Super-poissonian photon statistics and correlations between pump and probe fields in Electromagnetically Induced Transparency

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Abstract

We have measured the photon statistics of pump and probe beams after interaction with rubidium atoms in a situation of Electromagnetically Induced Transparency (EIT). Both fields present super-poissonian statistics, in agreement with our theoretical treatment. We also show that the measurement of the photon statistics improves the sensitivity for the detection of coherent effects in the atomic medium. Finally, we have measured an intensity correlation between the fields (initially independent) due to their interaction with the atoms.

Introduction

The phenomenon of Electromagnetically Induced Transparency (EIT) [1] is an interference effect that can be observed in a three-level atomic system interacting simultaneously with two laser beams (pump and probe, resonant with two different atomic transitions). Although apparently an intrinsically quantum effect, EIT has a classical counterpart in a very simple system with only two harmonic oscillators and a harmonic driving force [2,3]. The new interest in this effect appears due to observation of very slow light pulse propagation in EIT media [4-6]. The quantum features of the effect have led several authors to suggest the possibility of applications in the field of quantum information [7,8].

The experimental work described below presents the first measurement of field statistics in a situation of EIT. We measured super-poissonian photon statistics for both pump and probe fields peaked on the EIT resonance. This is in very good qualitative agreement with our theoretical predictions. Furthermore, the fields are coupled by their interaction with the atoms and thus their intensities become correlated.

We verify that the coupling between the atoms and fields produces a spreading in the photon distribution of each field. The atoms act as “beamsplitters”, redistributing photons between the fields, in such a way that the mean numbers do not vary appreciably, but the variances are modified. This is the physics behind the observed super-poissonian photon statistics in both fields, mainly in the EIT resonance situation.

Our theoretical treatment was based on the quantum Langevin equations [9]. In order to simulate the interaction of the atoms with two propagating fields, we use the input-output formalism [10,11] and consider the interaction between the two fields and the atoms in a ring cavity, with external input fields. The fluctuations in the output fields result from fluctuations in the input fields and from the interaction with the atoms.

The noise spectra calculated for probe and pump amplitude quadratures and their correlations are plotted in Fig. 1, as a function of the probe frequency. The analysis frequency was \( \Omega = \Gamma / 6\pi \) (\( \Gamma \) is the total spontaneous
emission rate from the excited state) that is consistent with the experiment. The ring cavity length is large enough so that the atoms experience neither significant changes in their spontaneous emission rates nor collective effects. We took equal coupling constants for both transitions, pump strictly on resonance, and a ratio of intensities such that there is a very narrow and deep EIT resonance (pump intensity 9 times larger than the probe intensity). We find super-poissonian statistics for both fields, and intensity correlations (calculated with fields of equal intensities) peaked at the EIT resonance. The predicted correlations depend on the presence of absorption. In the EIT situation, absorption is suppressed for both fields, leading to intensity correlations.

**Experimental Setup**

Our experimental apparatus is showed in Fig. 2. It consists of two extended-cavity diode lasers (ECDLs) to provide the pump and probe beams. A small portion of each beam is extracted and sent to auxiliary saturated absorption cells, used as frequency references. The pump beam is turned to the $^{85}\text{Rb}\left|5S_{1/2}, F = 3\right\rangle \rightarrow ^{85}\text{Rb}\left|5P_{3/2}, F' = 3\right\rangle$ transition, and the probe beam is scanned across the Doppler-broadened $^{85}\text{Rb}\left|5S_{1/2}, F = 2\right\rangle \rightarrow ^{85}\text{Rb}\left|5P_{3/2}, F = 1,2,3\right\rangle$ line. The two beams have orthogonal linear polarizations and are combined by means of a polarizing beamsplitter cube (PBS). At the output of the 5 cm long room-temperature Rb vapor cell we can separate the beams again with another PBS. We then have the option of detecting either beam with a balanced detection setup [12]. Half-wave plates also enable us to recombine the two beams and measure the photon statistics of the sum and difference intensities of the two beams. From these we can extract the intensity correlations.

![Fig. 2. Sketch of the experimental setup. DL1 and DL2 extended-cavity diode lasers; RF: Faraday rotator; GP: glass plate; PBS: polarizing beamsplitter cube; S.A.: spectrum analyser.](image)

**Results and Discussions**

The usual EIT signal can be observed by sending only the probe beam into the detection region and measuring the DC (average) intensity. We measure the photon statistics (intensity fluctuations) for the probe beam, yielding the signal presented in Fig. 3(a). For the range of frequencies spanned, the photon statistics is always super-poissonian, but it presents a sharp peak (almost 20 dB) corresponding to the EIT resonance. In this measurement, the initial photon statistics of the probe beam is poissonian (for the frequency of analysis chosen) and the pump initially has super poissonian statistics. The pump photon statistics presents similar behavior, as seen in Fig. 3(b). In Fig. 3(c) and (d) we present the Fano factors for the fields. The Fano factor is given by the ratio of the intensity fluctuations to the average intensity (shot noise level), and we plot it on a linear scale. The probe and pump intensities were 14.5 mW/cm$^2$ and 63.8 mW/cm$^2$, respectively. The observed behavior agrees very well with the theoretical predictions of Fig. 1. For typical EIT signals, in the presence of a strong pump field, the shot noise level also peaks, as expected, following the increasing DC intensity on EIT resonance. However if we lower the pump power, this effect tends to disappear. The probe DC signal, and consequently the shot noise level, no longer show any evidence of a coherent effect in the atomic medium for pump intensities lower than 0.45 mW/cm$^2$, for a probe intensity of
13.3 mW/cm² (it is the ratio of pump to probe intensities that is relevant). On the other hand, by looking at the photon statistics, the coherent effect is still clearly identifiable (Fig. 4).

![Graph: Noise spectra of probe and pump beams](image)

**Fig. 3.** (a) and (b) Noise spectra of the probe and pump beams, respectively, as a function of the probe frequency and corresponding shot noise (in red) and electronic noise (lower traces); (c) and (d) Fano factors deduced from (a) and (b), respectively.

![Graph: Noise spectrum and Fano factor](image)

**Fig. 4.** Noise spectrum (a) and Fano factor (b) of the probe field for very weak pumping. Probe intensity: 13.3 mW/cm²; pump intensity: 0.44 mW/cm².

We also measured the noise properties of the sum and difference beam intensities. This is done by sending each beam to one of the detectors. By subtracting the intensity-difference noise from the intensity-sum, we observe a clear correlation on the EIT resonance. The corresponding shot noise level is measured by mixing the two beams so that each detector receives half of each beam. These results are presented in Fig. 5. We observe ~7 dB splitting between the sum and difference fluctuations.
Conclusions
We have measured the photons statistics of probe and pump beams after interaction with an atomic medium, in a situation of EIT. We observed superpoissonian statistics, peaked on EIT resonance. The experimental result features agree very well with our theoretical predictions. The balanced detection scheme leads to enhanced sensitivity for detecting coherent effects in the atomic medium. We have also observed intensity correlations between the two initially independent fields, as a result of their interaction with atoms. This correlation is the first step towards the observation of quantum correlations in this system.

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