Improved Quantum Magnetometry beyond the Standard Quantum Limit

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In a *quantum metrology* protocol, a number of particles (N) are prepared, subjected to an evolution which depends on the parameter of interest, and measured. From the measurement results the parameter is then estimated. When particles are classically correlated and non-interacting, the Mean Squared Error (MSE) of the estimate decreases at best as $1/N$, following the *Standard Quantum Limit* (SQL) [2]. Yet, in the ideal noiseless setting, quantum resources allow for a quadratic improvement, i.e. the MSE of the estimate after a sufficient number of experimental repetitions can scale as $1/N^2$ yielding the the so-called *Heisenberg Limit* [2].

On the other hand, it has been proved that generic uncorrelated noise-types constrain the ultimate asymptotic scaling to be SQL-like [3], so that the MSE at best scales as c/N, where $c<1$ is a noise-determined, N-independent constant which inverse specifies then the ultimate quantum enhancement. However, the possibility of super-classical scaling has recently been demonstrated, for the first time, for an uncorrelated Markovian noise-model—*transversal dephasing*—which in principle allows for a $1/N^{5/3}$-scaling and thus an unconstrained quantum enhancement [4].

We argue [1] that such a noise model applies to *atomic magnetometry* experiments exhibiting *local T_2-spin-decoherence*, in particular, the one of [5] schematically depicted in Fig. 1. An atomic ensemble is subjected to a strong magnetic field B determining the energetic-level splittings, so that the system may be described as a collection of N qubits. In the protocol, a weak radio-frequency field B_{rf} is sensed that precesses in the perpendicular plane. We show that by considering *One-Axis-Twisted Spin-Squeezed states* and *Ramsey-type Measurements* a resolution of $1/N^{5/4}$ may then be even attained. In contrast to the original scheme [5] presented in Fig. 1(a) yielding SQL-bounded resolutions, in order to fully benefit from the geometry, one must prepare atoms with their mean, collective angular-momentum perpendicular initially to both B and B_{rf}, see Fig. 1(b).

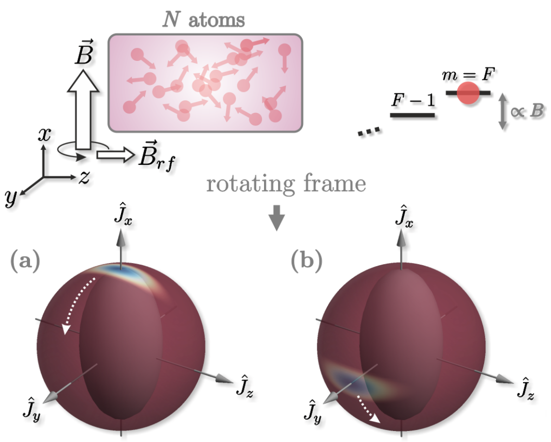

FIG. 1. Atomic magnetometry setup of [5], and the two potential preparation scenarios (a)/(b) of the atomic ensemble, yielding presented *squeezed* collective angular-momentum distributions.

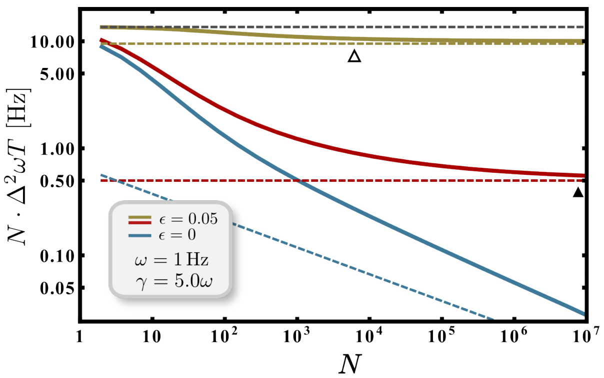

FIG. 2. Achievable resolutions ($\Delta^2\omega T$) for pure spin-decoherence noise [*blue*] ($\epsilon=0$), as compared when other noise sources are present ($\epsilon=0.05$). Same quantum-enhancement value is marked [*triangles*] for scenario (a) [*yellow*] and scenario (b) [*red*] to manifest robustness of the latter for much larger probe-sizes (N).

In our work [1], we consider experimental details of [5], in order to explicitly quantify real resolution-improvements reachable by the above geometry-based method. Moreover, we study the impact of other decoherence sources that, despite being much smaller, may often be non-negligible, e.g. the *T_1-spin-relaxation*. As depicted in Fig. 2, we show that they may still be made irrelevant by optimising the geometry, what postpones their effects to much larger N, despite the SQL-like scaling being then inevitable as $N\to\infty$.

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