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Quantum sensing of oscillating electric fields with trapped ions

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ABSTRACT

Quantum noise is a fundamental limitation for quantum sensors and results in the so-called shot-noise limit. Nowadays, several systems such as optical clocks or gravitational wave detectors approach measurement sensitivities where this limitation poses a major contribution to the total statistical uncertainty. It is known that this limit can be overcome by preparing the probe in a non-classical state.

We will give an overview over the different non-classical states that have been implemented in the motion of single trapped ions and discuss their individual advantages and limitations in metrology. Possible applications for the presented experiments are the measurement of small oscillating electric fields and trapping frequencies. The Focus will be on our experimental work on Fock states, where quantum-enhanced sensing in both scenarios is possible with the same quantum state.

1. Summary

The high level of control over the internal and external quantum states of single trapped ions makes them a promising platform not only for quantum computing [1] and optical clocks [2], but also as quantum sensors. Recent proposals for trapped ions as quantum sensors include gyroscopes [3], detectors for charged particles [4] and electric field sensors [5].

However, all these approaches have in common that the measured quantity is encoded in a qubit state of the ion. To reveal this information a quantum measurement is performed, which is associated with shot-noise, a noise process that originates from the quantum nature of the measurement probe. An intuitive explanation for this noise process is that in a projective measurement on a two-dimensional quantum system, the outcome is always one of the two eigenstates of the measurement operator. If the system was in a mixture or superposition of these states, the average over the outcome of multiple experimental cycles with identical settings can serve as an estimator for the expectation value of the observable for the underlying quantum state. For a finite number of repetitions N, the statistical uncertainty for the estimation of parameter θ is bounded by the Cramèr-Rao bound [6].

$$\Delta\theta \geq \frac{1}{\sqrt{\mathscr{F} N}}$$

where $\mathscr{F}$ is the Fisher information and can be interpreted as the “speed” of reduction of statistical uncertainty. The maximum of the Fisher information over all possible measurements is called the quantum Fisher information.

In the following we focus on displacement sensing, which is equivalent to a measurement of the change of the oscillation amplitude of the ion. In our previous work on Fock states [7], it was shown, that the quantum Fisher information for displacement sensing cannot exceed $\mathscr{F} = 4$ for classical motional states, i.e. states with a well-behaved Sudarshan-Glauber distribution. This limit is called the *standard quantum limit (SQL)*.

Preparing the ion in a non-classical state of motion allows to overcome the SQL. In the past, a variety of different non-classical states have been implemented. Here, we focus on the comparison of the three most prominent states, namely *squeezed states, Schrödinger cat states* and *Fock states* (see Fig. 1) and compare their performance with a particular focus on a scenario, where the phase of the oscillating force, that is sensed, is unknown. The result of this investigation is summarized in Fig. 2. Surprisingly, when averaged over the relative phase of the displacement and the orientation of the non-classical states, the performance of the quantum states is fully determined by the average phonon number. Only the dependence of the quantum gain on the exact phase is determined by the type of quantum state. Only the Fock state provides phase insensitive quantum gain in displacement sensing. Therefore, Fock states perform optimally in a scenario, where the phase is unknown, and the worst-case scenario must be assumed.

In our implementation with trapped ions, we focus on Fock-state metrology, while motional Schrödinger-cat states [9,10] and squeezed states [11,12] have been investigated before in displacement-sensing in single-ion scenarios. We trap a single $^{25}\mathrm{Mg}^{+}$ ion in a linear Paul trap and cool it to the motional ground state [12]. Two hyperfine states in $^{25}\mathrm{Mg}^{+}$

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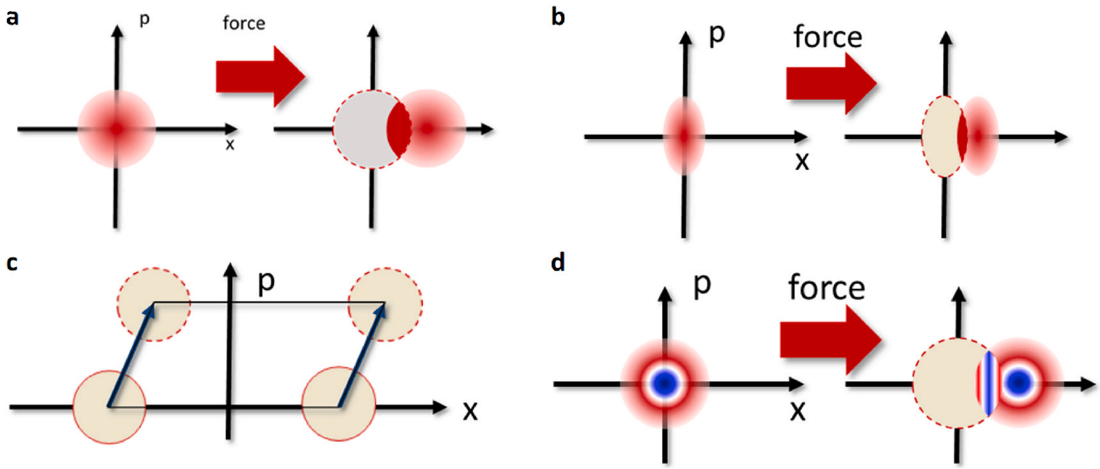

Fig. 1. Different displacement sensing schemes in phase space representation. **a** Vacuum state, **b** Squeezed state, **c** Schrödinger-cat state, **d** Fock state.

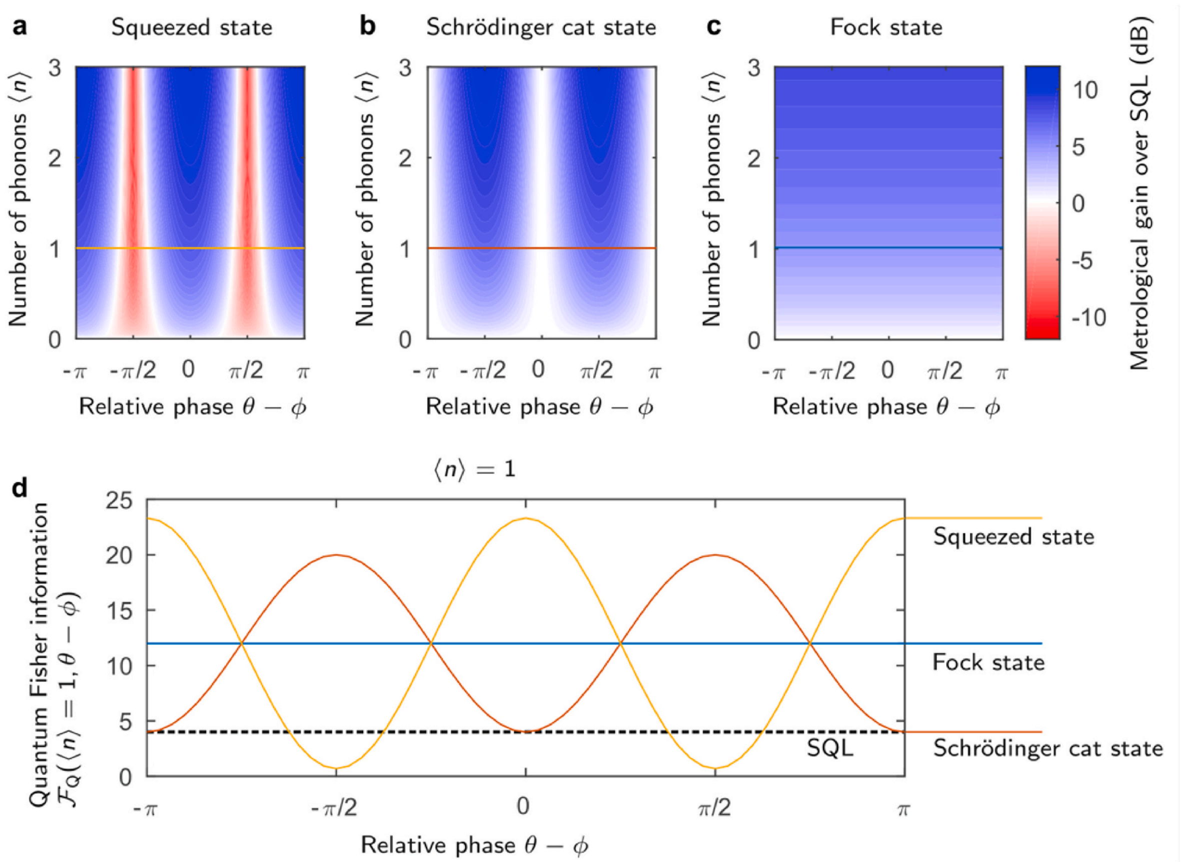

Fig. 2. Comparison of different non-classical states for displacement sensing. **a-c** show the quantum gain in a displacement measurement using the three different types of non-classical states for different average phonon numbers and different relative alignment between the orientation of the non-classical state and the displacement. **d** shows the quantum Fisher information for the three different states with an average motional excitation of a single photon. The dashed line shows the standard-quantum-limit. Reproduced from .[8]

serve as the qubit. The Fock state is produced by a sequence of side band pulses (see e.g. Ref. [13]). By applying an oscillating voltage between the endcap electrodes of the ion trap, we excite a coherent oscillation of the ion in the trap. The displacement measurement is performed by a STIRAP sequence [14], that maps the displacement information on the qubit state and subsequent fluorescence detection of the qubit state. In general, the operation that produces the non-classical state is laser driven and air pressure fluctuations can cause a disturbance of the phase from shot to shot. Therefore, robustness against these phase fluctuations is crucial for the performance of the protocol.

With this quantum-enhanced scheme, we could achieve sub-SQL scaling and a sensitivity in the measurement of the oscillating electric field amplitude of 7.5 $\frac{\mu V}{cm\sqrt{Hz}}$ and a final resolution of 56.0(31.2) $\frac{nV}{cm}$, that is still shot-noise limited and could further be improved by averaging more data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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