Integrated atom detector: Single atoms and photon statistics

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We demonstrate a robust fiber-optics-based fluorescence detector, fully integrated on an atom chip, which detects single atoms propagating in a guide with 66% efficiency. We characterize the detector performance and the atom flux by analyzing the photon statistics. Near-perfect photon antibunching proves that single atoms are detected, and allows us to study the second-order intensity correlation function of the fluorescence over three orders of magnitude in atom density.

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The ability to efficiently detect single particles is of fundamental importance to many branches of science. For example, the counting of single photons was one of the starting points of quantum optics [1], and single-particle (qubit) detection is one of the key ingredients for quantum technologies [2].

Detection of atoms is usually achieved by illumination with near-resonant light, followed by a measurement of the absorption, phase shift, or fluorescence. The placing of an optical cavity around the detection region significantly enhances the signal and single-atom sensitivity can be achieved [3–11]. Active alignment of the cavities is, however, technically challenging.

Single-pass absorption does not allow one to detect single free atoms [12]; it is necessary to hold the atom in a trap to reach sufficiently long integration times [13,14]. Similarly, fluorescence detection is very efficient if atoms are tightly localized in a trap and many photons can be collected. It is the method of choice for many single-atom or -ion experiments [15–21]. Free neutral atoms are considerably harder to detect because the few scattered photons are difficult to distinguish from background light. Recently, fluorescence detection of freely falling single atoms has been demonstrated by using macroscopic mirrors covering a solid angle of almost 4π [22].

In an ideal fluorescence detector, the background is negligible, and a single detected photon implies that an atom is present in the detection region. In this Rapid Communication, we present a simple fluorescence detector based on fiber optics fully integrated on an atom chip [23,24] that detects single atoms in a magnetic guide with high signal-to-noise ratio1 and an efficiency of 66%. Previous implementations of on-chip detectors have been based on absorption detection where small atomic ensembles (typical 100 atoms) could be detected [13], or used cavities [9–11], which are more complex to handle.

2The advantages of this setup are related to properties of a confocal microscope: The tapered lensed fiber delivers the excitation light efficiently to a small detection region, and the multimode fiber selectively collects the fluorescent photons from this small volume and a large fraction of the background noise is filtered away very efficiently, even when the detection region is located only 62.5 μm above the chip surface. The difference from a regular confocal microscope is that the involved point spread functions are different.

1Signal-to-noise ratio is defined as the signal count rate divided by the count rate of the background. In our present experiments it ranges between 20 and more than 100 and is limited only by the dark counts of the single-photon counting module.
The position of the magnetic guide above the chip surface is aligned with the focus of the tapered lensed fiber at the detection region by adjusting the current through the chip and the strength of the external magnetic field. Atoms passing through the focus of the lensed fiber are excited by laser light tuned near the $F=2 \rightarrow F'=3$ transition in $^{87}\text{Rb}$. Over the next 2000 ms atoms pass the detector and the arrival times of the fluorescent photons are registered. The experiment is repeated several times to measure the photon statistics.

One observation from these measurements is that the effects of stray light on the guided atoms can be neglected. This is quite remarkable, because magnetic traps are extremely sensitive to the presence of light close to resonance with an atomic transition. On average, scattering of a little more than a single photon is sufficient to pump the atom into a magnetically untrapped state, removing it from the magnetic guide.

When an atom arrives at the detector, it absorbs and then reemits photons. A few of these photons are counted by the SPCM. This photon scattering strongly disturbs the atom; it will pump it into a untrapped state, or even into a different hyperfine ground state which is not excited by the probing light. Consequently, after a time $\tau$ the atom will either leave the detection region or stop scattering photons. Except for random background counts with very low probability, the detector sees no further light until the next atom arrives (Fig. 3).

Therefore for small atom flux the photon count distribution should reflect both (i) the instantaneous photon emission of the detected atom and its decay at time scales $\sim \tau$, and (ii) the statistical distribution of the atoms at long time scales ($\gg \tau$).

To analyze these features, it is useful to measure the statistics and time correlations of the photon counts. In the experiments presented here we use thermal atoms in a multimode guide (typically more than $10^3$ transverse modes are occupied). Consequently, the atoms exhibit Poissonian statistics, as can be verified by a time interval analysis of the atom arrival distribution [30] described below.

In the case of a constant atom flux composed of uncorrelated atoms, the probability of finding $k$ consecutive bins that...
contain no photons is given by \( P_T(k) = (1 - p_0)p_0^k \), where \( p_0 \) is the probability for an empty bin. This means that \( \log P_T(k) \) is a linear function of \( k \). In Fig. 3 we see that the time interval distribution is composed of two exponential decays (red line). The steep slope for short time intervals is determined by the instantaneous fluorescence rate of individual atoms. For long time intervals the slope is given by the atom arrival rate. Our measurements show that in the latter region \( \log p_0 \) equals the mean rate of atom detections, consistent with a Poissonian distribution of arrival times. Any atom correlations present could be identified from time interval analysis of single measurements [30].

An analysis of the photon noise shows that we can relate the variance and mean of the photon counts directly to the average number of photons detected from each atom [31]. The photon flux from a constant source during time intervals much longer than the excited state lifetime \( 1/\Gamma \) is described by a Poissonian probability distribution, where the mean photon number and the variance are both equal to \( \langle n \rangle \). If the fluorescent photons come from a random flow of atoms described by a statistical distribution \( P_{\text{atom}}(m) \), then \( \langle n \rangle \) is not constant in time. Mandel’s formula must then be used to describe the statistics of these photons [9]:

\[
P(n) = \sum_m P(n|m)P_{\text{atom}}(m) \quad \text{where} \quad P(n|m) = \binom{n}{m} \exp(-\langle m \rangle) \quad \text{is the conditional probability of obtaining} \quad m \quad \text{photons when the observation region contains} \quad n \quad \text{atoms}. \]

The average number \( \alpha \) of photons detected per atom, defined by the relation \( \langle n \rangle = \alpha \langle m \rangle \), reduces to \( \langle n \rangle / \langle m \rangle = 1 + \alpha \). The conditional photon distribution is given by

\[
P(n|m) = \binom{n}{m} \exp(-\langle m \rangle) \quad \text{for the Poissonian distribution.} \]

For the mean and the variance of the photon distribution one obtains the ratio

\[
\frac{\text{var}(n_{\text{photons}})}{\langle n_{\text{photons}} \rangle} = 1 + \alpha \frac{\text{var}(m_{\text{atoms}})}{\langle m_{\text{atoms}} \rangle}. \tag{1}
\]

When the atoms obey Poissonian statistics, as in our experiments, Eq. (1) reduces to \( \text{var}(n) / \langle n \rangle = 1 + \alpha \). The mean number of photons detected from each atom \( \langle a \rangle \) can be directly retrieved from the ratio of variance to mean. If additionally a Poissonian background \( b \) is taken into account, the photon statistics can be expressed as

\[
\frac{\text{var}(n_{\text{photons}})}{\langle n_{\text{photons}} \rangle} = \frac{(1 + \alpha)\langle m_{\text{atoms}} \rangle + (b)}{\alpha \langle m_{\text{atoms}} \rangle + (b)}. \tag{2}
\]

The atom detection efficiency can be determined from \( \alpha \). If there is one atom in the detection region, it will generate at least one photon count with a probability \( P_{\text{detector}} = 1 - \exp(-\alpha) \). From the photon statistics in the data shown in Fig. 2, one obtains \( \alpha = 1.08 \pm 0.01 \) and \( P_{\text{detector}} = 66\% \) for 1 nW probe beam power, 3 MHz blue detuning, and 300 \( \mu \)s integration time.

The total number of photons scattered by the atoms can be independently obtained by measuring the ratio of the fluorescence counts for \( F = 2 \rightarrow F' = 1 \) and the \( F = 2 \rightarrow F' = 3 \) transitions. On the \( F = 2 \rightarrow F' = 1 \) transition an atom scatters slightly more than one photon before being optically pumped into the other hyperfine ground state, where it remains dark. From the measured ratio we conclude that each atom scatters \( \sim 120 \) photons before it leaves the detector. These numbers are in good agreement with \( \alpha = 1.08 \) and the photon detection efficiency \( P_{\text{det}} = 0.9\% \) given above. In addition the value of \( \alpha \) was confirmed from independent global atom number measurements using absorption imaging.

We can investigate if we really detect single atoms by looking at the correlations in the detected fluorescence photons. Since a single atom can emit only one photon at any given time, one would expect photon antibunching, characterized by \( g^{(2)}(\delta t) < 1 \) [32,33], where the second-order intensity correlation function is given by

\[
g^{(2)}(\delta t) = \frac{\langle E^\dagger(t)E^\dagger(t + \delta t)E(t)E^\dagger(t) \rangle - \langle E^\dagger(t)E^\dagger(t) \rangle^2}{\langle E^\dagger(t)E^\dagger(t) \rangle^2}. \tag{3}
\]

Figure 4(a) shows a measurement of \( g^{(2)}(\delta t) \) from the cross-correlation of photon counts in two SPCMs arranged in a Hanbury Brown–Twiss–type setup as shown in Fig. 1(a). The correlation function was reconstructed from the low-density tail of the atom distribution where the mean atomic distance is large enough to guarantee the presence of at most one atom in the detection region at any given time. An evaluation of the raw data results in a value of \( g^{(2)}(0) = 0.05 \). If we correct for coincidental background counts, \( g^{(2)}(0) \) is compatible with zero. Thus we observe near-perfect photon antibunching in the emission of single atoms passing the detector, a clear signature of single-atom detection.

For a single-mode field with mean photon number \( \langle n \rangle \) the second-order correlation at lag \( \delta t = 0 \) is limited by [32]

\[
g^{(2)}(0) \equiv 1 - \frac{1}{\langle n \rangle} \quad \forall \quad \langle n \rangle \gg 1, \tag{4}
\]

while for \( \langle n \rangle < 1 \) the lower limit is 0. For a Fock state with fixed photon number \( n \) the inequality (4) becomes an equality and the minimal value of \( g^{(2)}(0) \) is reached. While for classical light sources \( 1 \leq g^{(2)}(0) \ll \infty \) holds, the region \( g^{(2)}(0) < 1 \) is exclusively nonclassical and can be reached only by quantum emitters.
Since $g^{(2)}(\tilde{n})$ is evaluated when at least one photon count has been recorded, the mean photon number $\langle n \rangle$ has to be calculated under the condition $n \geq 1$. This leads to $\langle n \rangle = \alpha(N)/(1 - \exp(-\alpha(N)))$ with mean atom number $\langle N \rangle$. Hence $g^{(2)}(0)$ is limited by
\begin{equation}
g^{(2)}(0) \geq 1 - \frac{1 - \exp(-\alpha(N))}{\alpha(N)}. \quad (5)
\end{equation}
As can be seen from Fig. 4(b), the measured $g^{(2)}(0)$ follows the expected shape for the full atom pulse duration. With this measurement we extend the original experimental investigation [33,34] of the influence of atomic density on the second-order correlation function by almost three orders of magnitude change in atomic density.

To conclude, we have built and evaluated an atom detector which is fully integrated on an atom chip, alignment-free by fabrication, and mechanically very robust. It is capable of detecting single atoms with 66% efficiency and high signal-to-noise ratio, which allowed us to study the interplay between atom and photon statistics.

Low noise, high efficiency, and insensitivity to stray light are achieved using fiber optics to create very selective excitation of the atoms in a small, matched observation volume. The detection efficiency is currently limited by the numerical aperture of the multimode collection fiber. A straightforward substitution of the employed NA=0.275 fiber by a commercially available fiber with NA=0.53 increases the photon collection to $\alpha=4.5$ counts/atom and the single-atom detection efficiency to 95% at 50 kHz bandwidth. With these improvements, atom counting becomes feasible.

The high efficiency, signal-to-noise ratio, and bandwidth of our integrated detector make it suitable for many physical systems where only a few photons can be scattered, as in the detection of single trapped cold molecules. With its extremely low sensitivity to stray light, our detector is well suited for studies of correlated atomic systems and scalable quantum experiments on a single-atom or -molecule level.

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