Spectroscopy of pionic atoms in ^{122}Sn(d, ^{3}He) reaction and angular dependence of the formation cross sections[†]

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Spectroscopy of deeply bound pionic atoms has been contributing to understanding of non-perturbative low-energy region of the QCD.[1)] We have started an experimental spectroscopy of pionic atoms at RIBF and conducted our first experiment in 2010 by measuring ^{122}Sn(d, ^{3}He) reactions near the π^- emission threshold for about 15h. We employed deuteron beam with the energy of 498.9 ± 0.2 MeV and a typical intensity of 2×10^{11}/s accelerated by SRC. Such a high intensity deuteron beam may serve as an irreplaceable basis for high statistical and systematic precision in the spectroscopy and let us achieve opportunities to reach understanding of the the low-energy QCD with unprecedented accuracy.

During the experiment, the deuteron beam impinged on a thin ^{122}Sn target located at a nominal target position of BigRIPS. We used BigRIPS as a spectrometer to momentum-analyze the emitted ^{3}He and measured the Q-value of the reaction in the missing-mass measurement. We reconstructed the tracks of the ^{3}He by a set of tracking detectors placed near the F5 dispersive focal plane. We installed a set of scintillation counters at F5 and F7 focal planes and identified the particles. After applying detailed optical aberration corrections, we achieved excitation spectra of the target Sn nucleus with the best resolution of 0.42 MeV (FWHM). The absolute excitation energy is calibrated by using a polyethylene target to observe two-body reactions of H(d, ^{3}He)π^0.

In the measured excitation spectrum of the target Sn nucleus, we observe three prominent peak structures near the π^- emission threshold as depicted in Fig. 1 of our original paper Ref. 2). The left most peak in the smaller-mass side is assigned to the $1s$ pionic state mainly coupling with a neutron hole state of $(3s_{1/2})_n^{-1}$. The central peak is assigned mainly to formation of the $2p$ pionic state. The right most peak in the larger-mass side is contributed from higher pionic orbitals. The pionic states in ^{121}Sn are observed for the first time. We made an elaborate fitting of the observed spectrum and deduced the $1s$ and $2p$ binding energies and the $1s$ width. The deduced binding energies and the width agree with theoretical calculations.

In the measurement, a large angular acceptance of BigRIPS provided a very unique opportunity. As shown in Fig. 2 of Ref. 2), we observe reaction-angle dependence of the pionic atom formation spectra for the first time. The dependence of both $1s$ and $2p$ states are determined experimentally. Comparing the measured dependence with a theoretical prediction,[3)] they are qualitatively agreeing well, and the observed dependence directly confirms the assignment of the angular momenta of the structures in the spectrum.

Quantitatively comparing the measured absolute formation cross sections with the theoretical predictions, we find that the measured $2p$ cross section fairly well agrees with the theory and that the $1s$ cross section is smaller by a factor of about 20%. Since a ratio of the measured cross sections of the $1s$ to $2p$ state is attributed with relatively small errors, the deviation from the theory invokes important questions in understanding of the pionic atom formation reactions.

In conclusion, we conducted first pionic atom spectroscopy at RIBF and measured pionic ^{121}Sn as peak structures in the missing-mass spectrum for the first time. Reaction angle dependence of the pionic $1s$ and $2p$ formation cross sections are observed and compared with theoretical calculations. The measured dependence qualitatively agree with the theory confirming the correct assignment of the observed structures in the spectrum. Measured absolute $2p$ cross section well agrees with the theory but the theory overestimates the $1s$ cross section by a factor of about 5. The measurement firmly proves potential of the RIBF for future high precision spectroscopy of pionic atoms.

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