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Chiral Symmetry Restoration in Nucleus Observed in Pionic Atoms

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We conducted experimental and theoretical studies of chiral condensate in the nuclear medium through precision spectroscopy of pionic Sn atoms and subsequent analyses. The chiral condensate at $\sim 60\%$ of the nuclear saturation density is found to be reduced by $23 \pm 2\%$ compared to that in the vacuum.

topics: chiral symmetry, pionic atoms, quantum chromodynamics (QCD), vacuum

1. Introduction

What is the nature of the matter that constitutes our world? How was it formed, and what will be its fate in the future? These are fundamental questions that have been posed since the earliest times, related to the evolution of matter. In order to answer these questions, it is essential to consider the evolution of the ground state, i.e., the vacuum. Our study focuses on the meson–nucleus bound systems [1]. The objective is to elucidate the structure and properties of the vacuum by employing mesons as probes to investigate the modification of

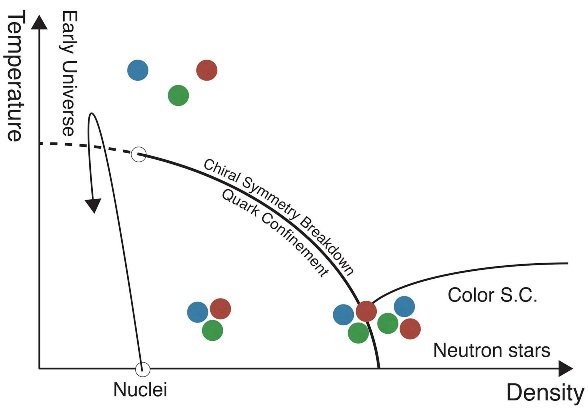

Fig. 1. QCD phase diagram.

the quantum chromodynamics (QCD) vacuum due to the medium effect of the high-density matter, i.e., the nuclei [2, 3].

Figure 1 illustrates the phase diagram of the vacuum on the plane of temperature and density. In the early universe at high temperatures, quarks exist in the quark–gluon plasma phase, where they have relatively long mean free paths. As the temperature decreases, the nature of the strong interactions, which are strongly coupled at low energies, makes the "empty" vacuum unstable, hence the vacuum contains a non-trivial structure. Theoretical studies indicate that as the temperature decreases, down to the present low-temperature universe, quark confinement and chiral phase transitions occur [4], resulting in the combining of quarks as hadrons and the condensation of quark–antiquark pairs in the vacuum. The expectation value of the chiral condensate $\langle \bar{q}q \rangle$, the quark–antiquark pair, is an order parameter of the chiral symmetry of the QCD vacuum. Its temperature dependence has recently been greatly improved by lattice QCD calculations that simulate QCD from the first principles [5, 6]. However, lattice QCD has computational difficulties due to the sign problems with respect to density dependence, and an understanding based on experimental data is particularly needed.

2. Chiral condensate and meson spectra

The quark–antiquark condensation in the vacuum cannot be observed directly in measurements, but can be estimated indirectly by their influence on various observables. For example, the pseudoscalar mesons (π, K, η, η'), which are the members of the lowest-mass nonet, are expected to degenerate upon the full manifestation of the chiral symmetry. A large mass difference between η and η' can be explained by axial U(1) quantum anomaly [7]. In this way, the hadron mass distribution reflects the properties of the bulk vacuum, and systematic observation will lead to an understanding of the properties of the vacuum [8]. This is similar to Mössbauer spectroscopy, which uses iron atoms as probes. The absorption spectrum is affected by electric and magnetic fields and reflects the symmetry of the vicinity of the iron sites. The phase diagram of a QCD vacuum is similar to that of a high-temperature superconductor at different temperatures and carrier concentrations. In the case of QCD, the dense matter of the nuclei can be regarded as impurities doped into the vacuum. This high density affects the chiral symmetry.

One of the features of spectroscopic measurements of meson–nucleus bound states is the identification of the quantum states. This provides information on the density effect with the least ambiguities. The binding energy and width of the state directly reflect the real and imaginary parts of the low-energy interaction of the meson with the nucleus. The interaction is modified by the medium effects of the high-density nuclei, including the restoration of chiral symmetry. As will be described below, we have succeeded in the quantitative evaluation of the reduction of $\langle \bar{q}q \rangle$ of the vacuum in nuclei by means of high-precision spectroscopy of the pionic atoms [1]. This result strongly supports the scenario that the vacuum has a structure and that its symmetry changes with the loaded density.

3. Spectroscopy of pionic atoms

Although X-ray measurements of the atomic de-excitation are widely used for the spectroscopy of the pionic atoms, we employ $(d, {}^3\mathrm{He})$ reaction for the production of the deeply bound pionic atoms with the incident deuteron energy of 250 MeV/u [9]. In the reaction, the pionic atoms are excited directly from the nucleus. By kinematically controlling the momentum of the pions, it is possible to selectively excite the quantum orbitals. For the same reason, the excitation cross-section is scattering-angle-dependent. In our pilot experiment (RIBF-27), measurements were carried out in the scattering angle (θ) range of 0–2 degrees for the first time [10]. The θ dependence was found to be in good agreement with theoretical expectations [11]. On the other hand, for the absolute value of the cross-section, the theory overestimates the cross-section by a factor of about 5 for the $1s$, although it agrees for the $2p$ state. This discrepancy, which is only observed in the $1s$ state, is interesting, but its origin is not understood to date.

The spectroscopic resolution of the pionic atoms requires extremely high precision to detect modification of the interaction for the medium effects and to determine the $\langle \bar{q}q \rangle$ changes. The incident beam momentum spread makes one of the largest contributions to the resolution. A way to solve

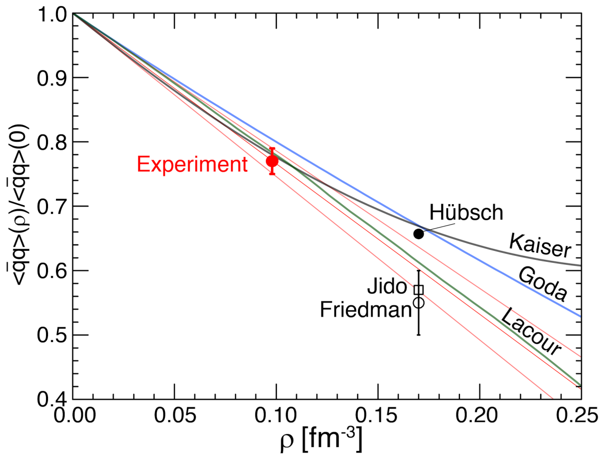

Fig. 2. Deduced in-medium $\langle\bar{q}q\rangle(\rho)/\langle\bar{q}q\rangle(0)$ and comparison with theories. The presently acquired data are shown by a red circle with error bars. Theoretical density dependent $\langle\bar{q}q\rangle$ is shown in black [20–24]. The red lines are linear extrapolation of the present data.

this without compromising the beam intensity is to construct dispersion-matching optics that analyze the primary beam momentum at the target. We have constructed dispersion-matching optics without modifying the existing accelerator and the beamline configurations at the Radioactive Ion Beam Factory (RIBF) [12] by calculating the ion optics taking into account the inside of the cyclotron accelerator and by developing a new optics setup method. This resulted in an improvement in spectral resolution in our new experiment (RIBF-54) [1]. A remaining experimental challenge is the calibration of the spectra. By measuring spectra with large θ, we simultaneously observed the $1s$ and $2p$ states of a pionic tin atom. This simultaneous observation drastically suppresses major systematic errors by taking into account the difference between the states. From the high-precision spectra thus obtained, the binding energies and widths are determined.

4. Conclusions

We quantitatively evaluate the order parameter of chiral symmetry $\langle\bar{q}q\rangle$ in the nuclear matter by deriving the interaction between the pion and the nucleus based on the binding energies and widths obtained above. During the derivation, we combined the latest knowledge of the density distribution of nuclei and nuclear reaction data with theoretical support to minimize the ambiguities [13–19]. Figure 2 shows $\langle\bar{q}q\rangle$ dependence on the density (see also [20–24]). The vertical axis represents the chiral condensate $\langle\bar{q}q\rangle$. The experimental result shown in red is $\langle\bar{q}q\rangle$ near 60% of the nuclear saturation density (density 0.099 fm^{-3}); the magnitude of $\langle\bar{q}q\rangle$ is reduced by $23 \pm 2\%$ [1]. This result is in good agreement with the predictions of the chiral effective theories (curves and points in the diagram) and strongly supports the scenario of the chiral condensate in the vacuum. To take this further forward, we are conducting systematic spectroscopy of Sn isotopes to determine the density derivative of the chiral condensate $d\langle\bar{q}q\rangle/d\rho$ in an experiment (RIBF-135R1). An experiment to measure pionic Xe isotope in an inverse kinematics reaction (RIBF-214) is also in preparation.

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