IL NUOVO CIMENTO **47 C** (2024) 229
DOI 10.1393/ncc/i2024-24229-2

Colloquia: HADRON2023

Chiral symmetry restoration in nuclear medium observed in pionic atoms

K. Itahashi(1)(2), T. Nishi(1), D. Ahn(1)(3), G. P. A. Berg(4), M. Dozono(1), D. Etoh(5), H. Fujioka(6), N. Fukuda(1), N. Fukunishi(1), H. Geissel(7), E. Haettner(7), T. Hashimoto(2)(8), R. S. Hayano(9), S. Hirenzaki(10), H. Horii(9), N. Ikeno(11), N. Inabe(1), M. Iwasaki(1)(2), D. Kameda(1), K. Kisamori(12), Y. Kiyokawa(12), T. Kubo(1), K. Kusaka(1), M. Matsushita(12), S. Michimasa(12), G. Mishima(9), H. Miya(1), D. Murai(1), H. Nagahiro(10), M. Niikura(9), N. Nose-Togawa(13), S. Ota(12)(*), N. Sakamoto(1), K. Sekiguchi(5), Y. Shiokawa(5), H. Suzuki(1), K. Suzuki(13), M. Takaki(12), H. Takeda(1), Y. K. Tanaka(2), T. Uesaka(1), Y. Wada(5), A. Watanabe(5), Y. N. Watanabe(9), H. Weick(7), H. Yamakami(6), Y. Yanagisawa(1) and K. Yoshida(1)

(1) *RIKEN Nishina Center for Accelerator-Based Science, RIKEN - Saitama, Japan*
(2) *RIKEN Cluster for Pioneering Research, RIKEN - Saitama, Japan*
(3) *Center for Exotic Nuclear Studies, Institute for Basic Science (IBS) Daejeon, Republic of Korea*
(4) *Department of Physics and the Joint Institute for Nuclear Astrophysics Center for the Evolution of the Elements, University of Notre Dame - Notre Dame, IN, USA*
(5) *Department of Physics, Tohoku University - Sendai, Japan*
(6) *Department of Physics, Kyoto University - Kyoto, Japan*
(7) *GSI Helmholtzzentrum für Schwerionenforschung GmbH - Darmstadt, Germany*
(8) *Advanced Science Research Center, Japan Atomic Energy Agency - Ibaraki, Japan*
(9) *Department of Physics, School of Science, University of Tokyo - Tokyo, Japan*
(10) *Department of Physics, Nara Women's University - Nara, Japan*
(11) *Department of Life and Environmental Agricultural Sciences, Faculty of Agriculture, Tottori University - Tottori, Japan*
(12) *Center for Nuclear Study, University of Tokyo - Saitama, Japan*
(13) *Research Center for Nuclear Physics, Osaka University - Osaka, Japan*

received 21 December 2023

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.

(*) Present address: Research Center for Nuclear Physics, Osaka University - Osaka, Japan

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 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 wave function 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 $T \sim 150\,\mathrm{MeV}$ [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 [10]. There are experimental projects to measure the mass modifications of the pseudoscalar or vector mesons in the nuclear medium [11,12]. 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 [13]. The isoscalar $b_0\rho$ and $\mathrm{Re}B_0\rho^2$ terms are correlated [14] indicating that the pion is sensitive to the potential at the effective density $\rho_e \simeq 0.098$ fm^{-3} [15], which corresponds to the overlap between the pion wave function 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 wave function 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

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

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 [16].

2. – Experiment and analysis

We made a spectroscopy experiment of pionic ^{121}Sn 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 10^{12}/s with an energy of 250 MeV/nucleon. The deuteron beam impinged on a ^{122}Sn target with a thickness of 12.5 ± 0.5 mg/cm^2 to make $(d, {}^3\mathrm{He})$ reactions. The emitted ^{3}He is momentum-analyzed by the fragment separator BigRIPS [18]. We installed two sets of multi-wire drift chambers to measure the ^{3}He tracks. The largest

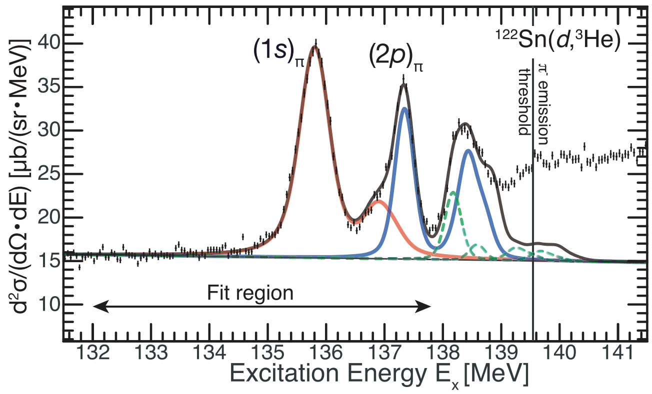

Fig. 1. – Measured excitation spectrum of the $(d, {}^3\mathrm{He})$ reaction for $\theta < 1.5$ degrees. The peak near $E_x = 135.7\,\mathrm{MeV}$ is assigned to formation of pionic ${}^{121}\mathrm{Sn}$ atoms in the $1s_\pi$ state and a smaller peak near $E_x = 137.3\,\mathrm{MeV}$ to the $2p_\pi$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

contribution to the resolution 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 $E_x \sim 138.5\,\mathrm{MeV}$.

The largest peak near $E_x = 135.7\,\mathrm{MeV}$ is assigned to the formation of pionic $1s_\pi$ state coupled with neutron hole states of $3s_{1/2}$. The second largest peak near the excitation energy $E_x = 137.3\,\mathrm{MeV}$ 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 on the spectroscopic factors of ${}^{122}\mathrm{Sn}$ [22] in the 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 $E_x = [132.0, 137.8]\,\mathrm{MeV}$. The fitting region is indicated by the arrows. We achieved $B_\pi(1s) = 3830 \pm 3(stat.)^{+78}_{-76}(syst.)$ keV, $B_\pi(2p) = 2265 \pm 3(stat.)^{+84}_{-83}(syst.)$ keV, $\Gamma_\pi(1s) = 1565 \pm 11(stat.)^{+43}_{-40}(syst.)$ keV, and $\Gamma_\pi(2p) = 314 \pm 12(stat.)^{+49}_{-28}(syst.)$ keV, with the fitting $\chi^2/\mathrm{n.d.f.} = 231.3/108$. A remarkable fact is the accuracy of the differences $B_\pi(1s) - B_\pi(2p) = 1565 \pm 4 \pm 11$ keV and $\Gamma_\pi(1s) - \Gamma_\pi(2p) = 194 \pm 16^{+31}_{-42}$ 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 the Klein-Gordon equation, we have calculated theoretical binding energies and widths, and compared them with the B_π and Γ_π obtained above to calcu-

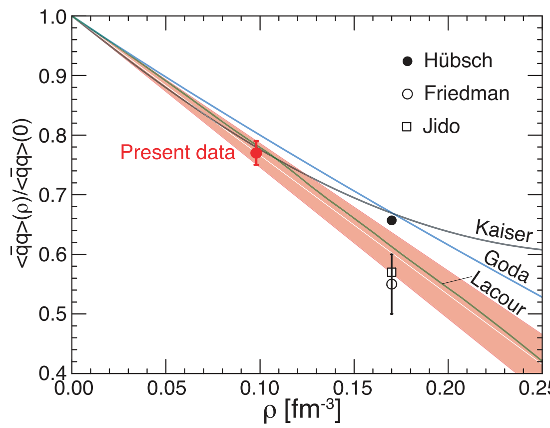

Fig. 2. – Deduced in-medium $\langle \bar{q}q \rangle (\rho)/\langle \bar{q}q \rangle (0)$ and comparison with theories.

late the likelihood. In the likelihood calculation, we have taken into consideration the statistical and systematic errors with correlations, and combined pionic-atom information 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 ImB_0, which has a maximum at $b_1 = -0.0952 m_\pi^{-1}$ and Im$B_0 = 0.0469 m_\pi^{-4}$. This achieved value shows a slight deviation from the value in a preceding experiment $b_1 = -0.1149 \pm 0.0074\ m_\pi^{-1}$ and Im$B_0 = 0.0472 \pm 0.0013\ m_\pi^{-4}$.

Before deduction of in-medium $\langle \bar{q}q \rangle$, we have introduced several corrections to improve its 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 $b_1 = -0.1163 \pm 0.0056\ m_\pi^{-1}$ and Im$B_0 = 0.0473 \pm 0.0013\ m_\pi^{-4}$.

3. – Discussion and conclusion

The above-deduced b_1 at $\rho = \rho_e$ is larger than in-vacuum $b_1^v = -0.0866 \pm 0.0010\ m_\pi^{-1}$ [15] showing clear enhancement of the pion-nucleus repulsive interaction due to the wave function renormalization. The deduced b_1 coincides with the preceding value of $b_1 = -0.1149 \pm 0.0074\ m_\pi^{-1}$. 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 $\rho_c = 0.17$ fm^{-3}. Theoretical values in refs. [5, 28-32] are also presented, showing fairly good agreement.

For further studies, we have performed systematic measurements of pionic Sn atoms to deduce the density derivative of $\langle \bar{q}q \rangle$. Experimental determination of the $\mathrm{d}\langle \bar{q}q \rangle/\mathrm{d}\rho$ 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.

* * *

The authors thank the staff of the RIBF for the stable operation. This experiment was performed at RIBF operated by RIKEN Nishina Center and CNS, University of Tokyo. This work is partly supported by Grants-in-Aid for Scientific Research (Nos. JP22105517, JP24105712, and JP15H00844, JP16340083, JP18H01242, JP16H02197, JP20540273, JP24540274, JP19K14709, JP12J08538, JP20KK0070), Institute for Basic Science (IBS-R031-D1), the Bundesministerium für Bildung und Forschung, and the National Science Foundation through Grant No. Phys-0758100, and the Joint Institute for Nuclear Astrophysics through Grants No. Phys-0822648 and No. PHY-1430152 (JINA Center for the Evolution of the Elements).

REFERENCES

[1] Nishi T. *et al.*, *Nat. Phys.*, **19** (2023) 788.
[2] Itahashi K., *Pionic Atoms in Experiment*, in *Hand. Nucl. Phys.*, edited by Tanihata I., Toki H. and Kajino T. (Springer, Singapore) 2023, pp. 2657–2697.
[3] Weise W., *Nucl. Phys. A*, **553** (1993) 59.
[4] Suzuki K. *et al.*, *Phys. Rev. Lett.*, **92** (2004) 072302.
[5] Jido D., Hatsuda T. and Kunihiro T., *Phys. Lett. B*, **670** (2008) 109.
[6] Kolomeitsev E., Kaiser N. and Weise W., *Phys. Rev. Lett.*, **90** (2003) 9.
[7] DeTar C. E. and Heller U. M., *Eur. Phys. J. A*, **41** (2009) 405.
[8] Fu W. J., Pawlowski J. M. and Rennecke F., *Phys. Rev. D*, **101** (2020) 054032.
[9] Stock R., *Relativistic Heavy Ion Physics*, in *Landolt-Börnstein Group I Elementary Particles, Nuclei and Atoms*, Vol. **23** (SpringerMaterials) 2010.
[10] Suganuma H. *et al.*, *J. Phys. G: Nucl. Part. Phys.*, **44** (2017) 124001.
[11] Tanaka Y. K. *et al.*, *Phys. Rev. Lett.*, **117** (2016) 202501.
[12] Muto R. *et al.*, *Phys. Rev. Lett.*, **98** (2007) 042501.
[13] Ericson M. and Ericson T. E. O., *Ann. Phys.*, **36** (1966) 323.
[14] Seki R. and Masutani K., *Phys. Rev. C*, **27** (1983) 2799.
[15] Itahashi K. *et al.*, *Phys. Rev. C*, **62** (2000) 025202.
[16] Hirtl A. *et al.*, *Eur. Phys. J. A*, **57** (2021) 70.
[17] Nishi T. *et al.*, *Phys. Rev. Lett.*, **120** (2018) 152505.
[18] Kubo T., *Nucl. Instrum. Methods Phys. Res. B*, **204** (2003) 97.
[19] Nishi T. *et al.*, *Nucl. Instrum. Methods Phys. Res. B*, **317** (2013) 290.
[20] Fujita H. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **484** (2002) 17.
[21] Ikeno N. *et al.*, *Prog. Theor. Phys.*, **126** (2011) 483.
[22] Szwec S. V. *et al.*, *Phys. Rev. C*, **104** (2021) 054308.
[23] Batty C., Friedman E. and Gal A., *Phys. Rep.*, **287** (1997) 385.
[24] Friedman E. and Gal A., *Nucl. Phys. A*, **724** (2003) 143.
[25] Ikeno N., Yamagata-Sekihara J., Nagahiro H. and Hirenzaki S., *Prog. Theor. Exp. Phys.*, **201** (2015) 033D01.
[26] Terashima S. *et al.*, *Phys. Rev. C*, **77** (2008) 024317.
[27] Nose-Togawa N., Nagahiro H., Hirenzaki S. and Kume K., *Phys. Rev. C*, **71** (2005) 061601.
[28] Friedman E. and Gal A., *Phys. Lett. B*, **792** (2019) 340.
[29] Hübsch S. and Jido D., *Phys. Rev. C*, **104** (2021) 015202.
[30] Kaiser N., De Homont P. and Weise W., *Phys. Rev. C*, **77** (2008) 025204.
[31] Goda S. and Jido D., *Phys. Rev. C*, **88** (2013) 065204.
[32] Lacour A., Oller J. A. and Meissner U.-G., *J. Phys. G*, **37** (2010) 125002.