Weakly invasive metrology: quantum advantage and physical implementations

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Abstract. One exciting prospect of quantum technologies are more precise photonic measurements through the use of quantum correlations [1]. Given a fixed (average) photon number N, a variety of quantum states can surpass the shot-noise limit imposed by coherent states, such as squeezed, NOON or twin Fock states [2]. One of the motivations to limit N is that some photosensitive materials, such as biological samples [3], may be damaged when they absorb too many photons. However, in this case it may be more meaningful to constrain the number of photons absorbed by the sample N_{abs}, instead of N [4]. While in interferometric measurements this constraint is equivalent to fixing N, in this work we show that it leads to qualitatively new results in frequency measurements in which photons are allowed to interact continuously with the sample.

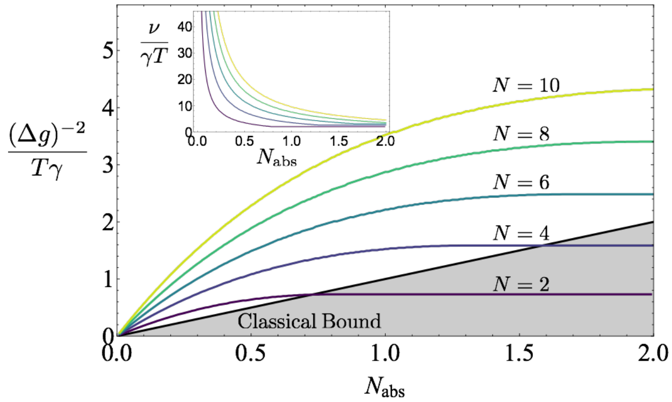

Figure 1 Measurement precision of the estimated parameter g per unit of time as a function of N_{abs} for twin Fock states (TFS) of low N, together with the classical bound for coherent states corresponding to the limit N to infinity, and infinite measurements. These results confirm the possibility of noticeable quantum advantages using low-photon entangled states over coherent states of arbitrary intensity in photosensitive samples.

We consider the measurement of a Hamiltonian parameter (with units of frequency) of a set of identical samples. We set as constraints the total time T of the experiment and N_{abs}, the number of photons that the sample can tolerate before being damaged or destroyed, and leave the photon number N unconstrained –in contrast to previous works on frequency measurements in atomic ensembles [5]. The samples are processed sequentially, and the same test is applied to each of them. Under those constraints, we prove that quantum metrological protocols involving a small amount $N \approx 5 - 10$ of photons (prepared in NOON or twin-Fock states) and a finite amount of samples, can overcome classical strategies using coherent states of (potentially) arbitrary intensity and an arbitrarily large number of samples —see Figure 1. That is, finite quantum resources for metrology (finite photon number, finite number of samples, finite time) become more powerful than infinite classical resources (unbounded photon number, unlimited number of samples, finite time) in frequency measurements of photosensitive samples. We derive general upper and lower bounds on the quantum advantage as a function of N_{abs}, and show that such enhancements can be realised in state-of-the-art technologies using a cavity or circuit QED setup. Our results suggest similar advantages in frequency measurements of delicate samples where photon absorption can be modelled as a Markovian process.

Keywords: Quantum Metrology, Photosensitive materials, Cavity QED.

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