Experimental Demonstration of Zero-Photon Subtraction

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Abstract: We demonstrate conditional attenuation of quantum optical states by subtracting zero photons at a variable beam splitter. The attenuation exhibits an interesting dependence on initial photon statistics that mirrors the effects of single-photon subtraction.

1. Introduction

In quantum optics, the bosonic annihilation operator $\hat{a}$ can be experimentally realized by "single-photon subtraction" (SPS), illustrated in Figure 1(a) [1]. The modified output state $|\psi\rangle_{out} \propto \hat{a}|\psi\rangle_{in}$ is heralded by the detection of one photon in the auxiliary mode of a weakly reflecting beamsplitter. This operation can generate useful states for quantum information such as Schrödinger kittens [2]. Additionally, SPS can dramatically alter the photon number distribution of quantum states and produce counterintuitive effects. In particular, applying SPS to super-Poissonian states results in a "photon excess" [3], in which the expected photon number of the output actually *increases* despite having "removed" one photon from the system [4].

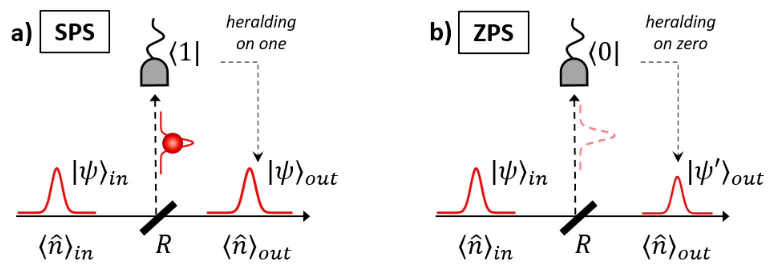

Figure 1 – (a) Single-photon subtraction (SPS) at a beamsplitter. (b) Zero-photon subtraction (ZPS). SPS can produce a "photon excess" $\langle\hat{n}\rangle_{out} > \langle\hat{n}\rangle_{in}$, while ZPS attenuates superpositions of Fock states: $\langle\hat{n}\rangle_{out} < \langle\hat{n}\rangle_{in}$. Note: SPS requires $R \ll 1$ to faithfully implement $\hat{a}$.

Somewhat surprisingly, subtracting *zero* photons in this manner can also modify quantum states [5]. Figure 1(b) shows zero-photon subtraction (ZPS) at a beamsplitter with reflectance $\boldsymbol{R}$. In contrast to SPS, ZPS is conditioned on a null measurement of zero photons in the reflected mode [6]. Despite no photons being lost, the heralded output $|\psi'\rangle_{out}$ has a lower expected photon number than the input, $\langle\hat{n}\rangle_{out} \leq \langle\hat{n}\rangle_{in}$, with equality holding only for pure Fock states [7]. This transformation amounts to *noiseless attenuation*, which has applications in quantum communications [8].

In this study, we experimentally demonstrate ZPS and observe reduction in mean photon number for several input states. As with SPS, the effects of ZPS depend on the statistics of the input state, exhibiting complementary behavior through a shared connection to Mandel's Q-parameter [9].

2. Experiment

We prepare three different input states for ZPS: (1) a coherent state $|\alpha\rangle$ (Poissonian statistics), (2) a single-mode squeezed vacuum (SMSV) state $|\xi\rangle$ (super-Poissonian), and (3) a single-photon mixture $\hat{\rho}_1 = (1-\beta)|0\rangle\langle 0| + \beta|1\rangle\langle 1|$ (sub-Poissonian). The coherent state is produced in a 100 MHz pulse train from a femtosecond fiber laser (Menlo Systems C-Fiber 780). These pulses are frequency-doubled and used to pump Type-II spontaneous parametric down-conversion (SPDC). The SPDC output is used to generate the SMSV and single-photon states with a combination of Hong-Ou-Mandel interference [10] and conditional measurements [5].

The beamsplitter in Figure 1(b) is implemented with a tunable fiber coupler, giving us variable reflectance R. The reflected mode is measured with an avalanche photodiode (APD) detector D_1, and ZPS succeeds when D_1 measures zero photons in a "no-click" event. The degree of attenuation is quantified with the ratio:

$$K(R) \equiv \frac{\langle\hat{n}\rangle_{out}}{(1-R)\langle\hat{n}\rangle_{in}}$$

where the numerator corresponds to the ZPS output, and the denominator corresponds to ordinary attenuation by beamsplitter without conditional measurements. The transmitted output mode is measured with a second APD D_2, and $K(R)$ is calculated using the rate of D_2 "clicks" with and without conditioning on a "no-click" at D_1 [5].

3. Summary of Results

The results are summarized in Figure 2, showing excellent agreement with theoretical predictions when accounting for experimental values of loss and detector inefficiency. The Poissonian coherent state serves as a benchmark with $K(R) = 1$ for all R, while the (super-)sub-Poissonian states exhibit (negative) positive slopes. The SMSV is attenuated more by ZPS than by ordinary attenuation ($K < 1$), exhibiting a "photon deficit" complementary to the "excess" of SPS. This highlights a connection between the two processes. Both the slope of $K(R)$ for ZPS and the change in mean photon number for SPS are given directly by Mandel's Q-parameter in the regime of weak reflectance $R \ll 1$.

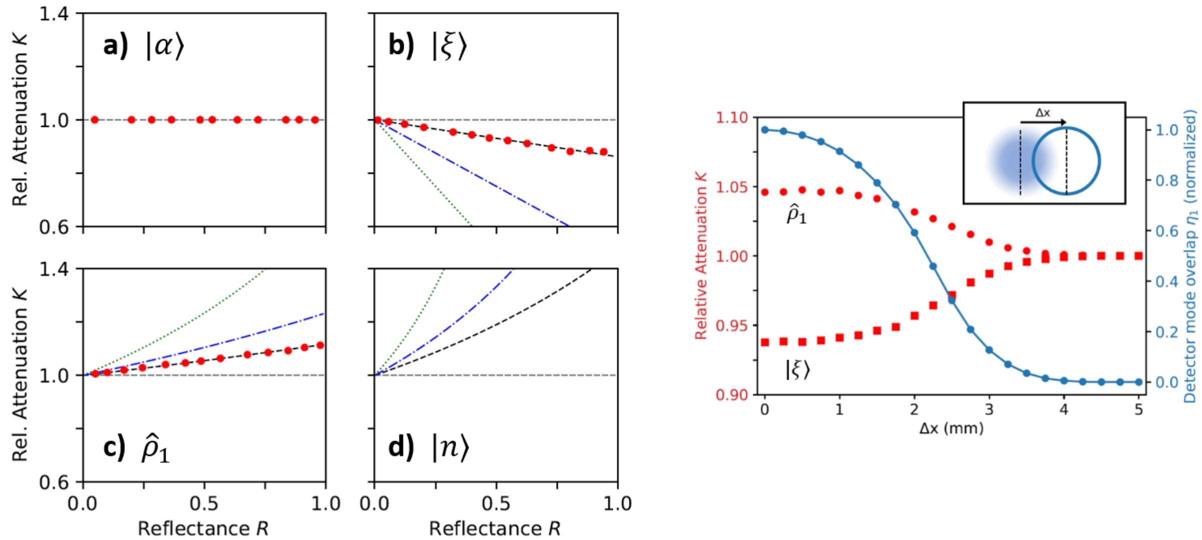

Figure 2 – On the left, the observed ZPS attenuation for three input states (a-c) and (d) a theoretical Fock state. Each curve indicates a different value of overall channel loss: dotted green is the ideal 0% case, dot-dashed blue is 50%, and dashed black is the higher experimental value. On the right, relative attenuation $K(R)$ for $R \approx 0.5$ converges to unity as the D_1 detection channel is displaced from the mode of interest by Δx.

Additionally, the efficacy of ZPS is reduced if the heralding D_1 channel is displaced from the mode of interest (right side of Figure 2), illustrating the necessity for low loss and high efficiency when heralding on zero [6].

4. References

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