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Quantum sensing of a quantum field

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Abstract: Estimating a classical parameter encoded in the Hamiltonian of a quantum probe is a fundamental and well-understood task in quantum metrology. A textbook example is the estimation of a classical field's amplitude using a two-level probe, as described by the semi-classical Rabi model. In this work, we explore the fully quantum analogue, where the amplitude of a coherent quantized field is estimated by letting it interact with a two-level atom. For both metrological scenarios, we focus on the quantum Fisher information (QFI) of the reduced state of the atomic probe. In the semi-classical Rabi model, the QFI is independent of the field amplitude and grows quadratically with the interaction time τ. In contrast, when the atom interacts with a single coherent mode of the field, the QFI is bounded by 4, a constant dictated by the non-orthogonality of coherent states. We find that this bound can only be approached in the vacuum limit. In the limit of large amplitude α, the QFI is found to attain its maximal value 1.47 at $\tau=O(1)$ and $\tau=O(\alpha2)$, and also shows periodic revivals at much later times. When the atom interacts with a sequence of coherent states, the QFI can increase with time but is bounded to scale linearly due to the production of entanglement between the atom and the radiation (back-action), except in the limit where the number of modes and their total energy diverge. Finally, in the continuous-field limit, where the atom interacts with a continuous source of weak coherent states, this back-action can be simply interpreted as spontaneous emission; we find that the optimal atomic QFI rate is finite, depends on the source intensity, and is upper bounded by the constant rate at which the QFI is emitted by the radiation source.
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