Noisy atomic magnetometry in the linear-Gaussian regime

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Quantum atomic sensors that operate in real time must be described by means of continuous measurement theory. When sensing an external magnetic field in the linear-Gaussian regime, they have been predicted to ideally achieve the ultimate Heisenberg limit imposed by quantum mechanics. In our work, we rigorously study how such conclusions change when the inevitable impact of imperfections is taken into account. In particular, we solve the sensor dynamics and construct the optimal field estimator in the form of a Kalman filter, while accounting for the collective noise, as well as stochastic fluctuations of the field in time. Although we prove that even an infinitesimal amount of noise makes the Heisenberg limit unattainable, we demonstrate that the canonical continuous measurement model is then sufficient in various noise regimes to efficiently spin-squeeze the ensemble and achieve the optimal quantum enhancement of precision. We are able to do so by resorting to the quantum version of the Bayesian Cramér-Rao Bound and establishing its continuous-time form, which applies irrespective of the ensemble initial state and its conditional dynamics.