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 re-excitation. 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 a 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 an active stabilization of photon number at stable points. However, such predictions have generally been made on the basis of single-atom theory [12]. 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 microaser [10], in which sub-Poisson photon statistics has been inferred from the measurement of atom state statistics [11]. 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, 13]. The optical resonator is a symmetric near-planar Fabry-Perot cavity (radius of curvature r_0 = 10 cm, mirror separation L ≈ 0.94 mm, finesse F ≈ 9.4 × 10^6 at λ = 791 nm, cavity linewidth Γ_c/2π ≈ 150 kHz). Barium atoms in a supersonic beam traverse the TEM_{00} cavity mode (mode waist ω_m = 41 µm) which is near resonance with the 1S_0 ↔ 3P_1 transition of ^{138}Ba (λ=791.1 nm, linewidth Γ_a/2π ≈ 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(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 plane containing the atomic beam direction and cavity field.

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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, Counter1,2: counter/timing boards.
axis) via a 250 μm × 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 [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 $\Delta v$ the width of the distribution (FWHM). However, under these conditions the oven lifetimes were impractically short. Instead, we used a lower temperature oven, which results in longer oven lifetime but a broader velocity distribution, $\Delta v/v_0 \approx 45\%$ with $v_0 \approx 750$ m/s. The interaction time for an atom at velocity $v_0$ is $t_{\text{int}} = \sqrt{\pi \omega_m/v_0} \approx 0.10\, \mu s$.

In the tilted atomic beam configuration the microlaser exhibits two cavity resonances at $\omega_m \pm kv_0 \theta$, 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 $2kv_0\theta \approx 30$ 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 piezo actuator 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 beamsplitter 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 $t_{\text{int}}$ is given by $P_n = \sin^2 \left(\sqrt{n} + \sqrt{g}t_{\text{int}}\right)$, 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 [12, 13], given by $d\langle n \rangle/dt = G(\langle n \rangle) - L(\langle n \rangle)$, where $G(\langle n \rangle) = \sin^2 \left(\sqrt{n} + \sqrt{g}t_{\text{int}}\right)/t_{\text{int}}$ the gain or emission rate of photons into the cavity mode and $L(\langle n \rangle) = \Gamma_c \langle n \rangle$ 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).

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 $\tau_c$, 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 $\Gamma_c$ 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 $\tau_c = \left[\partial(L - G)/\partial n\right]^{-1}$. The enhancement 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 $Q = (\langle n^2 \rangle/\langle n \rangle - 1)$ with $\langle n^2 \rangle - \langle n \rangle^2$ the photon number variance [13], is approximately given by $Q \approx G'(n_0)/\left[\Gamma_c - G'(n_0)\right]$ from the one-atom micromaser theory [1] with $G'(n_0) \equiv \partial G/\partial n|_{n_0}$. Using the expression for $\tau_c$ above, we then obtain a simple relation between the Mandel $Q$ and the correlation time: $Q = \Gamma_c \tau_c - 1$.

In the experiment we first measured $\langle n \rangle$ as the mean number of atoms $\langle N \rangle$ in the cavity was varied (Fig. 8(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 [17]. The first direct observation of these jumps (or multiple thresholds) in the microlaser has recently been achieved [8, 12].

The $\langle n \rangle$-versus-$\langle N \rangle$ data can be well described by a quantum microlaser theory, i.e., the one-atom micromaser theory [12] extrapolated to large $\langle N \rangle$, by the reasons to be discussed below. Fig. 8 shows the fit obtained by using this extrapolated quantum microlaser theory incorporating atomic velocity distribution via averaging of $G(n)$ over the velocity distribution.

For $\tau_c = 0$, 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 statis-
tics to be observed. To accomplish this, we developed a novel high-throughput multi-start multi-stop photon correlation system based on PC timing boards \(^\text{20}\) and performed extensive averaging. With approximately 3 MHz count rates on the two detectors and 300 sec total acquisition time, 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(b). 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 \(\tau_c\) and \(Q\) shown in Fig. 4. Plots A and B in Fig. 3(b), 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, the correlation time is obtained via the quantum regression theorem \(^\text{21}\). The predictions of the two theories are similar, and in agreement with experiment. For small atom number, \(\tau_c\) is much larger than cavity decay time \(\Gamma^{-1}\) but rapidly decreases with increasing \(\langle N \rangle\) to about half the cavity decay time. For the highest densities the \(\tau_c\) may show a gradual increase. 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.

Fig. 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 integrating the gain function over the atomic velocity distribution function. 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. By contrast, the predictions for \(\langle n \rangle\) and \(\tau_c\) versus \(\langle N \rangle\) (Figs. 3(a) and 4(a), respectively) agree with the data.

There may be several factors contributing to the disagreement in Fig. 4(b). First, one may consider the cavity decay during the interaction time and simultaneous presence of many atoms in the cavity, both of which are not included in the quantum microlaser theory. However, we found from quantum trajectory simulations (QTS) \(^\text{22, 23}\) that the inclusion of the cavity decay would increase \(Q\) by at most 0.1 \(^\text{24}\). We obtained similar results for the many-atom effects \(^\text{24}\).

Second, atomic velocity distributions may be inadequately treated in the quantum theory by averaging of the gain \(G(n)\). We have performed additional QTS, which can more realistically describe velocity spread, and found that for large velocity widths QTS generally predicts a broader photon number distribution than does quantum microlaser theory \(^\text{26}\). The results suggest that the primary reason for the disagreement between theory and experiment is that the velocity distribution may not be treated adequately by the quantum microlaser theory. We are exploring modifications to the quantum theory to treat velocity distribution more accurately.

Note that enhanced (reduced) restoring action in Fig. 2 corresponding to a sub- (super-) Poisson distribution, occurs when \(\partial G/\partial n < 0\) (> 0), and thus results in a correlation time shorter (longer) than the cavity decay time.
In the semiclassical limit, Mandel $Q$ is related to the correlation time by the relation $Q = \Gamma \tau_c - 1$ as discussed above. This relation is shown in Fig. 11 where correlation times larger than the cavity decay time $\Gamma^{-1}$ correspond to $Q > 0$ whereas the correlation time much shorter than the cavity decay time correspond to $Q < 0$. However, 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 discrepancy might be due to the non-negligible atom/cavity damping and significant atomic velocity spread, which could introduce additional fluctuations in the cavity field and thus a slightly 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 describe even the microlaser average photon number with a large number of atoms in the cavity mode. We have found that the cavity-QED microlaser can be well described by the (modified) single-atom micromaser theory \cite{12}, as long as $g_{\text{int}} \ll \sqrt{\langle n \rangle}$ \cite{24}, which is well satisfied in the present experiments. Under this condition, photon emission/absorption satisfies $|\Delta \phi| \approx g_{\text{int}} |\Delta n| / \sqrt{n+1} \ll 1$ 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 \cite{17}.

In conclusion, we have performed the first direct measurement of nonclassical photon statistics in the cavity-QED microlaser. 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 lineshape \cite{27}.

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