Atomic Clocks Below the Standard Quantum Limit

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State-of-the-art atomic clocks and other atomic interferometers operate at or near the standard quantum limit (SQL), where the device precision is dominated by the quantum projection noise of the atomic ensemble. The standard quantum limit can be overcome by using a quantum correlated (entangled) state of the atomic ensemble as input state to the Ramsey sequence.

One class of entangled states that can be used to overcome the SQL are squeezed spin states[2]. In these states, the quantum noise is redistributed so as to decrease the noise in the variable of interest (the phase of the Bloch vector) at the expense of increased noise in another variable (the z-component of the Bloch vector) that does no directly affect measurement precision.

The generation of entangled states in an atomic ensemble requires an interaction between the atoms. While this interaction can be provide by interatomic collisions in a Bose-Einstein condensate, such collisions are generally not desirable for atomic clocks, as they reduce the ultimately achievable accuracy of the device. Alternatively, it is possible to provide effective atom-atom interactions via the atoms' coupling to a light beam[3,4]. This has the advantage that the effective interaction can be used for preparation of the squeezed input state, but turned off completely during the ensuing Ramsey sequence.

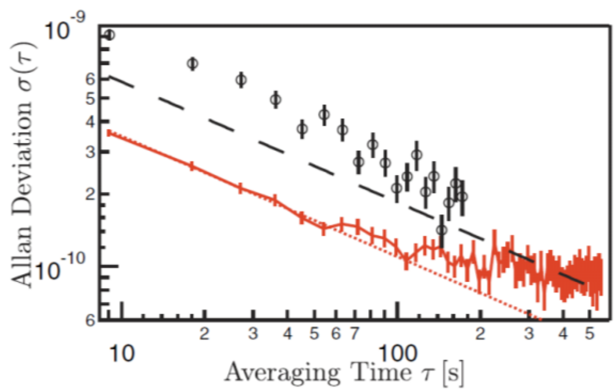

Fig. 1: Allan deviation of a squeezed clock operating below the SQL. The solid red line with error bars was measured using a squeezed input state. The open black circles were measured with a traditional clock using an uncorrelated input state. The dashed black line indicates the SQL. From Ref. [1].

We have realized a squeezed atomic clock operating on the hyperfine clock transition of ^{87}Rb. While the absolute precision is modest, the clock clearly surpasses the SQL for the same atom number and interrogation time (see Fig. 1). We are currently building an optical-transition atomic clock using Yb atoms to demonstrate spin squeezing in a state-of-the-art system.

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[2] D. J. Wineland, J. J. Bollinger, W.M. Itano, F. L. Moore, and D. J. Heinzen, "Spin squeezing and reduced quantum noise in spectroscopy", Phys. Rev. A **46**, R6797 (1992).

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