High efficiency photon counting using stopped light

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Single-photon detection and photon counting play a central role in a large number of quantum communication and computation protocols. While the efficiency of state-of-the-art photo-detectors is well below the desired limits, quantum state measurements in trapped ions can be carried out with efficiencies approaching 100%. Here, we propose a method that can in principle achieve ideal photon counting, by combining the techniques of photonic quantum memory and ion-trap fluorescence detection: after mapping the quantum state of a propagating light pulse onto metastable collective excitations of a trapped cold atomic gas, it is possible to monitor the resonance fluorescence induced by an additional laser field that only couples to the metastable excited state. Even with a photon collection/detection efficiency as low as 10%, it is possible to achieve photon counting with efficiency approaching 100%.

Quantum information science has emerged as a truly interdisciplinary field involving the contributions of physicists, engineers, and computer scientists. Despite the impressive progress in theory within the last 8 years, experimental implementation of quantum information processing in physical systems remains as a major challenge. A significant fraction of key experiments in the field, such as Bell’s inequality violations, quantum key distribution and quantum teleportation, have been carried out using photons and linear optical elements such as polarizers and beam splitters. Even in these earlier experiments, efficiency of single-photon detection had been a limiting factor. Recently, Knill, Laflamme, and Milburn have shown theoretically that efficient linear optics quantum computation (LOQC) can be implemented using on-demand single-photon pulses and high-efficiency photon-counters. The required photon-counting efficiency for LOQC is estimated to exceed 99%: this is beyond the capability of state-of-the-art devices, which can only provide single-photon detection (and not photon counting) efficiencies below 90%.

In this Letter, we propose a scheme to carry out photon-counting with efficiency potentially exceeding 99%. The proposed method combines the techniques of ion-trap quantum-state measurements with that of quantum memory for photons based on electromagnetically induced transparency (EIT). The first step in this proposal is the mapping of the quantum state of the propagating light pulse onto collective excitations of an atomic gas, as described below. The number of collective excitations are then measured efficiently using the state-selective fluorescence measurements developed for trapped ions. Both steps in the process can in principle be carried out with efficiency exceeding 99%, limited only by the dephasing time of the collective atomic excitations.

Arguably, the only physical system where a quantum state measurement with efficiency approaching 100% has been demonstrated, is trapped ions. The goal of these measurements is to determine whether an ion is in its ground state (|g⟩) or in a (pre-selected) hyperfine-split metastable excited state (|m⟩). The measurement proceeds by coupling state |m⟩ to an excited fluorescing state |f⟩ (that decays by spontaneous emission back to state |m⟩) using a resonant laser field. If no photon is detected, the state of the ion collapses onto |g⟩. Similarly, observation of scattered photons (i.e. resonance fluorescence) projects the state of the ion onto |m⟩. By choosing the states |m⟩ and |f⟩ to be the |F = 2, mF = 2⟩ and |F = 3, mF = 3⟩ states of the ground and excited levels respectively, one can ensure that the decay of state |f⟩ will only populate state |m⟩ and that many photons can be scattered.

Hyperfine-split states of the ground electronic level of an ion or an atom constitute an ideal quantum bit (qubit), due to the ultra-long decoherence time of these states. In the case of an ensemble of atoms, these long decoherence times have also been utilized in experiments demonstrating electromagnetically induced transparency (EIT). The essence of EIT is the creation of coherence between two long lived atomic states by two laser fields in an optically thick medium: the absorption experienced by the optical field that couples the ground atomic state |g⟩ to a common excited state |e⟩ (Fig.1), is eliminated by the non-perturbative coupling laser field that is applied at the |m⟩ − |e⟩ transition. Elimination of resonant absorption in EIT is due to a quantum interference effect that leads to a cancellation of optical excitation probability amplitudes only when the probe and the coupling fields satisfy exact Raman resonance. The narrow transparency window for the probe field is accompanied by a very steep variation of the refractive index with frequency, leading to ultra-slow group velocity of probe pulses travelling in EIT medium.

A probe laser pulse may enter an EIT medium without experiencing any loss or reflection, provided that its bandwidth Δνprobe is much smaller than the width of the transparency window Δν. Under these condi-
tions, the incident probe pulse excites coupled collective excitations of atoms and light inside the medium, which propagate with an ultra-slow group velocity [11]. The quantum state inside the medium that corresponds to an incoming probe pulse with exactly \( n \) photons is

\[
|\Phi_n\rangle = \frac{1}{\sqrt{n!}} \left[ \frac{\Omega_c(t)}{\sqrt{\Omega_c^2(t) + g^2 N}} \hat{a}^\dagger(z,t) - \frac{g\sqrt{N}}{\sqrt{\Omega_c^2(t) + g^2 N}} \hat{\sigma}_{mg}(z,t) \right]^n |G\rangle \otimes |0\rangle , \tag{1}
\]

where \(|G\rangle = |g\rangle_1 |g\rangle_2 \ldots |g\rangle_N\) is the ensemble atomic state where all \( N \) atoms are in the ground-state and \(|0\rangle\) is the vacuum state of the probe field mode. \( \Omega_c(t) \) and \( g \) denote the Rabi frequency of the coupling field and the single-atom-field interaction strength of the probe transition, respectively. The operator \( \hat{a}^\dagger(z,t) \) creates a travelling probe photon; \( \hat{\sigma}_{mg}(z,t) \) is the collective atomic raising operator. Extension of these atom-field states to arbitrary incoming field states is straightforward [12]. The corresponding excitations are referred to as dark-state polaritons, since atomic excitations take place between (spontaneous-emission-free) states \(|g\rangle\) and \(|m\rangle\).

It has been first noted by Fleischauer and Lukin [8] that it is possible to make the dark-state polaritons purely atom-like by adiabatically turning the coupling field off. When this transformation is implemented, we end up with a purely atomic collective excitation; in this limit, the group velocity of the dark-state polariton is zero. It has also been shown in Ref. [8] that by turning the coupling laser back on adiabatically, it is possible to reverse the quantum-state transfer and re-generate the probe field pulse in the original quantum state. This proposal has been realized experimentally using an ultracold atomic sample in Ref. [13], and warm Rb atoms in Ref. [14].

The first step of the photon counting procedure that we propose is based on this transfer between the quantum states of the probe pulse and the metastable collective atomic excitations. After the state transfer is completed by adiabatically turning the coupling laser Rabi frequency \( \Omega_c(t) \) off, we have a \( 1 \rightarrow 1 \) mapping between the incoming photons and the collective atomic excitations [8]. More precisely, the number of atoms in the metastable state \(|m\rangle\) is exactly equal to that of the number of incoming photons. Since the atomic excitation is collective, the probability of finding any single atom in state \(|m\rangle\) remains small. The state mapping process can in principle be carried out with efficiency approaching 100%. Initial experiments already demonstrated reversible quantum state transfer with efficiencies exceeding 20% [13, 14].

The principal idea of the proposal is that it is possible to use a warm atomic gas [14] as a medium to store and subsequently release light at a later time. After turning the coupling laser off, we turn on a "detection" laser field that is resonant with the dipole allowed transition between state \(|m\rangle\) and state \(|f\rangle\). Just as in the ion trap experiments, we choose states \(|m\rangle\) and \(|f\rangle\) to be \(|F = 2, m_F = 2\rangle\) and \(|F = 3, m_F = 3\rangle\) states of the ground \((S)\) and excited \((P)\) levels respectively. The ground state \(|g\rangle\) could then be the \(|F = 1, m_F = 0\rangle\) or the \(|F = 1, m_F = 1\rangle\) state, depending on the geometry of the coupling field. Assuming \( I = 3/2 \) nuclear spin typical for alkali atoms, this choice guarantees that scattering of laser photons always project the atoms back to state \(|m\rangle\) and allows for multiple photon scattering events.

To the extent that the number of atoms far exceeds the maximum number of photons, the detection of scattered photons constitutes a nearly ideal projective measurement of the photon number. To highlight this fact, we can consider a (single atom) light scattering time of 100\(\text{ns}\); for \( \eta_s = 1\% \) detection efficiency of scattered photons, we expect to count 100 photons in 1\(\mu\text{sec}\) for each atom in state \(|m\rangle\). Assuming Poisson statistics for scattered photons, we will then be able to distinguish between photon number states \(|n\rangle\) that have small occupancy compared to \( |n_{\text{max}} = 100\rangle \). Naturally, longer measurement times or higher \( \eta_s \) will allow for higher sensitivity and larger \( n_{\text{max}} \). Since dephasing times of hyperfine split states can be much longer than 1\(\mu\text{sec}\), loss of dark-state coherence will not be important for a large class of photon counting measurements.

The requirements for efficient quantum state transfer can be met using either trapped cold or non-trapped warm atomic gases, provided that Doppler free configuration is utilized in the latter. The principal requirement is that the medium is optically thick, i.e. \( \alpha = N\sigma/(2A) \gg 1 \), where \( \sigma \) is the absorption cross-section of the \(|g\rangle - |e\rangle\) transition (in the absence of the coupling field) and \( A \) is the cross-sectional area of the probe pulse. For a probe pulse collimated to within 100\(\mu\text{m}\) over 1\(\mu\text{m}\) interaction region of a cigar shaped cold atomic gas with \( N = 10^5 \) atoms, this condition is easily satisfied.

From a practical point-of-view, it would be a great simplification to be able to use a warm atomic gas [14]. The principal limitation of this set-up would be the off-resonant absorption of the detection laser by the ground state atoms. The maximum number of atoms allowed in the ground state will be determined by the ratio of the off-resonant and resonant scattering rates, for atoms in state \(|g\rangle\) and \(|m\rangle\), respectively. Assuming that the ground-state hyperfine splitting determines the detuning of the detection laser from state \(|g\rangle\), we find that \( N_{\text{max}} \approx 10^6 \) (in the absence of Doppler broadening). For \( N \geq N_{\text{max}} \), the proposed detector will effectively exhibit high dark counts.

Photon counting using dark-state polaritons in atomic media is relatively slow due to the slow response time of atoms. The bandwidth of the transparency window is given by \( \Delta \nu = \Omega_c^2(t)/(\Gamma_c \sqrt{\alpha}) \), and determines the short-
est possible pulse-length of the probe field [2]. Here, $\Gamma_e$ is the spontaneous emission rate of the excited state $|e\rangle$ (Fig. 1). State-selective fluorescence technique requires that the atoms scatter many photons; having a large $\Gamma_e$ will then speed up the photon counting process. Given these considerations, one may conclude that implementation of EIT and quantum-state transfer in semiconductors can lead to faster photon counting [10].

As mentioned earlier, the state transfer method is reversible. If the detection process had not altered the phase imprinted on the atomic sample, it would have been possible to re-convert the atomic collective excitation into probe photons. The overall process would then have realized a quantum nondemolition (QND) measurement of the photon number operator $\hat{n}$, with nearly unity efficiency. An interesting future direction would be to determine if a photon-number QND measurement can be implemented using the described techniques.

The fascinating proposal for implementing efficient quantum computation using linear optics has two key requirements: (a) deterministic generation of single-photon pulses, (b) photon counting with efficiency exceeding 99% [9]. Since significant advances in single-mode single-photon sources have already been achieved [11], an experimental realization of the photon counter proposed in this Letter could enable the implementation of basic elements of LOQC. One could argue that a third requirement for LOQC is the possibility of storing multimode multi-photon entangled states that are prepared off-line; the quantum-state transfer technique that we utilize would be an ideal candidate for that task. Finally, we note that quantum state-transfer is a linear process; the nonlinearity required for photon counting is provided by the anharmonicity of the atomic spectrum, probed by the detection laser.

Photon counting in general, and single-photon detection in particular has found many applications in basic physics experiments. In particular, most of the Bell’s inequality violation experiments have utilized single-photon detection [3]. However, none of these experiments can eliminate the so-called "detection loophole" [3] that arises from low detection efficiency and could in principle allow for a local realistic interpretation. The only Bell’s inequality violation experiment that avoided the detection loophole was in fact carried out using trapped ions and the state-selective fluorescence detection: this experiment however, cannot eliminate the "lightcone loophole" [4]. When realized, the photon counter described in this Letter could allow for the first loophole-free demonstration of Bell’s inequality violation.

In summary, we have described a photon counter which realizes a projective photon number measurement with efficiency approaching 100%. The device combines the experimentally demonstrated techniques of state-selective fluorescence detection, and quantum-state transfer between photons and collective atomic excitation.

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FIG. 1. The energy level diagram of the atoms used in quantum state transfer and state-selective fluorescence detection. An electromagnetically induced transparency is established for the probe field at frequency $\omega_p$ using the coupling field at frequency $\omega_c$ and Rabi frequency $\Omega_c(t)$. When the coupling field intensity is turned off adiabatically, each probe photon will be stored as an atomic excitation in the metastable state $|m\rangle$. By turning on a detection laser at the $|m\rangle - |f\rangle$ transition, we can scatter many photons that will reveal the number of atoms in state $|m\rangle$. The energy levels are chosen assuming that the atomic gas is Doppler-free.