Nonlinear interferometer giving ultra-sensitive atomic spin measurements

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A nonlinear interferometer experiences phase shifts ϕ that depend on N, the particle number, e.g. $\phi = \kappa N \mathcal{Y}$ for a Kerr-type nonlinearity $\mathcal{Y}$, where κ is a coupling constant. This implies a shot-noise-limited sensitivity $\Delta\mathcal{Y} \propto N^{-3/2}$ even without quantum enhancement [1]. In contrast, entanglement-enhanced linear measurement achieves at best the so-called "Heisenberg limit" $\Delta\phi = N^{-1}$.

The faster scaling of the nonlinear measurement suggests a decisive technological advantage for sufficiently large N [2–9]. However, no experiment has yet employed improved scaling to give superior absolute sensitivity, and several theoretical works [10–13, 16] cast doubt upon this possibility for practical and/or fundamental reasons.

Here we demonstrate that a quantum-noise-limited nonlinear measurement can indeed achieve a sensitivity unreachable by any linear measurement. We study in detail the sensitivity and scaling of nonlinear Faraday rotation by alignment-to-orientation conversion (AOC) recently used to generate spin-squeezing [17] via quantum non-demolition measurement [18] in an optical magnetometer. Relative to earlier nonlinear strategies [19], AOC allows increasing N by an order of magnitude, giving 20 dB more signal and 10 dB less noise. The resulting spin alignment sensitivity surpasses by 9 dB the best possible sensitivity of a linear measurement with the same resources. This demonstrates the practical advantage of nonlinear measurement in a quantum-limited scenario [20].

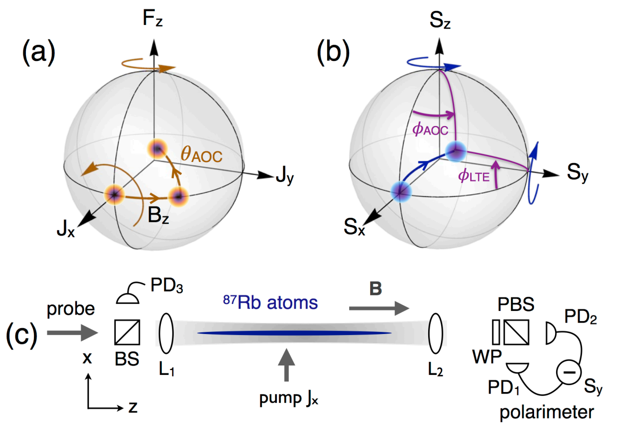

FIG. 1. AOC measurement of atomic spins. (a) An unknown field B_z rotates an initially J_x–polarized state in the J_x–J_y plane. The J_y component is detected using an S_x–polarized probe, which produces a rotation of J_y toward F_z by an angle θ_{AOC}. (b) Simultaneously, paramagnetic Faraday rotation produces a rotation of S_x toward S_y. The net effect is a nonlinear rotation ϕ_{AOC}, observed by detecting S_y. (c) Experimental geometry.

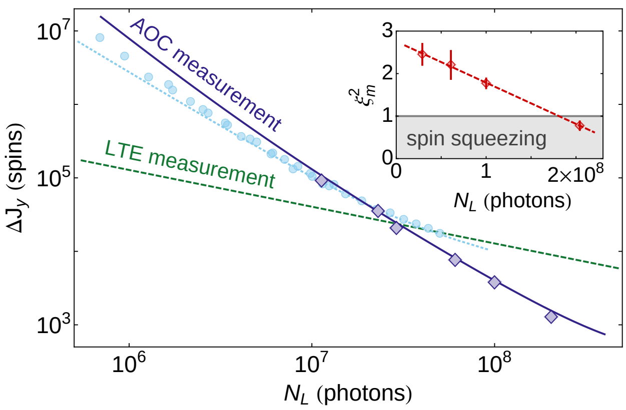

FIG. 2. Log–log plot of the uncertainty ΔJ_y of the AOC measurement. Nonlinear enhanced scaling of the sensitivity is observed over more than one order of magnitude. Blue curve: theory, with no free parameters. Dashed green curve: ideal linear measurement of J_y. Error bars for standard errors would be smaller than the symbols and are not shown. Inset: Metrologically significant spin squeezing as a function of photon number.

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