Superradiant Criticality and Quantum-Enhanced Sensing in a Quantum Rabi Ring

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Quantum many-body system operating near criticality can exhibit high-precision sensing capabilities. In this work, we investigate a quantum Rabi ring (QRR), formed by coupled quantum Rabi sites with tuneable light-matter coupling strength, hopping phase, and number of sites. The hopping phase generates an effective artificial magnetic flux through the ring, providing a controllable parameter for tuning the superradiant phase transition and its associated critical points.

We analyse how the critical behaviour depends on these parameters and obtain phase diagrams that differ remarkably between odd and even number of sites. This distinction reveals a parity-dependent structure that can be exploited for sensing. To quantify the sensing performance, we use the quantum Fisher information (QFI), which measures the sensitivity of the quantum state to small parameter changes. Near the phase transition, the QFI increases sharply and is expected to diverge in the ideal critical limit.

We further compare the sensing enhancement with relevant resource costs, including the total photon number and the adiabatic preparation time, which is estimated from the inverse of the first excitation gap. This comparison provides a framework for assessing whether increasing the number of sites enhances the metrological gain under resource constraints.

These results suggest that critical quantum Rabi rings provide a promising platform for resource-aware quantum-enhanced sensing.