Precision Spectroscopy of Pionic Atom at RIKEN-RIBF

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We performed a precision spectroscopy experiment of the pionic atom at the RIKEN RI beam factory (RIBF) in October 2010. A new ion-optical setup was developed for both the beam transfer (BT) line to the target and the spectrometer in order to accomplish the dispersion matching which eliminates the effect of the momentum spread of the primary beam. We measured the first data of the deeply bound states of the pionic ^{121}Sn atom and observed the angular dependence of the bound states.

1 Introduction

The order parameter of the chiral symmetry breaking, the quark condensate $\langle \bar{q}q \rangle$, is expected to change in nuclear medium. At normal nuclear densities, the quark condensate is reduced by 30% compared the vacuum value. The experimental determination of this in-medium change is one of the important themes in contemporary hadron physics. However, the quark condensate is not physically observable. Therefore, we combine two relations, the in-medium Glashow-Weinberg relation [1] and the in-medium Tomozawa-Weinberg relation [2], to formulate the in-medium change of the quark condensate in terms of the physical observable b_1, which is the isovector pion-nucleus scattering length.

A precise spectroscopic experiment at GSI for the pionic ^{115}Sn, ^{119}Sn and ^{123}Sn atoms yielded the first accurate measurement of the b_1 enhancement at normal nuclear density

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with the result $b_1^{\rm free}/b_1 = 0.78$ [3], where the $b_1^{\rm free}$ was very precisely determined by the pionic hydrogen x-ray spectroscopy at PSI [4]. However, the values of b_1 where not as accurately determined as the $b_1^{\rm free}$ parameter. Therefore, the objective of the present project is to improve the in-medium b_1 accuracy. This requires a better energy resolution.

We plan systematic measurements of the pionic atoms for several stable isotope and isotone targets at RIBF [5]. Especially, we expect that the measurement for isotones will help reduce the uncertainty due to the neutron distributions. We call this project the pionic Atom Factory (piAF) project [6]. In October 2010, we performed a pilot experiment of the piAF project in order to develop the method of precision spectroscopy at RIBF. We chose ^{122}Sn as the first target of the piAF project because ^{122}Sn located at the intersection of two chains of isotopes and isotones.

2 Experiment

We used the (d,^{3}He) reaction to produce the pionic atom. The deuteron beam energy of $T_d = 500$ MeV was chosen to satisfy the recoilless condition. We measured the momentum of the helium using the BigRIPS spectrometer [7] to analyze the Q-value of the (d,^{3}He) reaction. At the dispersive focal plane F5, we installed two sets of multi-wire drift chambers and one set of segmented scintillation counters. At the achromatic focal plane F7, we installed a scintillation counter. The particle identification was performed by the measurement of the energy loss in the scintillation counters and the time of flight between F5 and F7.

One advantage of using the RIKEN facility is the high beam intensity, which is higher by a factor of ten compared to the beam that was used in the GSI experiment. Hence, we can use thinner target allowing for better resolution. On the other hand, the momentum spread of the primary beam of the RIKEN is larger by a factor of three compared to the momentum spread at GSI. Therefore, we use the dispersion matching [8] which eliminates the effect of the large momentum spread in order to achieve a resolution better by a factor of about two, i.e. about 200 keV (FWHM).

The dispersion matching condition is described as

(1) $$b_{16}s_{11} + b_{26}s_{12} + Cs_{16} = 0,$$

where b_{ij} and s_{ij} denote the R-matrix elements of the BT line and the BigRIPS spectrometer, respectively, and C is the kinematic factor of the (d,^{3}He) reaction at the target. The kinematic factor is 1.3 for the pionic atom production. The elements s_{ij} were selected to achieve a resolving power of 3500, such that $s_{11} = -1.8$, $s_{12} = 0.0$ mm/mrad, and $s_{16} = 64$ mm/%. The elements b_{ij} were selected to satisfy the matching condition specified in equation (1), namely $b_{16} = 46$ mm/% and $b_{26} = 0.0$ mrad/%. The momentum dispersion s_{16} and b_{16} were measured by scaling beam line magnets with the results 61.8 mm/% and 43.8 mm/%, respectively. The measured values were in sufficient agreement with the design values.

3 Results

The panel on the left side of Figure 1 shows measured counts as a function of the horizontal position at the dispersive focal plane F5. The x-axis is proportional to the momentum increases from left to right. The panel on the right side of Figure 1 shows the 2-dimentional scatter plot of the vertical angle of F5 versus the horizontal position. This is the first data of the deeply bound states of the pionic ^{121}Sn atom and the first observation of the angular dependence of the deeply bound states.

The panel on the left side of Figure 2 shows position spectrum at F5 with the condition $\theta < 15$ mrad, where θ is the beam angle at the target. The right-side panel of Figure 2 shows the calculated spectra for the formation of the pionic bound states [9]. In this calculation, the experimental energy resolution is assumed to be 150 keV (FWHM).

Our result at forward angles is consistent with the theoretical calculation and we identify the peak at the right as the 1s pionic state. A more detailed analysis to deduce the binding energy and the width of each peak and to identify the configuration of each peak is ongoing.

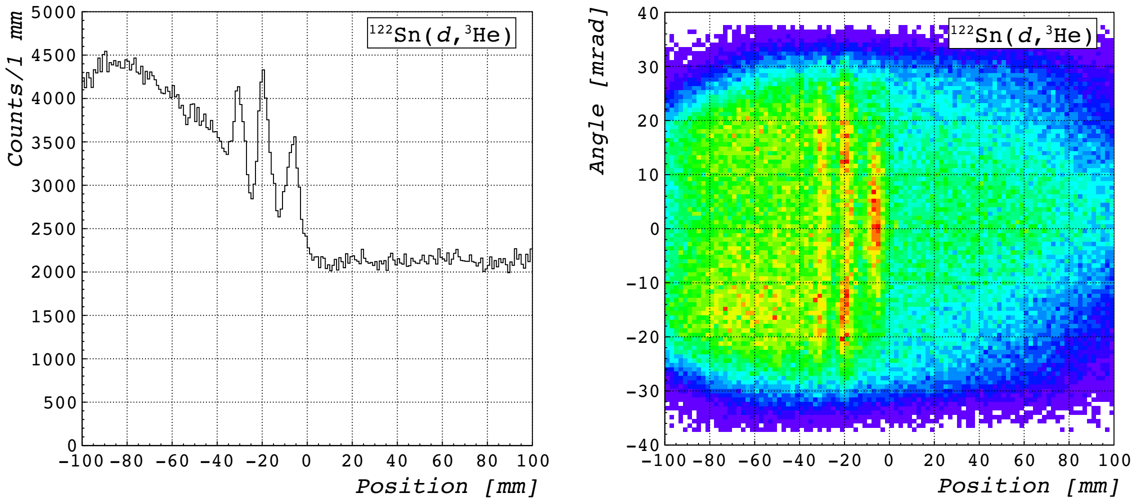

Figure 1: A position spectrum at the dispersive focal plane F5 (left) and a 2-dimentional scatter plot of the vertical angle versus the horizontal position at F5 (right) are shown.

Acknowledgments

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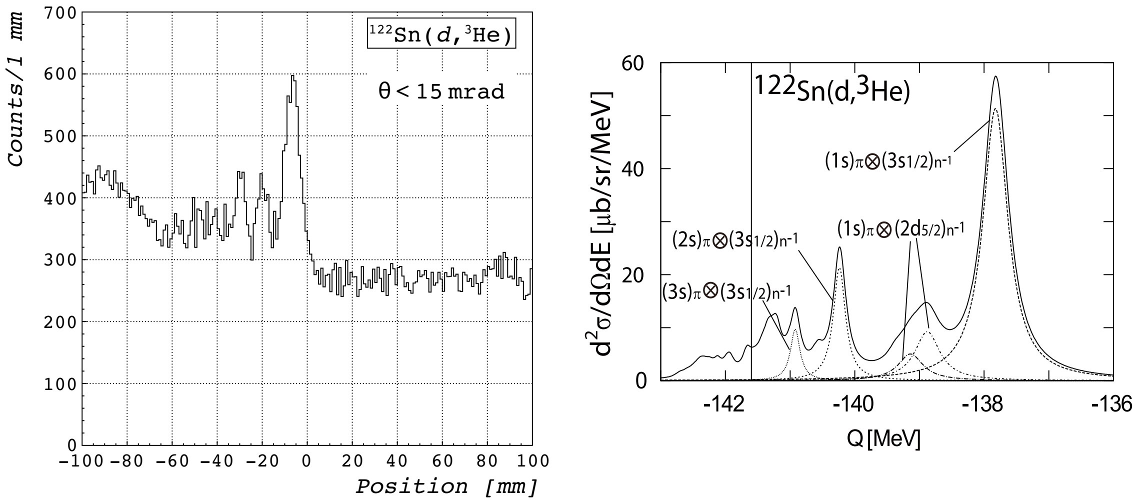

Figure 2: A position spectrum at forward angles ($\theta < 15$ mrad (left) and the theoretical calculation of the Q-value spectrum [9] (right) are displayed.

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