CEWQO 2019

Non-gausian states for enhanced sensing of magnetic fields (experiment)

Vasiliy Makhalov, Alexandre Evrard, Thomas Chalopin, Tanish Satoor, Jean Dalibard, Raphael Lopes, and Sylvain Nascimbene

Laboratoire Kastler Brossel, Collège de France, CNRS, ENS-PSL University, Sorbonne Université, 11 Place Marcelin Berthelot, 75005 Paris, France

March 1, 2019

Abstract

We report on preparation of non-gaussian (oversqueezed) states of electronic spin of a highly magnetic atom. Non-classical states are produced within the one-axis twisting Hamiltonian evolution induced by spin-dependent light-shifts. Single magnetic sublevel resolution allows full characterization of the quantum state and to quantity its sensitivity under small magnetic field variations. We demonstrate that the oversqueezed state reaches an optimal sensitivity about half the Heisenberg limit and well above the sensitivity of the squeezed state. The optimal sensitivity is reached at shorter evolution times (up to factor 5) than the time of a fully entangle NOON state, which paves the way for future metrological measurements with enhanced robustness against environmental noise.

In a quantum mechanical measurement, when one aims at detection of response of a quantum probe to external impact, the result will always contain uncertainty, even if experimental conditions are perfect. The uncertainty is manifested in quantum fluctuations of a measured quantity which are fundamentally non-zero [1]. Statistics allows reduction of uncertainty by a factor of $\sqrt{N}$, where N is the number of independent measurements or a number of probes. Such scaling is known as the Standard quantum limit(SQL). The fluctuations can be reduced with an entangled quantum state of the probe, leading to increase in precision [2]. The ultimate limit of precision is known as the Heisenberg limit and constitutes scaling of N. There are different families of quantum states which help to overcome the SQL, for instance, squeezed states. In the most common protocols for the squeezed states, uncertainty can be reduced by a factor of $N^{2/3}$ [3]. Such states are characterized by gaussian quantum fluctuations. States with non-gaussian quantum fluctuations (oversqueezed ones) contain high-order correlation, thus leading to a higher metrological gain [4]. However, accessing these correlations is highly challenging since it requires to measure high-order statistical moments.

We use ultracold samples of atomic Dysprosium to study the magnetic-field sensitivity of gaussian and non-gaussian quantum spin states, encoded for each atom in its electronic spin of size $J = 8$ – equivalent to a set of $2J = 16$ elementary spin-1/2 particles. We use spin-dependent light shifts to induce non-linear dynamics described by the one-axis twisting Hamiltonian [3]: $\hat{H} = \hbar\chi J_x^2$. These dynamics generate gaussian squeezed states at short times before the stretching of spin distribution leads to non-gaussian 'oversqueezed' states. Single magnetic sublevel resolution (extracted by Stern-Gerlach experiment) gives us access to the magnetic sensitivity hidden in non-gaussian quantum fluctuations, yielding a spectroscopic enhancement of 8.6(6) compared to the SQL, consistent with the maximum sensitivity $J + 1/2$ expected for oversqueezed states and about half the Heisenberg limit. The Heisenberg limit $G = 16$ could in principle be achieved using the maximally entangled N00N state [5]; however, the required interaction time is much longer than the time of an oversqueezed state (up to factor of 5). This makes the NOON state more fragile to decoherence. Oversqueezed states thus appear as a compromise which superposes both enhanced robustness against environmental noise and enhanced sensitivity.

[1] : C. W. Helstrom, *Quantum detection and estimation theory*, J. Stat. Phys **1**, 231 (1969).

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

[3] : M. Kitagawa and M. Ueda *Squeezed spin states*, Phys Rev A **47**, 5138 (1993).

[4] : M. Gessener, A. Smerzi, and L. Pezzè *Metrological Nonlinear Squeezing Parameter*, arXiv:1811.12443 (2018).

[5] : T. Monz, P. Schindler, J. T. Barreiro, M. Chwalla, D. Nigg, W. A. Coish, M. Harlander, W. Hänsel, M. Hen- nrich, and R. Blatt *14-Qubit Entanglement: Creation and Coherence*, Phys. Rev. Lett. **106**, 130506 (2011).