n|_{n_0}$. Using the expression for τ_c above, we then obtain a simple relation between the Mandel Q and the correlation time: $Q = \Gamma_c\tau_c - 1$. It is, however, expected that $Q > \Gamma_c\tau_c - 1$ when additional randomness is introduced such as super-Poisson injection of atoms [1], significant cavity damping, and atomic velocity distribution.

In the experiment we first measured $\langle n\rangle$ as the mean number of atoms $\langle N\rangle$ in the cavity was varied [Fig. 3(a)]. The photon number increases with $\langle N\rangle$ until it stabilizes (or saturates) around $\langle N\rangle \approx 200$. Further increase in $\langle N\rangle$ results in a jump in $\langle n\rangle$. Similar jumps have been observed in micromaser experiments from sudden changes in atomic state [19]. The first direct observation of these jumps (or multiple thresholds) in the microlaser has recently been achieved [8,9].

The $\langle n\rangle$-versus-$\langle N\rangle$ data can be well fit by a quantum microlaser theory, i.e., the one-atom micromaser theory [10] extrapolated to large $\langle N\rangle$, by the reasons to be discussed below. Figure 3(a) shows the fit obtained by using this extrapolated quantum microlaser theory which incorporates atomic velocity distribution via averaging of $G(n)$ over the velocity distribution. The amplitude of oscillation in Fig. 2(a) is reduced by the velocity averaging, but regions of negative slope still remain as shown in Fig. 3(b).

For $\tau = 0$, the second-order correlation function is related to the photon number distribution for a stationary single mode by $g^{(2)}(0) = 1 + Q/\langle n\rangle$. For our experimental parameters, sub-Poisson statistics requires several hundred photons to be present in the cavity. Thus, $g^{(2)}(0)$ is very close to 1, as $Q \geq -1$, requiring very low noise measurements of $g^{(2)}(\tau)$ for sub-Poisson statistics to be observed.

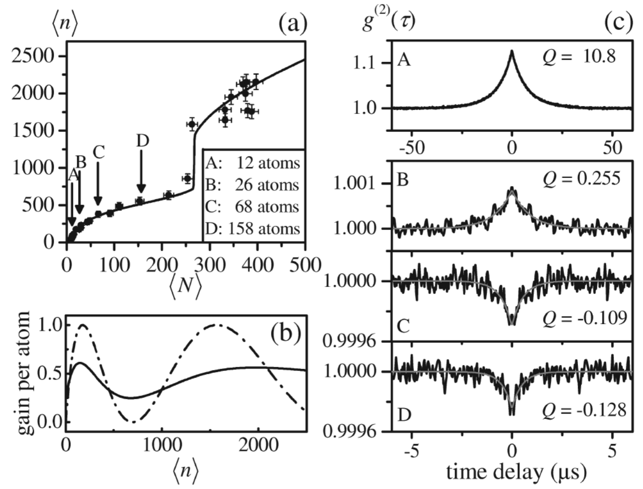

FIG. 3. (a) Observed $\langle n\rangle$-versus-$\langle N\rangle$ curve. The solid curve is a fit based on the quantum microlaser theory employing the averaged gain function in (b). (b) Solid line: normalized gain function per atom averaged over the velocity distribution corresponding to the present experiment. Dot-dashed line: gain function for a monovelocity distribution. (c) Measured second-order correlation function $g^{(2)}(\tau)$ for $\langle N\rangle = 12$, 26, 68, and 158. Each result is well fit by an exponentially decaying function.

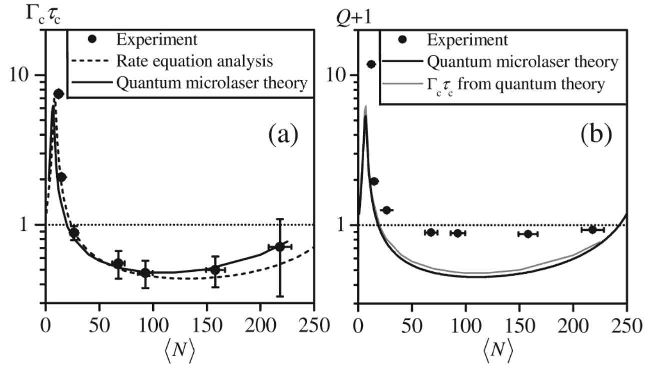

FIG. 4. Microlaser correlation times (a) and Q values (b) versus $\langle N\rangle$, compared with theory. In (a), cavity decay time is represented by a horizontal dotted line. Solid line, quantum theory. Dashed line, semiclassical theory. In (b), solid line is the quantum theory.

To accomplish this, we developed a novel high-throughput multistart multistop photon correlation system based on PC timing boards [20] and performed extensive averaging. With a count rate of approximately 3×10^6 cps on the two detectors and a total acquisition time of 300 sec, the rms shot noise in $g^{(2)}(\tau)$ was 0.00013.

We measured $g^{(2)}(\tau)$ for seven representative points in the $\langle n\rangle$-versus-$\langle N\rangle$ curve. The results for four points labeled A, B, C, and D are shown in Fig. 3(c). They are well fit by a function $g^{(2)}(\tau) = 1 + C_0 e^{-\tau/\tau_c}$, where negative (positive) C_0 corresponds to antibunching (bunching). From these fits we obtain the values of τ_c and $Q(= C_0\langle n\rangle)$ shown in Fig. 4. Plots A and B in Fig. 3(c), obtained in the initial threshold region, exhibit photon bunching. Data at C and D, from the region where photon number stabilization occurs, exhibit antibunching. The greatest degree of antibunching occurs at D, where $\langle N\rangle \approx 158$ and $Q = -0.13$, corresponding to reduction in photon number variance by 13% relative to a Poisson distribution.

In Fig. 4(a), the observed correlation times are compared with the predictions by quantum and semiclassical theories. In the quantum theory, τ_c is obtained from $g^{(2)}(\tau)$ calculated by using the quantum regression theorem [21] whereas τ_c is given by $\tau_c^{-1} = \partial(L - G)/\partial n|_{n_0}$ in the semiclassical theory. In both theories, the gain per atom assuming monovelocity is averaged over the velocity distribution [see Fig. 3(b)] as in the calculation of the mean photon number. The predictions of the two theories are similar and in excellent agreement with experiment. Although somewhat better agreement is obtained for the quantum theory, the observed correlation times are consistent with both theories, suggesting that the correlation time is primarily dependent on the dynamics of the mean photon number in the semiclassical limit.

Figure 4(b) shows Q values for the different values of $\langle N\rangle$, along with the predictions of the quantum microlaser theory, in which atomic velocity spread is included by preaveraging the gain per atom over the atomic velocity distribution as discussed above. For this time, however, the predictions of the theory do not agree with the data: the transition from super- to sub-Poisson distributions occurs at smaller $\langle N\rangle$ than the measured values, and the magnitudes of Q in the sub-Poisson region are about 5 times larger than those in the experimental results.

There may be several factors contributing to the disagreement in Fig. 4(b). The most important factor might be the inadequate treatment of atomic velocity distribution in the quantum theory via preaveraging the gain function $G(n)$. Although such preaveraging might be adequate when at most one atom can be present in the cavity [10], we have many atoms simultaneously interacting with the cavity with different velocities. Therefore, assuming the same averaged gain function for all those atoms may not fully account for the fluctuation in the photon number. In order to confirm this, we have performed quantum trajectory simulations (QTS) [22,23], which can more realistically describe velocity fluctuations from atom to atom and found that for large velocity widths QTS produces much broader photon number distributions than the quantum microlaser theory [24].

One may consider the cavity decay during the interaction time and many-atom effect itself without velocity fluctuations, both of which are not included in the quantum microlaser theory, for the other causes of the discrepancy. However, we found from additional QTS that the inclusion of the cavity decay would increase Q by at most 0.1 [8,25]. We obtained similar results for the many-atom effect [26].

Note that the observed correlation time when the transition from super- to sub-Poisson distributions occurs ($\langle N\rangle \approx 40$) is shorter than the cavity decay time. This is consistent with the observation $Q > \Gamma_c \tau_c - 1$, which leads to $\tau_c < \Gamma_c^{-1}$ for $Q = 0$. Significant atomic velocity spread and non-negligible atom/cavity damping mentioned above would introduce additional fluctuations in the cavity field and thus an enhanced restoring rate than the cavity decay rate would be needed in order to achieve a Poisson distribution for the cavity field.

It may seem surprising that a single-atom theory can even describe the microlaser average photon number when a large number of atoms is present in the cavity mode. We have found that the cavity-QED microlaser can be well described by the (modified) single-atom micromaser theory [10], as long as $gt_{\mathrm{int}} \ll \sqrt{\langle n\rangle}$ [26], which is well satisfied in the present experiments. Under this condition, photon emission or absorption by other atoms in the cavity does not affect the Rabi oscillation angle ϕ of a particular atom interacting with the common cavity field since the angle change $|\Delta\phi|$ due to single photon emission or absorption satisfies $|\Delta\phi| \simeq gt_{\mathrm{int}}|\Delta n|/\sqrt{n+1} \ll 1$ for $\Delta n = \pm 1$. Therefore, the mean number of atoms $\langle N\rangle$ in the cavity becomes a pumping parameter in the framework of an extrapolated single-atom micromaser theory [17]. This theory or the quantum microlaser theory, however, fails to account for the fluctuations of the cavity photon number when the many atoms in the cavity have significantly different velocities, as discussed above.

In conclusion, we have performed the first direct measurement of nonclassical photon statistics in the cavity-QED microlaser operating with hundreds of atoms in the cavity. The transition from super- to sub-Poisson photon statistics was observed as the mean number of atoms in the cavity was increased. A minimum Q of -0.13 was observed for mean photon number about 500. The observed correlation times and connection with the observed Q are consistent with a gain-loss feedback model. Values of Q reflect a lower reduction in photon number variance compared to the predictions of the quantum theory; this disagreement will require further study. Our analysis suggests that in future experiments with a velocity distribution width of 15% it will be possible to observe values of Q as low as -0.5. Other future directions include investigation of the microlaser field during jumps and measurement of microlaser line shape [27].

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