Chiral symmetry restoration at high matter density observed in pionic atoms†

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Based on theoretical and experimental studies, the magnitude of chiral symmetry breaking is believed to depend on the temperature and the matter-density.[1)] Whereas hadronic matters at zero and high temperature have been well investigated, the experimental knowledge at finite densities is limited. Pionic atoms, bound systems of a π^- and a nucleus, provide quantitative information of an order parameter of the chiral symmetry breaking, or the quark condensate ($\langle\bar{q}q\rangle$), in nuclei.[2)] A major part of the pion wavefunction is located near the surface of the nucleus ($\rho \simeq 0.098$ fm^{-3}) in a counter balance between the Coulomb interaction and the s-wave pion-nucleus strong interaction. For pionic atoms with relatively heavy nuclei, the binding energies and widths of the pionic $1s$ states are predominantly determined by the s-wave strong interaction modified by the medium effect. The isovector scattering length b_1, the density dependent parameter, is model-independently related to the ratio of $\langle\bar{q}q\rangle$ in the vacuum ($\rho = 0$) and the medium with density ρ by

$$\frac{\langle\bar{q}q\rangle(\rho)}{\langle\bar{q}q\rangle(0)} \simeq \left(\frac{b_1(0)}{b_1(\rho)}\right)^{1/2}\left(1-\gamma\frac{\rho}{\rho_c}\right), \tag{1}$$

where $\rho_c \equiv 0.17$ fm^{-3} is the normal nuclear density and the coefficient $\gamma = 0.184 \pm 0.003$.[3)]

At RIBF, we established a new method of formation and observation of pionic atoms to achieve high spectral resolution ($\simeq$300 keV) in the nuclear reactions with the scattering angles θ up to several degrees,[4)] by applying the ion-optical "dispersion-matching" technique. As a result, we succeeded in the precise measurements of deeply bound pionic $1s$ and $2p$ states of ^{121}Sn simultaneously, reducing the systematic errors arising from energy calibration, beam optics aberration, and other factors. The optical potential parameters, including b_1, were deduced to reproduce the measured binding energies ($B_\pi(1s), B_\pi(2p)$) and natural widths ($\Gamma_\pi(1s)$, $\Gamma_\pi(2p)$), taking into account the statistical and systematic errors and their correlations. The analysis was performed incorporating the recent experimental and theoretical progress, such as neutron density distribution data in Sn,[5)] calculation with the Green Function method,[6)] and residual interaction between the pion and the nucleus with a neutron-hole.[7)]

Finally, we deduced the π^--nucleus isovector parameter $b_1 = (-0.1163 \pm 0.0056)\ m_\pi^{-1}$. This value is enhanced by $34 \pm 7\%$ compared with the isovector strength in vacuum of $b_1 = (-0.0866 \pm 0.0010)\ m_\pi^{-1}$.[8)] This enhancement agrees with the predicted values of ∼30% in the chiral perturbation theory.[9)] This agreement endorses the theoretical perspectives on the chiral symmetry breaking and its partial restoration in the nuclear matter. By linear extrapolation to the normal nuclear density of $\rho_c = 0.17$ fm^{-3}, we conclude that $\langle\bar{q}q\rangle(\rho_c)$ is $60 \pm 3\%$ lower than $\langle\bar{q}q\rangle(0)$. These deduced factors will serve as a new basis to construct a comprehensive understanding of the origin of the hadron masses and the structure of the vacuum.

We are preparing systematic studies of pionic atoms with higher precision to further investigate the low-energy high-matter-density sector of the QCD.[10)]

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References

1) W. Weise, Nucl. Phys. A **553**, 59 (1993).
2) K. Suzuki *et al.*, Phys. Rev. Lett. **92**, 072302 (2004).
3) D. Jido *et al.*, Phys. Lett. B **670**, 109 (2008).
4) T. Nishi *et al.*, Phys. Rev. Lett. **120**, 152505 (2018).
5) S. Terashima *et al.*, Phys. Rev. C **77**, 024317 (2008).
6) N. Ikeno *et al.*, Prog. Theor. Exp. Phys. **2015**, 033D01 (2015).
7) N. Nose-Togawa *et al.*, Phys. Rev. C **71**, 061601 (2005).
8) A. Hirtl *et al.*, Eur. Phys. J. A **57**, 70 (2021).
9) G. Chanfray *et al.*, Phys. Lett. B **563**, 61 (2003).
10) S. Matsumoto *et al.*, RIKEN Accel. Prog. Rep. **55**, 10 (2022).

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