CEWQO 2019

Invited

Motional Fock states for quantum-enhanced amplitude and phase measurements with trapped ions

Fabian Wolf[1], Chunyan Shi[1], Jan C. Heip[1], Manuel Gessner[2], Luca Pezzè[2], Augusto Smerzi[2,4], Marius Schulte[3], Klemens Hammerer[3], and Piet O. Schmidt[1,4]

[1] Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany

[2] QSTAR, INO-CNR and LENS, Largo Enrico Fermi 2, I-50125 Firenze, Italy

[3] Institute for Theoretical Physics, Institute for Gravitational Physics (Albert Einstein Institute), Leibniz Universität Hannover, Appelstrasse 2, 30167 Hannover, Germany

[4] Institut für Quantenoptik, Leibniz Universität Hannover, 30167 Hannover, Germany

Abstract

We report on the experimental realization of a novel quantum metrology scheme based on motional Fock states in a trapped ion system. By measuring the overlap between a Fock state and the displaced Fock state, a displacement resolution below the standard quantum limit (SQL) independent of the displacement direction is possible. We demonstrate that this Fock-state metrology scheme can be employed to measure small forces as well as trapping frequencies with a resolution below the SQL. Among other applications, non-destructive state detection of molecular ions can benefit from this technique.

Advances in the ability to control quantum systems together with the suppression of classical noise originating from technical imperfections, has led to the emergence of sensors that are limited in their performance by quantum noise. For more than thirty years it has been known that certain types of non-classical states can reduce the effect of quantum noise and thus enhance the sensitivity of measurement devices beyond the classical limit [1]. Taking advantage of this sub-SQL sensitivity requires not only the preparation of the non-classical state with high fidelity, but also the prevention of signal loss in the entire measurement protocol. This has been achieved e.g. with squeezed states and Schrödinger-cat or N00N states in interferometric settings with photons and atoms. A common restriction of these types of non-classical states is the need for control over the relative phase between the state creation and the measurement interaction. In a phase-space picture, squeezing along the displacement direction enhances the sensitivity for amplitude measurements, but weakens the sensitivity for phase evolution measurements. Here we present sub-SQL measurements of amplitude and phase evolution of the motional state of a trapped ion using the same motional Fock state [2]. This is enabled by the implementation of a novel measurement scheme that allows direct detection of individual Fock state populations. We realize a displacement or force sensor by varying the amplitude of the ion's oscillation while the phase is kept constant. By using the same motional quantum state in a different protocol, the Fock state is displaced with a fixed amplitude in a Ramsey-like interferometry sequence to measure the phase evolution of the ion's oscillation. This implements a measurement of the oscillation frequency of the ion in the trap. Furthermore, we show that Fock states are optimal for sensing displacements for which the phase between creation and measurement interaction is unknown [2].

Besides applications in the measurement of small optical and electrical forces, this scheme could improve non-destructive state detection of a molecular ion using quantum logic techniques [3, 4].

[1] C. M. Caves, "Quantum-mechanical noise in an interferometer," Phys. Rev. D **23**, 1693 (1981).

[2] F. Wolf, C. Shi, J.C. Heip, M. Gessner, L. Pezzè, A. Smerzi, M. Schulte, K. Hammerer, and P.O. Schmidt, "Motional Fock states for quantum-enhanced amplitude and phase measurements with trapped ions," arXiv:1807.01875 (2018).

[3] P. O. Schmidt, T. Rosenband, C. Langer, W. M. Itano, J. C. Bergquist, and D. J. Wineland, "Spectroscopy Using Quantum Logic," Science **309**, 749–752 (2005).

[4] F. Wolf, Y. Wan, J. C. Heip, F. Gebert, C. Shi, and P. O. Schmidt, "Non-destructive state detection for quantum logic spectroscopy of molecular ions," Nature **530**, 457–460 (2016).