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Microscopic Encoding of Macroscopic Universality: Scaling properties of Dirac Eigenspectra near QCD Chiral Phase Transition

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Macroscopic properties of the strong interaction near its chiral phase transition exhibit scaling behaviors, which are the same as those observed close to the magnetic transition in a 3-dimensional classical spin system with $O(4)$ symmetry. We show the universal scaling properties of the chiral phase transition in Quantum Chromodynamics (QCD) at the macroscale are, in fact, encoded within the microscopic energy levels of its fundamental constituents, the quarks. We establish a connection between the cumulants of the chiral order parameter, i.e. the chiral condensate, and the correlations among the energy levels of quarks in the background of gluons, i.e. the eigenspectra of the massless QCD Dirac operator. This relation elucidates how the fluctuations of the chiral condensate arise from the correlations within the infrared part of the energy spectra of quarks, and naturally leads to generalizations of the Banks–Casher relation for the cumulants of the chiral condensate. Then, through (2+1)-flavor lattice QCD calculations with varying light quark masses near the QCD chiral transition, we demonstrate the correlations among the infrared part of the Dirac eigenvalue spectra exhibit same universal scaling behaviors as expected of the cumulants of the chiral condensate. We find that these universal scaling behaviors extend up to the physical values of the up and down quark masses. Our study reveals how the hidden scaling features at the microscale give rise to the macroscopic universal properties of QCD.

Topical area

QCD at Non-zero Temperature

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