論文の内容の要旨

論文題目
Precision spectroscopy of deeply bound pionic states in ^{121,116}Sn

(^{121,116}Sn 中における π 中間子の深い束縛状態の精密分光)

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One of the most important concepts in understanding the low energy Quantum ChromoDynamics (QCD) is “chiral symmetry breaking”. Spontaneous break-down of the chiral symmetry is known to be an under-lying mechanism for hadrons to acquire their masses dynamically. The chiral symmetry is expected to be partially restored in a high temperature and/or high density condition. The experimental evaluation of the partial restoration of chiral symmetry breaking is one of the most important subjects in modern hadron physics.

An established approach for quantitative evaluation of the chiral symmetry breaking in finite density is a study of pion-nucleus interaction through the experimental measurement of pion-nucleus bound systems, pionic atoms. Theories predict strength of isovector interaction between pion and nucleus, represented by a parameter b_1, is enhanced by nuclear medium effects of the strong interaction, which is related to the partial restoration of the chiral symmetry breaking. The pion nucleus interaction is formulated in an optical potential of a conventional Ericson-Ericson type, and the parameter b_1 appears in the local part. The local part uses three parameters, isoscalar (b_0), isovector (b_1) and a complex parameter mainly describing the nuclear absorption (B_0) and is expressed as

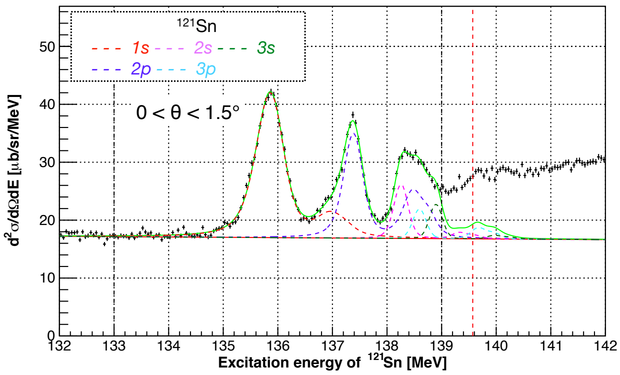
$$V_s(r) = -\frac{2\pi}{\mu}[\epsilon_1\{b_0\rho(r) + b_1\delta\rho(r)\} + \epsilon_2 B_0\rho(r)^2],$$

where r denotes radius measured from the center of the nucleus, ρ nuclear density distributions, $\delta\rho$ density difference between neutron and proton distributions, μ the reduced mass of π and the nucleus. The symbols ϵ_1 and ϵ_2 are $1 + m_\pi/M_{\text{nucleon}}$ and $m_\pi/2M_{\text{nucleon}}$, respectively. Experimentally, the b_1 parameter in vacuum is deduced from X-ray spectroscopy of $1s$ states of pionic hydrogen and deuterium to be $b_1 = -(0.0868 \pm 0.0014)\ m_\pi^{-1}$. To evaluate the partial restoration of chiral symmetry breaking in finite density precisely, deduction of b_1 in medium and comparison with that in vacuum is essential.

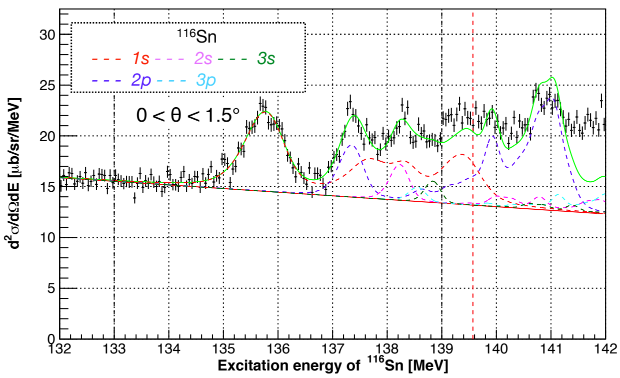
In order to obtain the b_1 in medium, pionic bound states in lower orbitals such as $1s$ or $2p$ in relatively heavy nuclei, so called "deeply bound pionic states", play the important roles. These states have a large overlap between their orbitals and the nuclear densities, and probe the effect in the finite density. So far the value of b_1 at finite density was measured at GSI, Germany, through the spectroscopy of deeply-bound pionic atoms. They determined the binding energies and widths of $1s$ states in ^{115,119,123}Sn, and derived the optical potential parameters. The obtained value of b_1 is $-(0.115 \pm 0.007)\ m_\pi^{-1}$, which shows more than 3 σ deviation from that in vacuum. This deviation suggests partial restoration of the chiral symmetry at finite density. However, the evaluated value in medium still has large errors compared with that in vacuum.

For the further study of b_1, we performed precision spectroscopy of deeply bound pionic states in ^{121,116}Sn at RIKEN, RI Beam Factory in June 2014. We aim at measuring pionic atoms with a spectral resolution comparable or better than the $1s$ natural width of about 300 keV and at determining b_1 value with comparable precision to that in GSI, an error level of $\pm 0.007\ m_\pi^{-1}$. In the experiment, the pionic atoms are produced by the ^{121,116}Sn$(d, {}^3$He) reactions, which are interpreted that the incident deuteron beam picks up a neutron in the target, and at the same time a π^- is transferred to the target nucleus producing pionic atoms. A ^{3}He is emitted in the reaction with the kinetic energy of $\sim$ 365 MeV reflecting the produced configurations of the π^- and the neutron hole states. The emitted ^{3}He in the $(d, {}^3$He) reaction is magnetically momentum-analyzed by a spectrometer. From the momentum of ^{3}He, we obtain the excitation energy spectra of ^{121,116}Sn. The facility RIBF has two key components for the experiment, namely a high intensity (a few 100 pnA) deuteron beam with the kinetic energy of 500 MeV provided by Super Conducting Cyclotron (SRC) and a fragment separator BigRIPS, which is used as a high-resolution and large-angular-acceptance spectrometer. Beam intensity is effectively about 60 times larger in RIKEN than that in GSI and helps to reduce the statistical errors. The angular acceptance is larger by about 8 times, and allow us to measure not only the $1s$ state, but also other states such as the $2p$ state, which are enhanced with the finite reaction angle in our experimental condition. To achieve high resolution in the spectroscopy, we performed (1) tuning accelerator conditions to reduce the beam emittance and momentum. (2) tuning of the ion optics from an extraction point of SRC to the target. We measured two pionic states, the $1s$ and $2p$ states simultaneously in order to deduce the difference of the binding energies precisely. Taking difference suppress ambiguities arising from the determination of the absolute energies. Especially, the uncertainties arising from the absolute beam energy ambiguities and calibration peak position determination is largely suppressed.

Figure 1 shows the excitation spectra of ^{121,116}Sn for the reaction angles of $0° < \theta < 1.5°$. The spectra are composed of spectral functions of several different pionic states and neutron holes states. In order to deduce the binding energies and widths, the excitation spectra are decomposed by fitting with theoretically calculated spectral functions based on the eikonal approximation and the effective number approach. The spectra are fairly well reproduced by the theoretically calculated functions and we made fitting by varying the binding energies, widths and strengths of each pionic state. By the fitting, we obtained the binding energies and widths of pionic $1s$, $2p$ and $2s$ states in ^{121,116}Sn. In both of the spectra, the structures corresponding to the pionic states in $1s$, $2p$ and $2s$ orbits are observed clearly. Deeply bound pionic states in a nucleus with an even mass number, ^{116}Sn, are observed for the first time. Finally, we evaluated the optical potential parameter b_1 most precisely using the binding energies and widths of pionic states. The obtained value of b_1 is consistent with that in the preceding experiment at GSI, which provides a further evidence that the chiral symmetry breaking is partially restored at finite densities.



(a) Excitation spectrum of ^{121}Sn for $0° < \theta < 1.5°$ and the fitting results.



(b) Excitation spectrum of ^{116}Sn for $0° < \theta < 1.5°$ and the fitting results.

Figure 1: Excitation spectrum of ^{121,116}Sn in $0° < \theta < 1.5°$ and the fitting results. The green solid line is the sum of contributions of the pionic states. The other colored dashed lines correspond to each contribution of the pionic state as shown in the figures. The fitting are performed between the vertical black dashed lines (133–139 MeV). The red vertical dashed lines correspond to the quasi-free π^- emission threshold. The χ^2/ndf of the fitting are 192.1/119 and 161.0/119, respectively.