Quantum ergotropy: breaking passivity by fully-quantum approach to energy extraction

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Ergotropy, the maximum extractable energy from a quantum system via cyclic unitary operations, traditionally stems from a semi-classical perspective, where a quantum system, such as an atom, interacts with a classically treated field like a laser. This approach inherently overlooks the key genuine quantum features such as the field statistics, atom-field entanglement, population collapse and revival, quantum fluctuations, and so on. To explore the impact of a fully quantum approach, we investigate energy extraction in the paradigmatic Jaynes-Cummings model, where an atom interacts with a single-mode electromagnetic field under the rotating wave approximation. We consider the field initially prepared in a coherent state, ensuring consistency with the semi-classical regime for large coherent amplitudes. Introducing *quantum ergotropy*—the extractable energy under a fully quantum framework—we demonstrate that this approach significantly enhances energy extraction, particularly in the low to moderate coherent amplitude regime, where quantum ergotropy can substantially exceed its conventional counterpart. Remarkably, we find that states considered passive in the semi-classical framework, such as the maximally mixed state, can become energetic and provide useful work in the fully quantum approach. Additionally, by analyzing the signal-to-noise ratio of the field state, we highlight the practical utility of the extracted energy. Beyond enhancing the extractable energy, we show that the fully quantum approach facilitates faster energy extraction, reducing the optimal time for maximal energy transfer from the atom to the field. Our findings provide deeper insights into a promising direction for energy extraction from quantum systems and highlight the advantages of a fully quantum approach. This work paves the way for further investigations into optimizing quantum energy transfer and developing more efficient quantum energy storage devices.