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Operator Spectral Statistics, Chaos, and Asymptotic Freeness in Quantum Many-Body Systems

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We systematically investigate the {\it spectral statistics of operators} in quantum many-body systems, focusing on their connections to quantum chaos and free probability theory. Specifically, we numerically analyze the mixed-field Ising model with disorder, the Sachdev-Ye-Kitaev (SYK) model, and a random unitary model, using direct diagonalization to study the eigenvalue density, nearest-neighbor level spacing statistics, and r-parameter statistics. Our results show that the dynamics can be classified as chaotic, integrable, or near-integrable based on the asymptotic freeness of the fundamental operators of the theory, leading to universal behavior in the eigenvalue density of certain combinations of operators. We also discuss the implications of these findings for correlation functions and how the concept of freeness connects different manifestations of quantum chaotic behavior. Finally, we assess the utility of the spectral statistics of out-of-time-order operators in diagnosing chaos across different dynamical regimes.

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