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Beyond Mean-Field: Modelling Atom Interactions in Compact Rotation Sensors

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Atomic matter-wave interferometers have demonstrated exceptional long-term stability in precision rotation sensing under controlled laboratory conditions [1]. Translating this performance to compact, mobile platforms could revolutionise navigation technologies. Guided matter-wave gyroscopes, which confine ultracold atomic gases in optical potentials, offer a promising route toward miniaturisation and ruggedisation [2]. However, the tight confinement required for portability inherently enhances interatomic interactions—introducing complex many-body effects that are absent in free-space configurations [3].

To assess the feasibility of such devices, it is essential to quantify how atom-atom interactions degrade interferometric sensitivity. In this work, we present a detailed numerical characterisation using the multi-mode truncated Wigner (TW) method [4], which captures quantum fluctuations and spontaneous scattering processes beyond the scope of mean-field Gross-Pitaevskii treatments [5]. We also perform an analytical analysis using a simple few mode ansatz in order to fully understand the underlying mechanisms by which the atom-atom interactions cause significant degradation.

By isolating and characterising the degradation due to phase diffusion and four-wave mixing, we identify optimal operating regimes and design parameters for guided matter-wave gyroscopes. This work lays the foundation for compact, high-precision rotation sensors suitable for mobile platforms, and highlights the necessity of many-body quantum modelling in the development of practical cold atom technologies.

[1] R. Geiger et al. *AVS Quantum Sci.* 2, 024702 (2020).

[2] M. M. Beydler et al. *AVS Quantum Sci.* 6, 014401 (2024).

[3] T. L. Gustavson et al. *Class. Quantum Grav.* 17, 2385 (2000).

[4] S. A. Haine, *New J. Phys.* 20, 033009 (2018).

[5] J. L. Helm et al. *Phys. Rev. Lett.* 114, 134101 (2015).

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