Journal of Physics: Conference Series

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To cite this article: Y N Watanabe *et al* 2014 *J. Phys.: Conf. Ser.* **503** 012037

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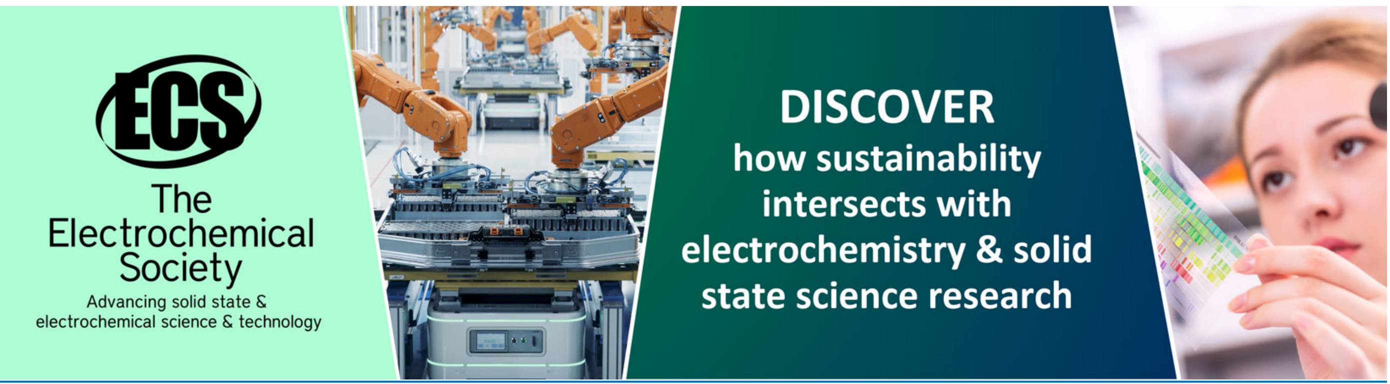

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Status and future plan of the spectroscopy of pionic atoms

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Abstract. The spectroscopy of deeply bound pionic atoms provides a way to understand the restoration of chiral symmetry breaking at finite density. We have been performing a series of experiments of missing-mass spectroscopy of the (d,^{3}He) reaction at RIBF to investigate pionic atoms of several Sn isotopes. As a first step, we conducted a pilot experiment to measure deeply bound pionic states of ^{121}Sn and successfully observed the deeply bound pionic states. In addition to the experiment at RIBF, we are planning the spectroscopy of deeply bound pionic atoms in inverse kinematics and conducted a feasible study by simulations. We showed that by using a deuterium gaseous active target TPC and silicon detectors, the Q-value resolution is about 500 keV (FWHM) and the yield of the pionic 1s state is 20 counts/day, indicating the experiment is feasible.

1. Introduction

Chiral symmetry and its spontaneous breakdown plays an important role in the low energy quantum chromodynamics. The chiral symmetry is known to be restored in hot or dense medium and the order parameter of the chiral symmetry breaking $|\langle\bar{q}q\rangle|$ is reduced[1, 2]. The spectroscopy of deeply-bound pionic atoms is one of the methods that enables us to investigate experimentally the chiral symmetry restoration in the nuclear medium. The order parameter $|\langle\bar{q}q\rangle|$ is related

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to the isovector parameter b_1 of the s-wave part of the pion-nucleus optical potential[3, 4, 5, 6]

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

In deeply-bound pionic states such as the 1s state, the pion probes a fraction of 0.6 of the normal nuclear density (ρ_0) due to the large overlap between the wavefunctions of the pion and the nucleus and the in-medium b_1 value is deduced from the binding energy and the width of the pionic states. Comparing it with the b_1 value in vacuum, the reduction of $|\langle\overline{\mathrm{q}}\mathrm{q}\rangle|$ is evaluated. In previous experiments at GSI with the missing-mass spectroscopy of $(d, {}^3\mathrm{He})$ pion transfer nuclear reaction, deeply-bound pionic ${}^{123,119,115}\mathrm{Sn}$ atoms were measured and the results indicated symmetry restoration in the nuclear medium[7, 8, 9, 10, 11]. However, there were large statistical and systematic uncertainties in these experiments.

For further studies of pionic atom spectroscopy, there are two directions. The first is to determine the b_1 value more precisely. We are working for this purpose at the RI beam factory (RIBF) and will report preliminary results in Section 2.

The other is to evaluate b_1 value at density other than 0.6 ρ_0 and study the density dependence of $|\langle\overline{\mathrm{q}}\mathrm{q}\rangle|$. For this, we need to measure pionic atoms with unstable nuclei. This is because pionic atoms with stable nuclei probe only densities around 0.6 ρ_0[12], but with neutron rich unstable nuclei the pion is pushed outward and it is expected that they probe lower densities. We conducted a feasibility study for this experiment by simulations and will present the design of the experimental setup and the results of the study in Section 3.

2. Experiment at RIBF

We plan to perform a series of experiments at RIBF using the $(d,{}^3\mathrm{He})$ reaction near the pion emission threshold. Exploiting the intense deuteron beam, several targets around Sn nuclei will be studied to suppress the systematical errors mainly caused by the ambiguity of the nuclear properties. A first pilot experiment using the missing-mass spectroscopy of ${}^{122}\mathrm{Sn}(d,{}^3\mathrm{He})\pi^- \otimes {}^{121}\mathrm{Sn}$ reaction has been carried out.

2.1. Experimental Setup

Figure 1. shows the setup of the pilot experiment. The BigRIPS fragment separator is used as a high-resolution spectrometer with a newly developed optics. A 10^{12} particle per second, 250 MeV/u deuteron beam impinged on a ${}^{122}\mathrm{Sn}$ target at the nominal target position and ${}^3\mathrm{He}$ was produced by the ${}^{122}\mathrm{Sn}(d,{}^3\mathrm{He})\pi^- \otimes {}^{121}\mathrm{Sn}$ reaction. With this energy, the momentum transfer in the reaction is small and pionic s states are selectively populated. The horizontal position and the angle of the produced ${}^3\mathrm{He}$ were measured at the F5 focal plane by two multi-wire drift chambers (MWDCs) which were aligned in the beam direction. To determine the reaction Q-value, the momentum of ${}^3\mathrm{He}$ was deduced by the position and the angle at F5.

The main background was protons produced by nuclear-breakup reaction and it was about 10^3 times more abundant than the ${}^3\mathrm{He}$ events. The background was clearly identified against the ${}^3\mathrm{He}$ events by measuring the time of flight between F5 and F7 and the energy loss in the scintillation counters.

2.2. Results and discussion

Figure 2. shows the acceptance-corrected Q-value spectrum of the ${}^{121}\mathrm{Sn}(d,{}^3\mathrm{He})$ reaction with ${}^3\mathrm{He}$ particles emitted at angles smaller than 1°. The red line indicates the pion emission threshold. The peaks of interest ride on a constant background of ${}^3\mathrm{He}$ particles that are produced in nuclear reactions without pion production. On the right side of the threshold, peak structures corresponding to the pionic bound states were observed. The spectrum is in

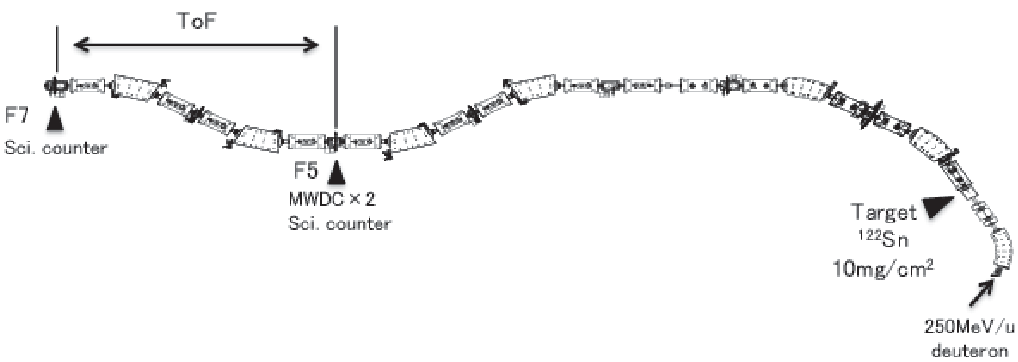

Figure 1. The setup of the experiment. A deuteron beam is injected into the BigRIPS spectrometer and the position and the angle of the produced ^{3}He particles are measured at the F5 dispersive focal plane using MWDCs.

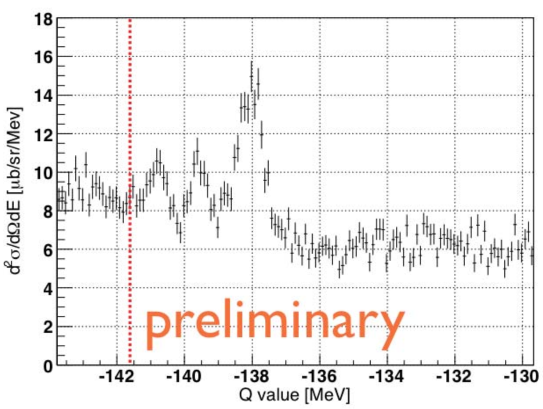

Figure 2. Preliminary Q-value spectrum of the^{121}Sn(d,^{3}He) reaction at the forward angles. The red dotted line corresponds to the pion emission threshold.

qualitatively agreement with the theoretical calculation including the angular dependence of the emitted ^{3}He[13].

3. Feasibility study of the spectroscopy using inverse kinematics

We are now planning to conduct the spectroscopy of pionic atoms with unstable nuclei. In order to use unstable nuclei, the inverse kinematics method is adopted where heavy ions are used as a beam and deuterons are used as a target. A dedicated setup is needed for the inverse kinematics measurement because the momentum of the emitted ^{3}He is only about 60 MeV with the recoilless condition in the center of momentum frame. Therefore, the signal ^{3}He particles are sensitive to the energy loss in the target so that the information of the reaction is easily lost. To suppress the influence of the energy loss, we plan to employ an active-target time projection chamber (AT-TPC) with silicon strip detectors.

3.1. Design of the experiment

Figure 3. shows the conceptual design for the inverse kinematics measurement with AT-TPC and silicon detectors. A 250MeV/u heavy ion beam is bombarded onto a deuterium-filled AT-

TPC that is placed in a uniform magnetic field of about 1T to separate the signal ^{3}He from the heavy ion beam. Inside the AT-TPC, 1500μm thick silicon strip detectors are installed to measure the full energy of the ^{3}He.

To determine the reaction Q-value, the momentum of ^{3}He at the reaction point should be measured in a similar way in experiments with normal kinematics. In this experiment, the momentum is deduced from three observables listed below:

- the energy loss along the path from the reaction point to the silicon detector
- the full energy at the silicon detector
- the angle of the emitted ^{3}He at the reaction point

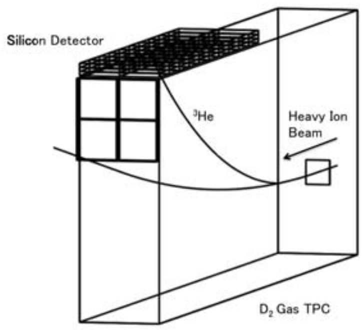

Figure 3. Conceptual design of the TPC and the silicon detectors. A heavy ion beam is injected into the TPC and the energy of the emitted ^{3}He is measured by the silicon detectors. Magnetic field is applied in the perpendicular direction to the beam.

3.2. Yield and resolution estimation

In such a setup, the yield of the pionic 1s state and the Q-value resolution were estimated by simulations with the condition shown in Table 1. The total cross section is estimated from past experiments.There are three main components contributing to the Q-value resolution:

- resolution of silicon detectors
- vertex position resolution
- energy straggling along the path from reaction point to the silicon detector

Besides these quantities, the energy spread of the incident beam may affect the resolution, but this contribution is relatively small.

Using these conditions, the yield of the pionic 1s state is calculated to be 20 counts/day. The estimated Q-value resolution from each of the components is shown in Table 2. The total resolution is 500 keV (FWHM).

Beam intensity	10^6 /s
D_2 gas thickness	1 m
Cross section	$5\times10^{-2}\mu$b
AT-TPC position resolution	500 μm
Energy resolution of Si detector at 60 MeV^{3}He	0.1 %

Table 1. Simulation conditions.

Resolution contribution	Contribution to Q-value resolution (FWHM) [keV]
Energy straggling	350
Vertex position resolution	150
Energy resolution of Si detectors	350
Total	500

Table 2. Estimate of Q-value resolution from each components.

3.3. Discussion

The resolution of 500 keV (FWHM) is sufficient to separate the peaks as the energy difference between typical pionic states is about 1MeV. The yield of 20 counts/day for pionic 1s state is not so large, but we expect the peak structures observed for about ten days measurements. Therefore, this result indicates that the spectroscopy of pionic atom with inverse kinematics is feasible using the presented conceptual design.

4. Summary and future prospect

A pilot experiment of the spectroscopy of deeply bound pionic ^{121}Sn was conducted at RIBF and the pionic states were successfully observed. We are now finalizing the analysis of the pilot experiment to determine the isovector parameter b_1 and preparing for the main experiment with several targets.

We conducted a feasibility study of the spectroscopy of pionic atom in inverse kinematics using AT-TPC. The results indicate that the experiment is feasible in terms of resolution and yield. Preparations for this experiment are presently under way. We have started to develop the AT-TPC and are now working on the silicon detectors.

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