Measurements with prediction and retrodiction on the collective spin of 10^{11} atoms beat the standard quantum limit

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Quantum probes using N uncorrelated particles give a limit on the measurement sensitivity referred to as the standard quantum limit (SQL). The SQL, however, can be overcome by exploiting quantum entangled states, such as spin squeezed states. We report generation of a quantum state, that surpasses the SQL for probing of the collective spin of 10^{11} Rb atoms contained in a vapor cell. The state is prepared and veried by sequences of stroboscopic quantum non-demolition (QND) measurements, and we apply the theory of past quantum states to obtain the spin state information from the outcomes of both earlier and later QND measurements. In this way, we obtain a conditional noise reduction of 5.6 dB, and a metrologically-relevant squeezing of 4.5 ± 0.40 dB. The past quantum state yields tighter information on the spin component than we can obtain by a conventional QND measurement. Our squeezing results are obtained with 1000 times more atoms than in any previous experiments with a corresponding record $4.6 \times 10^{-13} rad^2$ variance of the angular uctuations of a squeezed collective spin [1]. We have applied the protocol to experimentally demonstrate a quantum-enhanced atomic magnetometer, and also illustrated the retrodiction beyond the Heisenberg uncertainty relation [2].

[1] Han Bao, Junlei Duan, Shenchao Jin, Xingda Lu, Pengxiong Li, Weizhi Qu, Mingfeng Wang, Irina Novikova, Eugeniy E. Mikhailov, Kai-Feng Zhao, Klaus Mølmer, Heng Shen, and Yanhong Xiao, Spin squeezing of 10^{11} atoms by prediction and retrodiction measurements, , Nature **581**, 159-163 (2020)

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