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The first precision measurement of deeply bound pionic states in ^{121}Sn

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Abstract. We performed a precision missing-mass spectroscopy experiment of the deeply bound pionic states in a ^{121}Sn atom using the $(d,^3\text{He})$ reaction near the π^- emission threshold. The experiment serves as a pilot experiment for our new 'pionic atom factory project' at RIBF, which aims at precision spectroscopy of the energy spectrum of the pionic atom of isotopes and isotones. The result of the pilot experiment demonstrated the potentiality of BigRIPS and of the RIBF facilities for the project. The current status of the analysis is reported.

1 Introduction

The chiral condensate $\langle qq \rangle$ is an order parameter of the chiral symmetry spontaneous breaking. The magnitude of the $\langle qq \rangle$ is expected to decrease according to the partial restoration of the chiral symmetry in a high temperature/density condition [1, 2]. The experimental evaluation of the change of $\langle qq \rangle$ is one of the most important subjects in modern hadron physics. Recent studies suggested that the magnitude of the $\langle qq \rangle$ at the normal nuclear density, that is, at high density and low temperature condition, can be deduced by the isovector scattering length b_1 [3–5] in the pion-nuclear s-wave optical

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potential of the Ericson-Ericson type. The potential is expressed as

$$V_s(r) = -\frac{2\pi}{\mu}[\epsilon_1\{b_0\rho(r) + b_1\delta\rho(r)\} + \epsilon_2 B_0\rho(r)^2]. \tag{1}$$

Here, ρ and $\delta\rho$ mean $\rho_n + \rho_p$ and $\rho_n - \rho_p$, respectively, μ is the reduced mass, and ϵ_1, ϵ_2 represent the $1 + m_\pi/M_{\mathrm{nucleon}}$ and $m_\pi/2M_{\mathrm{nucleon}}$, respectively.

The b_1 in the medium can be determined from the spectroscopy of a 'deeply-bound pionic atom' that is heavy atoms capturing a pion in deep (such as $1s$) atomic orbits similar to the capture of an electron in a shell. So far at GSI the $1s$ pionic states in ^{205}Pb and ^{115,119,123}Sn have been discovered [6–10]. The deduced value of b_1 was compared with that of the vacuum, which was measured from the pionic hydrogen [11]. Although these data suggested partial chiral restoration, the evaluated value still had large systematic and statistical errors. The main part of the systematic error comes from the ambiguity of neutron density function in nuclei, because b_1 appears in the potential with $\delta\rho(r)$ as shown in eq (1).

In order to reduce these errors, we are planning the pionic Atom Factory (piAF) project, in which the deeply-bound pionic atoms of isotopes and isotones will be studied. We will perform the project at the RI Beam Factory (RIBF), RIKEN [12], where a high intensity (≈100 pnA) and high energy (T_d = 250 MeV/u) deuteron beam, and the high resolving-power spectrometer BigRIPS are available.

2 Pilot experiment

A pilot experiment was carried out in October 2010 [13, 14] with ^{122}Sn target. The purpose of the experiment was to examine the whole experimental setup, including a newly-developed ion optics. We produced pionic states in ^{121}Sn by the ^{121}Sn(d,^{3}He) reaction near the π^- emission threshold and collected data for 3 days. The Q value was deduced by measuring the ^{3}He momentum and calculating the missing mass . In this experiment the recoil-free condition was satisfied by choosing the deuteron beam energy of 250 MeV/u. Under this condition the zero angular momentum transfer is preferred, so that ΔL = 0 reactions such as $(1s)_{\pi^-} \otimes (3s_{1/2})_{n^{-1}}$, or sensitive states to s-wave potential, become dominant.

The beam impinged on the ^{121}Sn target at the F0 focal plane and ^{3}He was produced in the (d,^{3}He) reaction. The momentum of ^{3}He was magnetically analyzed by a fragment separator, BigRIPS, and measured by two multi-wire drift chambers (MWDCs) at the F5 dispersive focal plane. The ^{3}He particles were identified by the time of flight and the energy loss using a plastic scintillator immediately after the MWDCs and another plastic scintillator at a focal plane at down stream. The count rate at the dispersive focal plane was about 100 Hz for ^{3}He particles and about 200 kHz for break-up protons. In spite of this condition, we succeed to identify ^{3}He by scintillators clearly and to reconstruct the trajectories of ^{3}He at the dispersive focal plane by the two MWDCs as the left panel of Fig. 1.

We developed a new ion optical mode to apply the dispersion-matching method [15]. At RIBF, the momentum spread of the beam is about ±0.1% and it affects the resolution of the spectroscopy. To cancel the effect of the primary beam momentum spread, the dispersion-matching method had to be applied. The details about the optics and the dispersion-matching method are described in Ref. [16].

The right panel of Fig. 1 shows a preliminary result for the acceptance-corrected Q-value spectrum obtained in this experiment. The red vertical dashed line in the figure represents the quasi-free π^- production threshold. The Q value was calculated by the ^{3}He trajectory (horizontal position and horizontal/vertical angle) at the dispersive focal plane and the primary beam momentum, which was estimated from the NMR in the dipole magnets in the beam line. The relation between the position at the dispersive focal plane and the ^{3}He momentum was calibrated using the $p(d,^3\mathrm{He})\pi^0$ reaction peak

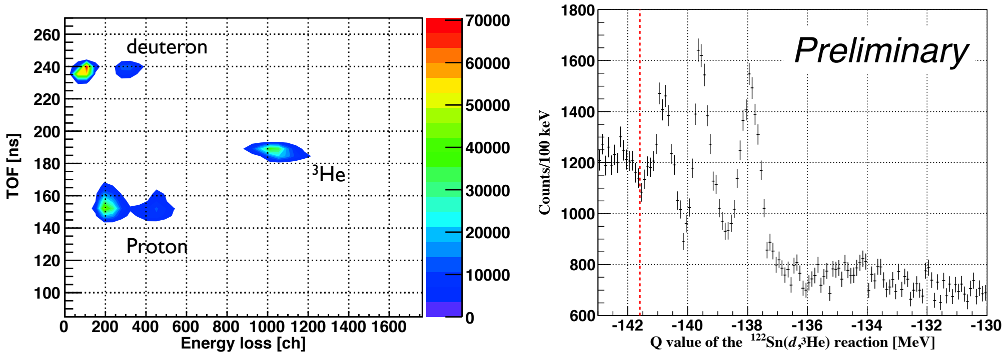

Figure 1. (Left) The time of flight and the energy loss measured by scintillators. The ^{3}He particles are clearly identified with excellent background rejection. (Right) The preliminary Q-value spectrum of the ^{122}Sn(d,^{3}He) reaction. The red vertical dashed line represents the quasi-free π^- production threshold.

with a polyethylene $(CH_2)_n$ target. The higher order aberration in the ion optics and a position/angular acceptance were already corrected in the spectrum [16], although these corrections and momentum calibration are yet to be optimized.

3 Discussion

In the Q-value spectrum shown in Fig. 1, the peaks on the right side of the quasi-free π^- threshold represent the pionic bound states. Although the spectrum is yet to be finalized, three peaks are clearly observed. Each peak had a different angular dependence, which indicate different momentum transfers for the peaks. This is the first observation of the the pionic states in ^{121}Sn and of the angular distribution of the pionic state production cross section in the $(d, {}^3\mathrm{He})$ reaction. The measured spectrum is qualitatively in good agreement with theoretically-calculated spectrum [17], including the angular dependence of the production cross section.

4 Conclusion and future perspectives

In this pilot experiment, the pionic bound states and their angular dependence were observed for the first time in the short data-acquisition period of 3 days. This high-speed data acquisition is essential for systematic spectroscopy. The preliminary results are in good qualitative agreement with the theoretically calculated spectrum.

These results demonstrated a potentiality of BigRIPS and the RIBF facility for the ‘pionic atom factory project’, in which the deeply-bound pionic atoms of a wide range of isotopes and isotones will be produced. We are now finalizing the result of the pilot experiment to deduce the binding energies and widths of the pionic bound states.

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