EPJ Web of Conferences **37**, 09018 (2012)
DOI: 10.1051/epjconf/20123709018

Formation of deeply bound pionic atoms in Sn isotopes

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Abstract. We study the formation of deeply bound pionic atoms in the (d,^{3}He) reactions theoretically and show the energy spectra of the emitted ^{3}He at finite angles. We find that the different combinations of the pion-bound and neutron-hole states dominate the formation spectra at different scattering angles because of the matching condition of the reaction. We conclude that the observation of the (d,^{3}He) reaction at finite angles will provide the systematic information of the pionic bound states in each nucleus, and it will help to develop the study of the pion properties and the partial restoration of chiral symmetry in nuclei.

1 Introduction

Deeply bound pionic atom is one of the best systems to deduce pion properties at finite density and to obtain precise information on partial restoration of chiral symmetry in nuclei [1].

So far, the deeply bound pionic states have been experimentally produced in the forward (d,^{3}He) reaction. The (d,^{3}He) spectra have been obtained in near recoilless kinematics to observe the peaks of the pionic state formation with a neutron hole in the quasi-substitutional configurations [2–4]. The Pb and Sn isotopes were used as the target nuclei in the experiments [2–4] since the spectra were expected to show the peak structures owing to one dominant $[\pi \otimes n^{-1}]$ configuration based on the theoretical evaluations [5,6]. The simple structure of the observed peak is important and effective to deduce the pion binding energies precisely from the observed spectra. Actually, in Ref. [3], the binding energy and width of the 1s states have been precisely measured in three Sn isotopes and isospin-density dependence of the s-wave pion-nucleus potential has been deduced. From these observations, the reduction of the chiral order parameter $\langle \bar{q}q \rangle$ in nucleus was concluded. A recent model independent theoretical analysis supported the way to extract the in-medium quark condensate from the pionic atom data and showed a relation connecting the in-medium quark condensate to the hadronic observables [7].

To develop the studies of pion properties and symmetry restoration in nuclei further, we need to obtain precise and systematic information on deeply bound pionic states. For example, we need more systematic information on the bound states for the unique determination of the pion-nucleus interaction, which is required to fix the potential strength related to chiral symmetry [8]. Recently, it was reported in Ref. [8] that the simultaneous observation of various pionic bound states such as $1s$ and $2s$ in the same nucleus may be helpful to reduce these errors and to develop our studies. Along with this line, in actual experiments, the pionic $2s$ state observation with the $1s$ state has been expected in new high precision experiment in RIBF/RIKEN [8–10].

In this paper, we consider theoretically the new possibility to observe various pionic bound states in the same nuclei by observing the (d,^{3}He) spectra at finite angles together with the forward direction. These observations at finite angles were reported by the experiments at RIBF/RIKEN [11]. At finite angle, we can expect to have the manifestation of different subcomponents of pion and neutron hole

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states due to the matching condition with different momentum transfer, and expect to determine the binding energies and widths of various pionic states simultaneously in each nucleus.

2 Formulation

We use the effective number approach to calculate the pionic atom formation cross sections [12]. We refine the theoretical model used in Refs. [5, 6, 13] to study the angular dependence of the $(d,{}^3\mathrm{He})$ spectra by including the kinematical correction factors K in Eq. (1) as explained below. The $(d,{}^3\mathrm{He})$ reaction cross section in the laboratory frame is expressed as,

$$\left(\frac{d^2\sigma}{dE_{\mathrm{He}}d\Omega_{\mathrm{He}}}\right)^{\mathrm{lab}}_{A} = \left(\frac{d\sigma}{d\Omega_{\mathrm{He}}}\right)^{\mathrm{lab}}_{\mathrm{ele}} \sum_{ph} K \frac{\Gamma}{2\pi} \frac{1}{\Delta E^2 + \Gamma^2/4} N_{\mathrm{eff}}, \tag{1}$$

where $\left(\frac{d\sigma}{d\Omega_{\mathrm{He}}}\right)^{\mathrm{lab}}_{\mathrm{ele}}$ indicates the elementary cross section for the $d + n \to {}^3\mathrm{He} + \pi^-$ reaction in lab frame. As the elementary cross section, we have used the experimental data of $p + d \to t + \pi^+$ reaction reported in Ref [14] in the CM frame by isospin symmetry.

The effective number N_{eff} defined as,

$$N_{\mathrm{eff}} = \sum_{JM} \left| \int d\mathbf{r} \chi^*_{\mathrm{He}}(\mathbf{r}) [\phi^*_{\ell_\pi}(\mathbf{r}) \otimes \psi_{j_n}(\mathbf{r})]_{JM} \chi_d(\mathbf{r}) \right|^2, \tag{2}$$

where ϕ_{ℓ_π} and ψ_{j_n} indicate the wavefunctions of the pion bound state in the daughter nucleus and the neutron bound state in the target nucleus, respectively. For the neutron wave function ψ_{j_n}, we use the calculated wave function using the neutron potential reported in Ref. [15]. The wave functions of the projectile (d) and the ejectile (^{3}He) are denoted by χ^*_{He} and χ_d. We introduce the distortion effects to the wavefunctions χ^*_{He} and χ_d by Eikonal approximation as described in Refs. [5, 6, 13].

The kinematical correction factor K is defined as,

$$K = \left[\frac{|\mathbf{p}^A_{\mathrm{He}}|}{|\mathbf{p}_{\mathrm{He}}|} \frac{E_n E_\pi}{E^A_n E^A_\pi} \left(1 + \frac{E_{\mathrm{He}}}{E_\pi} \frac{|\mathbf{p}_{\mathrm{He}}| - |\mathbf{p}_d| \cos\theta_{d\mathrm{He}}}{|\mathbf{p}_{\mathrm{He}}|} \right) \right]^{\mathrm{lab}}, \tag{3}$$

where A indicates the momentum and energy which should be evaluated in the kinematics of the nuclear target case. The superscript 'lab' indicates that all kinematical variables are evaluated in the laboratory frame. This correction factor is $K = 1$ for the recoilless kinematics at $\theta^{\mathrm{lab}}_{d\mathrm{He}} = 0^\circ$ with $S_n = 0$ and $B.E. = 0$. In Ref. [12], we find that the K factor gradually varies about 10% within the Q-value range considered here for both $\theta^{\mathrm{lab}}_{d\mathrm{He}} = 0^\circ$ and 2° cases, and the K factor decreases about 20% at $\theta^{\mathrm{lab}}_{d\mathrm{He}} = 2^\circ$ from the value at $\theta^{\mathrm{lab}}_{d\mathrm{He}} = 0^\circ$. Thus, we think the K factor should be introduced to study the angular dependence of the $(d,{}^3\mathrm{He})$ spectra.

3 Numerical Results and Discussions

In Fig. 1, we show the calculated $(d, {}^3\mathrm{He})$ spectra at finite angles for the bound pionic states formation. We find that the spectra have a strong angular dependence and the shape of the spectra are much different at finite angles from that at 0°. The largest peak structure at $Q = -137.8$ MeV in the forward spectra is strongly suppressed at finite angles and the spectra show the structure of three peaks at $\theta^{\mathrm{lab}}_{d\mathrm{He}} \geq 2^\circ$. The overall strength of the spectra has also angular dependence and is smaller for larger angles.

In Fig. 2, we show the dominant subcomponents of the $(d,{}^3\mathrm{He})$ spectra for each scattering angle $\theta^{\mathrm{lab}}_{d\mathrm{He}}$. At $\theta^{\mathrm{lab}}_{d\mathrm{He}} = 0^\circ$, since the reaction is close to recoilless, the peak of the $[(1s)_\pi \otimes (3s_{1/2})^{-1}_n]$ and

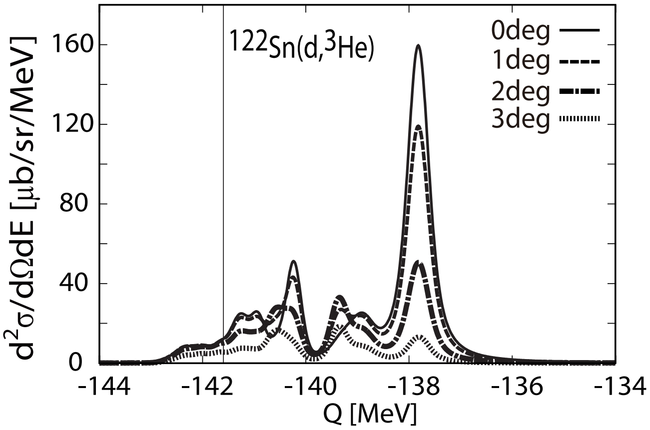

Fig. 1. Calculated ^{122}Sn(d,^{3}He) spectra for the formation of the pionic bound states at $\theta^{\rm lab}_{d{\rm He}} = 0°$ (solid lines), 1°(dash lines), 2° (dash-dotted lines) and 3° (dotted lines) plotted as functions of the reaction Q-value [12]. The incident deuteron kinetic energy is fixed to be $T_d = 500$ MeV. The instrumental energy resolution is assumed to be 300 keV FWHM. The vertical line indicates the pion production threshold $Q = -141.6$ MeV.

$[(2s)_\pi \otimes (3s_{1/2})_n^{-1}]$ subcomponents appear clearly in the spectra. At $\theta^{\rm lab}_{d{\rm He}} = 1°$, the contribution for $[(2s)_\pi \otimes (3s_{1/2})_n^{-1}]$ is suppressed and can only be seen clearly if the energy resolution is better than 300 keV. At larger angles, the pionic (2p) state contributions become relatively larger and dominate the peak structure around $Q = -139.4$ MeV and -140.4 MeV. We can expect to observe the peak structure composed from the $[(2p)_\pi \otimes (3s_{1/2})_n^{-1}]$, $[(2p)_\pi \otimes (2d_{3/2})_n^{-1}]$ and $[(2p)_\pi \otimes (1h_{11/2})_n^{-1}]$ subcomponents. Though, the separation energies of these 3 neutron levels differ from each other only within 60 keV [8] and their contributions can not be distinguished, we can expect to deduce the information on the pionic 2p state. These contributions of pionic 2p state can not be seen in the spectra at $\theta^{\rm lab}_{d{\rm He}} = 0°$ since they are hidden in the tail of the large 1s contributions. At finite angles, due to the significant suppression of the 1s contributions, the 2p contributions can be observed even if they are a little smaller than those at the forward angle. Thus, to observe the spectra at finite angle is valuable.

4 Summary

We study the formation of deeply bound pionic atoms in the (d,^{3}He) reactions theoretically. We develop the formula to include the kinematical correction factors to the effective number approach to obtain more realistic angular dependence of the (d,^{3}He) spectra. We show the angular dependence of the ^{122}Sn(d,^{3}He) spectra at $T_d = 500$ MeV for the formation of the pionic atoms.

We find that the spectra are dominated by the subcomponents including the $(2p)_\pi$ state at larger scattering angles $\theta^{\rm lab}_{d{\rm He}} \geq 2°$, while they are dominated by the $(1s)_\pi$ and $(2s)_\pi$ states at forward angles. The peaks are well isolated and can be observed in the experiments with the good energy resolution. Thus, we can conclude that we can obtain information on deeply bound pionic 2p state in addition to 1s and 2s states by observing the spectra at finite angles. As indicated in Ref. [8], the observation of several deeply pionic bound states in a certain nucleus will help to deduce precise information of pion properties and chiral dynamics at finite density [3,7,16]. We believe that our results provide a good evaluation for further experimental studies of the states reported here, which should contribute to the development of the field.

N. I. appreciates the support by the Grant-in-Aid for JSPS Fellows (No. 23·2274).

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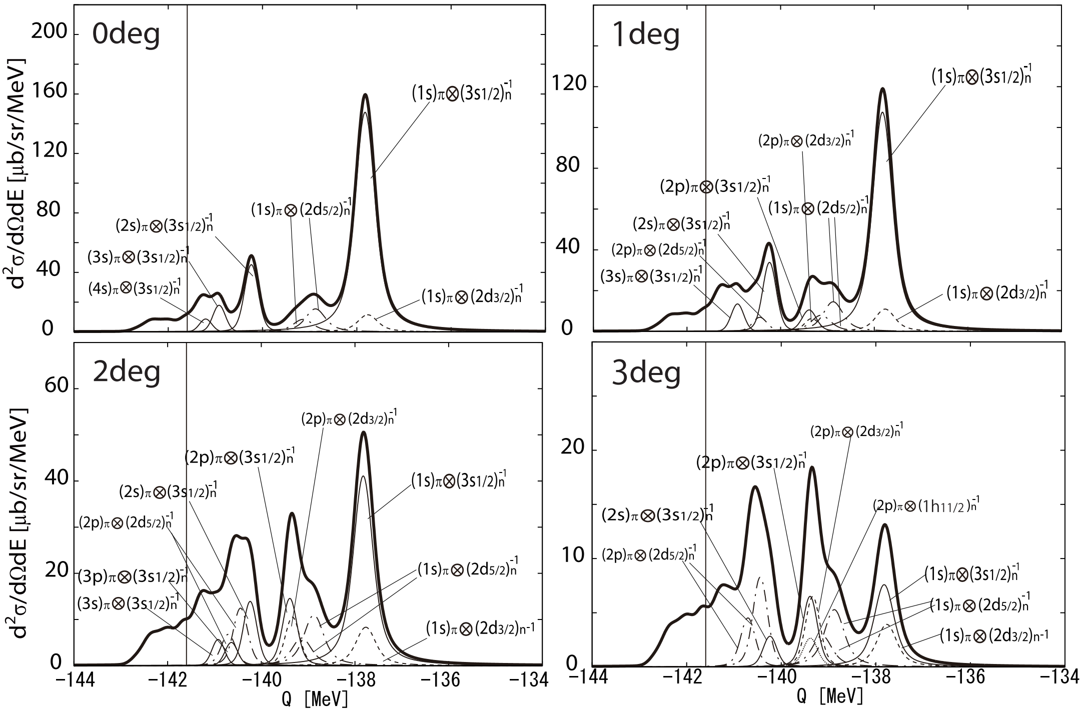

Fig. 2. Calculated ^{122}Sn(d,^{3}He) spectra for the formation of the pionic bound states at $\theta^{\rm lab}_{\rm dHe} = 0°, 1°, 2°$ and $3°$ are plotted as functions of the reaction Q-value [12]. Dominant subcomponents $[(n\ell)_\pi \otimes (n\ell_j)_n^{-1}]$ are indicated in the figure. The instrumental energy resolution is assumed to be 300 keV FWHM. The vertical line indicates the pion production threshold $Q = -141.6$ MeV.

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