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Phase structure of lattice QCD in the heavy quark high-density region and the three-state Potts model

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The nature of the finite temperature phase transition of QCD depends on the particle density and the mass of the dynamical quarks. It is known that the transition is first order in the region of zero density and heavy quark mass, and also first order in the region of light quark mass when the number of flavors is large. The intermediate region is the crossover region, and numerical simulations of lattice QCD have shown that the critical mass at which the first-order phase transition turns into a crossover in the heavy quark region increases with increasing density. When investigating high-density regions in lattice QCD simulations, a problem known as the sign problem arises, making research difficult. However, in regions where quarks are sufficiently heavy, the sign problem is relatively less serious, making research possible. On the other hand, the critical mass at which the first-order phase transition in the light quark region ends is also expected to increase with increasing density. If the region of the first-order phase transition in the light quark regime continues to expand with increasing density, the critical point should reach the heavy quark region where it can be studied.

In this study, we discuss whether there is a first-order phase transition region in the heavy quark high-density region that is different from the first-order phase transition in the low-density region. There is an effective theory that describes the heavy quark high-density limit of QCD. This effective theory is a simple model in which the Polyakov loop is a dynamical variable, and the quark Boltzmann factor is controlled by only one parameter, $C(\mu, m)$, which is a function of the mass m and the chemical potential μ . The Polyakov loop is the order parameter of the $Z(3)$ symmetry that is broken at the finite-temperature phase transition of QCD. We consider that the fundamental properties of a phase transition are determined only by the symmetry broken by the phase transition and the dimension of the space. By using an approximation in which the Polyakov loop is replaced by a $Z(3)$ spin, we find that the effective model is a three-dimensional three-state Potts model ($Z(3)$ spin model) with a complex external field term. We investigate the phase structure of the Potts model and apply it to QCD in the heavy quark region. As the density varies from $\mu = 0$ to $\mu = \infty$, we find that the phase transition is first order in the low-density region, changes to a crossover at the critical point, and then becomes first order again. This strongly suggests the existence of a first order phase transition in the high-density heavy quark region of QCD.

Parallel Session (for talks only)

QCD at nonzero temperature and density

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