

Chiral symmetry restoration in nuclear medium observed in pionic atoms

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Summary. — We interpret the spectral information of the pionic $1s$ and $2p$ states in the ^{121}Sn nucleus observed with unprecedented precision and resolution with respect to the in-medium pion-nucleus interaction to deduce partial restoration of the chiral symmetry in the high density of the nuclear matter. Most recent theoretical and experimental results are integrated to obtain the precision information on the partial restoration of the chiral symmetry. We find reduction of the chiral condensate in the Sn nucleus by a factor of $77 \pm 2\%$ at the nucleon density of 0.098 fm^{-3} . The result is compared with the chiral theories showing fairly good agreement.

1. – Introduction

Deeply bound pionic atoms have repulsive level shifts in the lowest orbitals representing the dominance of the s -wave strong interaction [1, 2], which is subject to modification in the nuclear medium effect [3]. Experimental and theoretical analyses of the the medium effect contribute to the understanding of the chiral symmetry at the high density using the pion as a probe [4, 5]. The s -wave interaction is modified due to the partial restoration of the chiral symmetry in the high-density nuclear matter through the wavefunction renormalization of the medium effects [6]. The expectation value of the chiral condensate $\langle \bar{q}q \rangle$ is an order parameter of the chiral symmetry, and its absolute value is known to be reduced at high temperature or high density [3]. The temperature dependence has been studied in the lattice QCD calculations, which show a phase transition near $T \sim 150$ MeV [7, 8]. High-energy nuclear collision experiments report the observation of the color deconfinement phase transition to the quark-gluon-plasma phase [9], where the color degree of freedom is manifested. It should be noted that the quark confinement transition must have a strong correlation with the chiral transition, but the relationship has not yet been elaborated [16]. There are experimental projects to measure the mass modifications of the pseudoscalar or vector mesons in the nuclear medium [10, 11]. However, our experimental knowledge of the density dependence of $\langle \bar{q}q \rangle$ has been limited. The powerful tool of the lattice QCD calculations faces the difficulties of the sign problems in the high densities.

The repulsive s -wave interaction provides information on $\langle \bar{q}q \rangle$ at nuclear densities. The interaction is phenomenologically described by an optical potential in Ericson-Ericson formulation [12]. The isoscalar $b_0\rho$ and $\text{Re}B_0\rho^2$ terms are correlated [13] indicating that the pion is sensitive to the potential at the effective density $\rho_e \simeq 0.098$ fm⁻³ [14], which corresponds to the overlap between the pion wavefunction and the nuclear densities. Since the isoscalar interaction is small, the leading term is the isovector term $b_1(\rho_n - \rho_p)$. Theoretically, b_1 has ρ dependence for the medium effect. Considering the wavefunction renormalization, the b_1 parameter is model-independently related to in-medium $\langle \bar{q}q \rangle$ [5] at the density ρ_e probed by the pionic atoms as

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

where $\rho_c \equiv 0.17$ fm⁻³ is the normal nuclear density and the coefficient $\gamma = 0.184 \pm 0.003$. $b_1^v = -0.0866 \pm 0.0010 m_\pi^{-1}$ denotes pion-nucleon isovector interaction determined in pionic hydrogen and deuterium measurements [15].

2. – Experiment and Analysis

We made a spectroscopy experiment of pionic ¹²¹Sn atoms to deduce $\langle \bar{q}q \rangle(\rho_e)/\langle \bar{q}q \rangle(0)$ through determination of b_1 . A key is to achieve high resolution and high statistical sensitivity. Simultaneous observation of the pionic $1s$ and $2p$ states [17] contributes largely to reduction of the systematic errors. However, this requires very high statistical sensitivity. The experiment was performed at the RI Beam Factory (RIBF), RIKEN. We employed deuteron beam of 10¹²/s with the energy of 250 MeV/nucleon. The deuteron beam impinged on a ¹²²Sn target with the thickness of 12.5 ± 0.5 mg/cm² to make ($d, ^3\text{He}$) reactions. The emitted ³He is momentum-analyzed by the fragment separator BigRIPS [18]. We installed two sets of multiwire-drift-chambers to measure the ³He

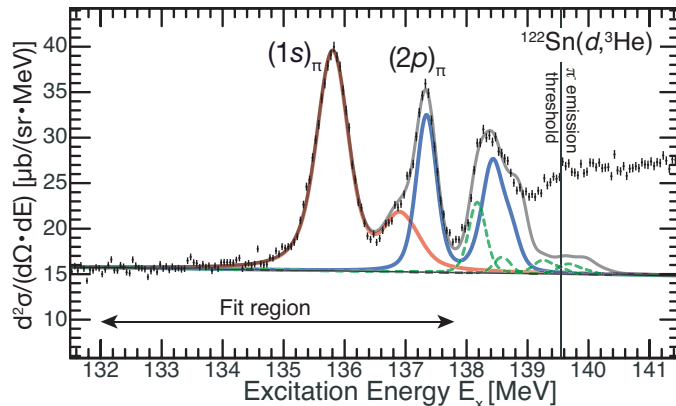


Fig. 1. – Measured excitation spectrum of the $(d, {}^3\text{He})$ reaction for $\theta < 1.5$ degrees. The peak near $E_x = 135.7$ MeV is assigned to formation of pionic ${}^{121}\text{Sn}$ atoms in the $1s_\pi$ state and a smaller peak near $E_x = 137.3$ MeV to the $2p_\pi$ state. The grey curve shows a fitting of the spectrum in the E_x region indicated by the arrows.

tracks. The largest resolution contribution was the beam momentum spread. We developed a dedicated ion-optics [19] to realize a dispersion matching condition [20] for the primary deuteron beam, which reduced the contribution.

The produced pionic atoms are coupled with neutron hole states mainly of $2d_{3/2}$, $3s_{1/2}$ and $2d_{5/2}$ [21]. We measured the missing mass spectrum near the pion emission threshold for the scattering angle $\theta < 1.5$ degrees as depicted in Fig. 1. The vertical bars show the statistical errors. As seen in the error bars, we achieved very high statistics. The abscissa is the excitation energy E_x of the reaction products. The π^- emission threshold is shown by the vertical line. The ordinate is the double differential cross sections. Note that the absolute value of the differential cross sections is associated with systematic uncertainty of about 30%. The energy resolution has a parabolic E_x dependence, and the best energy resolution is achieved to be 287 keV (FWHM) near $E_x \sim 138.5$ MeV.

The largest peak near $E_x = 135.7$ MeV is assigned to formation of pionic $1s_\pi$ state coupled with neutron hole states of $3s_{1/2}$. The second largest peak near the excitation energy $E_x = 137.3$ MeV is mainly contributed from $2p_\pi$. We have made a fit of the spectrum with a sum of theoretical spectra of each state calculated by the effective number approach [21]. We made use of recent data of the spectroscopic factors of ${}^{122}\text{Sn}$ [22] in calculation of the theoretical spectra. Fitting parameters are the binding energies (B_π), widths (Γ_π) and cross sections of the $1s_\pi$ and $2p_\pi$ states and a linear background. The fitting region was $E_x = [132.0, 137.8]$ MeV. The fitting region is indicated by the arrows. We achieved $B_\pi(1s) = 3830 \pm 3(\text{stat.})_{-76}^{+78}(\text{syst.})$ keV, $B_\pi(2p) = 2265 \pm 3(\text{stat.})_{-83}^{+84}(\text{syst.})$ keV, $\Gamma_\pi(1s) = 1565 \pm 11(\text{stat.})_{-40}^{+43}(\text{syst.})$ keV, and $\Gamma_\pi(2p) = 314 \pm 12(\text{stat.})_{-28}^{+49}(\text{syst.})$ keV, with the fitting $\chi^2/\text{n.d.f.} = 231.3/108$. A remarkable fact is the accuracy of the differences $B_\pi(1s) - B_\pi(2p) = 1565 \pm 4 \pm 11$ keV and $\Gamma_\pi(1s) - \Gamma_\pi(2p) = 194 \pm 16_{-42}^{+31}$ keV, where a large fraction of the systematic errors is eliminated in the binding energies since the systematic errors are mainly contributed from the E_x calibration.

The spectroscopic information of the pionic atoms sets constraints on the pion-nucleus interaction. Solving Klein-Gordon equation, we have calculated theoretical binding energies and widths, and compared with the B_π and Γ_π obtained above to calculate the likelihood. In the likelihood calculation, we have taken into consideration the statistical and systematic errors with correlations, and combined pionic-atom information

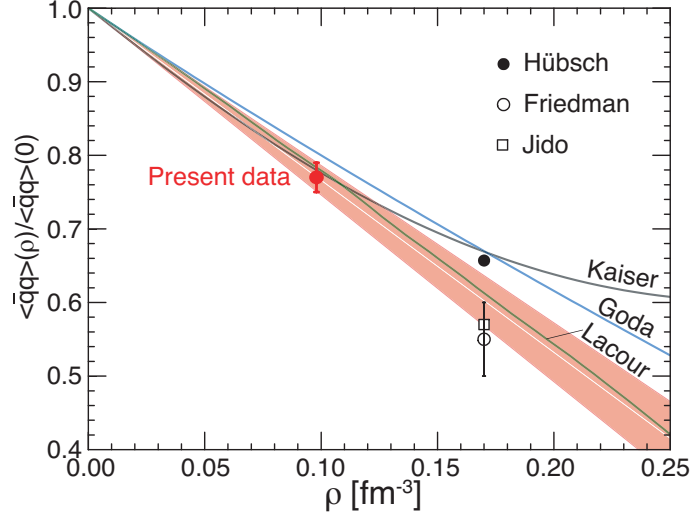


Fig. 2. – Deduced in-medium $\langle \bar{q}q \rangle(\rho) / \langle \bar{q}q \rangle(0)$ and comparison with theories.

of light spherical nuclei of ^{16}O , ^{20}Ne , and ^{28}Si [23] to set constraints in the isoscalar terms. The p -wave parameters are fixed to the “Global-2” parameters in Table 2 of Ref [24]. We thus obtained a likelihood contour on the plane of the isovector parameter b_1 and the absorption parameter $\text{Im}B_0$, which has a maximum at $b_1 = -0.0952m_\pi^{-1}$ and $\text{Im}B_0 = 0.0469m_\pi^{-4}$. This achieved value shows slight deviation from the value in a preceding experiment $b_1 = -0.1149 \pm 0.0074m_\pi^{-1}$ and $\text{Im}B_0 = 0.0472 \pm 0.0013m_\pi^{-4}$.

Before deduction of in-medium $\langle \bar{q}q \rangle$, we have introduced several corrections to improve the accuracy. We have considered differences in the theoretical spectra calculated by the effective number approach [21] and Green’s function method [25], differences in the $\rho_n(r)$ between the two-parameter Fermi model and high precision data of proton elastic scattering experiment [26], and the residual interaction between the pion and the nucleus [27]. These corrections affect the likelihood contour, and the finally deduced values are $b_1 = -0.1163 \pm 0.0056m_\pi^{-1}$ and $\text{Im}B_0 = 0.0473 \pm 0.0013m_\pi^{-4}$.

3. – Discussion and Conclusion

The above deduced b_1 at $\rho = \rho_e$ is larger than in-vacuum $b_1^v = -0.0866 \pm 0.0010m_\pi^{-1}$ [15] showing clear enhancement of the pion-nucleus repulsive interaction due to the wavefunction renormalization. The deduced b_1 coincides with the preceding value of $b_1 = -0.1149 \pm 0.0074m_\pi^{-1}$. However, applying the corrections listed above, they exhibit a discrepancy of about two sigmas. Now we calculate eq.1 and obtain $\langle \bar{q}q \rangle(\rho_e) / \langle \bar{q}q \rangle(0) = 0.77 \pm 0.02$. Thus deduced in-medium $\langle \bar{q}q \rangle$ is compared with values in the chiral effective theories. Figure 2 shows the deduced value in the red filled circle with the error bars. The red hatched region shows an extrapolation in linear density approximation to obtain $\langle \bar{q}q \rangle(\rho_c) / \langle \bar{q}q \rangle(0) = 60 \pm 3\%$ at the normal nuclear density $\rho_c = 0.17 \text{ fm}^{-3}$. Theoretical values in Refs. [5, 28, 29, 30, 31, 32] are also presented showing fairly good agreement.

For further studies, we have performed a systematic measurements of pionic Sn atoms to deduce the density derivative of $\langle \bar{q}q \rangle$. Experimental determination of the $d\langle \bar{q}q \rangle / d\rho$ at $\rho \sim \rho_e$ serves not only as confirmation of the theories but elaborate the insight of the non-trivial structure of the QCD vacuum.

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