Abstract  We study the formation of deeply bound pionic atoms in the \((d,^3\text{He})\) reaction theoretically. At different scattering angles, we find that the different subcomponents dominate the formation spectra because of the matching condition of the reaction. We also find that the pionic 1\(s\) state which is free from the residual interaction effects appears clearly in \(^{117}\text{Sn}(d,^3\text{He})\) spectra. We conclude that the observation of the \((d,^3\text{He})\) reaction for these new cases will provide more systematic and accurate information on the pionic bound states, 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]. The deeply bound states have been experimentally produced in the forward \((d,^3\text{He})\) reactions with Pb and Sn isotope targets [2,3] by following theoretical predictions [4,5]. In Ref. [3], the binding energy and width of the 1\(s\) 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.

To develop the studies of pion properties and symmetry restoration in nuclei further, we need to obtain more precise and systematic information on deeply bound pionic states. The information is, for example, necessary for the unique determination of the pion-nucleus interaction, which is required to fix the potential strength related to chiral symmetry [6].

In this paper, we consider theoretically two new studies of pionic atom formation in the \((d,^3\text{He})\) reaction. One is the pionic atom formation in the \((d,^3\text{He})\) reaction at finite angles [7–9], where we can expect to have the manifestation of different subcomponents of pion and neutron hole 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.

The other is the pionic atom formation on the odd nuclear target, which has not been investigated so far. For example, the odd nucleus \(^{117}\text{Sn}\) has a spin of \(\frac{1}{2}\). After the proton pick-up \((d,^3\text{He})\) reaction, we have the contributions for the pionic atom formation on the ground state of the even-even daughter nucleus \(^{116}\text{Sn}\) with the quantum number of \(0^+\). This pionic state does not have the additional shift due to the residual interaction effect [10,11]. For the even nuclear target cases, since the final pionic states are the pion-particle plus neutron-hole \([\pi \otimes n^{-1}]\) states, the residual interaction effects may shift the binding energies and widths.

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2 Formulation

We use the effective number approach to calculate the pionic atom formation cross sections [9]. We refine the theoretical model used in Refs. [4,5,12,13] to study the angular dependence of the \((d,^3\text{He})\) spectra by including the kinematical correction factors \(K\) in Eq. (1) as explained below. The \((d,^3\text{He})\) reaction cross section in the laboratory frame is expressed as,

\[
\left( \frac{d^2\sigma}{dE_{\text{He}}d\Omega_{\text{He}}} \right)_{\text{lab}} = \left( \frac{d\sigma}{d\Omega_{\text{ele}}} \right)_{\text{lab}} \sum_{p,h} K \frac{\Gamma}{2\pi} \frac{1}{\Delta E^2 + \Gamma^2/4} N_{\text{eff}},
\]

where \(\left( \frac{d\sigma}{d\Omega_{\text{ele}}} \right)_{\text{lab}}\) indicates the elementary cross section for the \(d + n \to ^3\text{He} + \pi^-\) reaction in lab frame, which is extracted from the experimental data [14].

The effective number \(N_{\text{eff}}\) is defined as,

\[
N_{\text{eff}} = \sum_{J^M} \int d\mathbf{r} \chi_{\text{He}}^*(\mathbf{r}) [\phi_{\ell\pi}^* (\mathbf{r}) \otimes \psi_{\mathbf{p}} (\mathbf{r})] J_M \chi_{\mathbf{d}} (\mathbf{r})^2,
\]

where \(\phi_{\ell\pi}\) and \(\psi_{\mathbf{p}}\) indicate the wave functions of the pion bound state in the daughter nucleus and the neutron bound state in the target nucleus, respectively. For the neutron wave function \(\psi_{\mathbf{p}}\), we use the calculated wave function using the neutron potential reported in Ref. [15]. The wave functions of the projectile \((d)\) and the ejectile \((^3\text{He})\) are denoted by \(\chi_{\text{He}}^*\) and \(\chi_{\mathbf{d}}\).

The kinematical correction factor \(K\) is defined as [9],

\[
K = \left[ \frac{\mathbf{p}_{\text{He}}^* A \int_{E_{\text{He}}} E_\pi |\mathbf{p}_{\text{He}}| - |\mathbf{p}_{\mathbf{d}}| \cos\theta_{\text{He}}}{\mathbf{p}_{\text{He}}^* A \int_{E_{\text{He}}} E_\pi |\mathbf{p}_{\text{He}}|} \right]_{\text{lab}}^{\gamma},
\]

where the superscript ‘\(A\)’ indicates the momentum and energy which should be evaluated in the kinematics of the nuclear target case. The superscript ‘\(\text{lab}\)’ indicates that all kinematical variables are evaluated in the laboratory frame.

3 Numerical Results and Discussions

In Fig. 1, we show the calculated spectra at finite angles for the bound pionic states formation in the \(^{122}\text{Sn}(d,^3\text{He})\) and \(^{117}\text{Sn}(d,^3\text{He})\) reactions. We find that the both spectra have a strong angular dependence and the shape of the spectra are much different at finite angles from that at 0°. In the \(^{122}\text{Sn}(d,^3\text{He})\) spectra, 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 \(\theta_{\text{lab}} \geq 2°\).

In the \(^{117}\text{Sn}(d,^3\text{He})\) spectra, we find that we can see clearly the peak structure of the pionic 1s state formation with the ground state of the even–even nucleus \(^{116}\text{Sn}\) at \(Q = -135.8\) MeV. This state does not have the additional shift due to the residual interaction effect. Therefore, we can expect that we obtain more precise information than that of the even nuclear target case [16].

In Fig. 2, we show the dominant subcomponents of the \(^{122}\text{Sn}(d,^3\text{He})\) spectra for each scattering angle \(\theta_{\text{lab}}\). At \(\theta_{\text{lab}} = 0°\), since the reaction is close to recoilless, the peak of the \([1s_\pi \otimes (3s_{1/2})^{-1}_n]\) and \([2s_\pi \otimes (3s_{1/2})^{-1}_n]\) subcomponents appear clearly in the spectra. At larger angles, the pionic \((2p)\) state contributions become relatively larger. We can expect to observe the peak structure composed from the \([2p_\pi \otimes (3s_{1/2})^{-1}_n]\), \([2p_\pi \otimes (2d_{3/2})^{-1}_n]\) and \([2p_\pi \otimes (1h_{11/2})^{-1}_n]\) subcomponents. Though, the separation energies of these 3 neutron levels differ from each other only within 60 keV [6] and their contributions can not be distinguished, we can expect to deduce the information on the pionic \(2p\) state.
Formation of Deeply Bound Pionic Atoms in Sn Isotopes

Fig. 1 Calculated spectra for the formation of the pionic bound states at $\theta_{\text{lab}}^{d,\text{He}} = 0^\circ, 1^\circ, 2^\circ$ and $3^\circ$ in the $^{122}\text{Sn}(d,\text{He})$ (left) and $^{117}\text{Sn}(d,\text{He})$ (right) reactions plotted as functions of the reaction $Q$ value [9,16]. 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 lines indicate the pion production threshold $Q = -141.6$ MeV (left) and $Q = -139.7$ MeV (right).

Fig. 2 Calculated $^{122}\text{Sn}(d,\text{He})$ spectra for the formation of the pionic bound states at $\theta_{\text{lab}}^{d,\text{He}} = 0^\circ, 1^\circ, 2^\circ$ and $3^\circ$ are plotted as functions of the reaction $Q$ value [9]. Dominant subcomponents $[(n\ell)_{\pi} \otimes (n\ell j)_{\text{np}}]^{-1}$ 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.

4 Summary

We study the formation of deeply bound pionic atoms in the $(d,\text{He})$ 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 $(d,\text{He})$ spectra. We show the angular dependence of the $^{122}\text{Sn}(d,\text{He})$ and $^{117}\text{Sn}(d,\text{He})$ spectra at $T_d = 500$ MeV. We find that the $^{122}\text{Sn}(d,\text{He})$ spectra are dominated by the subcomponents including the $(2p)_{\pi}$ state at larger scattering angles $\theta_{\text{lab}}^{d,\text{He}} \geq 2^\circ$, while they are dominated by the $(1s)_{\pi}$ and $(2s)_{\pi}$ states at forward angles. 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. [6], 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]. We also find that the pionic $1s$ state which is free from the residual interaction effects appears clearly in $^{117}\text{Sn}(d,\text{He})$ spectra. 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.

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