Pseudo-Spin Squeezing on an Atomic-Clock Transition

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The best atomic clocks perform at the ”standard quantum limit” set by the projection noise of uncorrelated individual two-level atoms[1]. Even higher precision can in principle be obtained from entangled ensembles[2,3,4]. In the Bloch vector representation, where the N-atom system is represented by an angular momentum $J = N/2$, such entanglement can take the form of spin squeezing[5], where the uncertainty of a component transverse to the Bloch vector is reduced below the coherent-state value $\sqrt{J/2}$.

We report measurement-induced spin squeezing on the $|F{=}1, m_F{=}0\rangle$ to $|F{=}2, m_F{=}0\rangle$ hyperfine clock transition in a sample of ^{87}Rb atoms trapped inside an optical resonator. After preparing a superposition of clock states with a $\pi/2$ pulse, we non-destructively measure the atom number difference between the two states. The measurement is performed by observing the frequency shift of one resonator mode induced by the atomic-state dependent index of refraction. Such measurement-induced squeezing requires the optical depth OD of the sample to be large. In our present system, $OD \leq 6000$.

We observe 7 dB of spin squeezing at a modest measurement-induced reduction in clock fringe visibility, corresponding to an improvement in clock sensitivity due to the squeezing. We discuss current limitations and possible future improvements, including an implementation with higher clock accuracy using magnetically trapped atoms[6,7] We believe that such squeezing methods hold great promise for further increasing the accuracy of optical clocks in a magic-wavelength optical lattice[8,9]

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[1] G. Santarelli, Ph. Laurent, P. Lemonde, A. Clairon, A. G. Mann, S. Chang, A. N. Luiten, and C. Salomon, “Quantum Projection Noise in an Atomic Fountain: A High Stability Cesium Frequency Standard”, Phys. Rev. Lett. **82**, 619 (1999).

[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).

[3] D. J. Wineland, J. J. Bollinger, W. M. Itano, and D. J. Heinzen, “Squeezed atomic states and projection noise in spectroscopy”, Phys. Rev. A **50**, R67 (1994).

[4] V. Meyer, M. A. Rowe, D. Kielpinski, C. A. Sackett, W. M. Itano, C. Monroe, and D. J. Wineland, “Experimental Demonstration of Entanglement-Enhanced Rotation Angle Estimation Using Trapped Ions”, Phys. Rev. Lett. **86**, 5870 (2001).

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

[6] D. M. Harber, H. J. Lewandowski, J. M. McGuirk, and E. A. Cornell, “Effect of cold collisions on spin coherence and resonance shifts in a magnetically trapped ultracold gas”, Phys. Rev. A **66**, 053616 (2002).

[7] Ph. Treutlein, Peter Hommelhoff, Tilo Steinmetz, Theodor W. Hänsch, and Jakob Reichel, “Coherence in Microchip Traps”, Phys. Rev. Lett. **92**, 203005 (2004).

[8] M. Takamoto, F.-L. Hong, R. Higashi, and H. Katori, “An optical lattice clock”, Nature **435**, 321 (2005).

[9] T. Ido, T. H. Loftus, M. M. Boyd, A. D. Ludlow, K. W. Holman, and J. Ye, “Precision Spectroscopy and Density-Dependent Frequency Shifts in Ultracold Sr”, Phys. Rev. Lett. **94**, 153001 (2005).