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Formation of ^{3}He in the reactions of stopped pion absorption

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Formation of ^{3}He in the reactions of stopped pion absorption

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Abstract. The results of the measurements of spectra and yields of helium isotope ^{3}He formed in the stopped pion absorption by nuclei are presented. The contributions of different mechanisms of the helium formation in these reactions on medium and heavy nuclei were determined. The proposed phenomenological model reproduces the ^{3}He spectra at energies >30 MeV satisfactorily.

1. Introduction

The reaction of stopped pion absorption is useful for the study of cumulative processes accompanying nuclear reactions at low and intermediate energies (100 MeV ÷ 1 GeV). The pion absorption by nuclei is multinucleon process in which various particles are produced. Particle formation occurs in several stages of the reaction. Firstly, pion is absorbed by intranuclear cluster, and primary particles are generated. Then the formation of secondary particles takes place at pre-equilibrium and evaporation stages of the reaction.

In the papers [1, 2] we proposed a phenomenological model which satisfactory describes the experimental spectra of charged particles (p, d, t) formed in the pion absorption. This model also was successfully applied to the spectra of ^{3}He formed in the reaction on medium and heavy nuclei. In this case ^{3}He yield with energy E > 20 MeV is determined only by the pre-equilibrium stage. This is due to the fact that the primary ^{3}He can be formed only in the absorption by exotic cluster ^{4}Li [3]. In this work an attempt was made to determine the specific mechanisms leading to the formation of pre-equilibrium ^{3}He nuclei on medium and heavy nuclei.

2. Experiment

The experiment was carried out on the synchrocyclotron at the St. Petersburg Nuclear Physics Institute using the semiconductor spectrometer [4]. A beam of π-mesons passed through a moderator and two monitor surface-barrier detectors, and then it was stopped by a target, which was turned to the beam at 45^0. Charged particles formed in the reaction were detected by two multilayer semiconductor telescopes.

Measurements were performed on the following set of targets: light nuclei $^{6,7}Li$, ^{9}Be, $^{10,11}B$, ^{12}C; medium nuclei ^{28}Si, ^{40}Ca, ^{59}Co, ^{93}Nb; tin isotopes $^{114,117,120,124}Sn$ and heavy nuclei ^{169}Tm, ^{181}Ta, ^{209}Bi. The accuracy of absolute normalization of the experimental data was 7%. The measurements were performed up to the kinematic limits of the reaction.

Examples of measured energy spectra of ^3He are shown in figure 1. For medium and heavy nuclei the shape of the spectra is similar. For light targets there are differences at high energies which are probably due to their cluster structure.

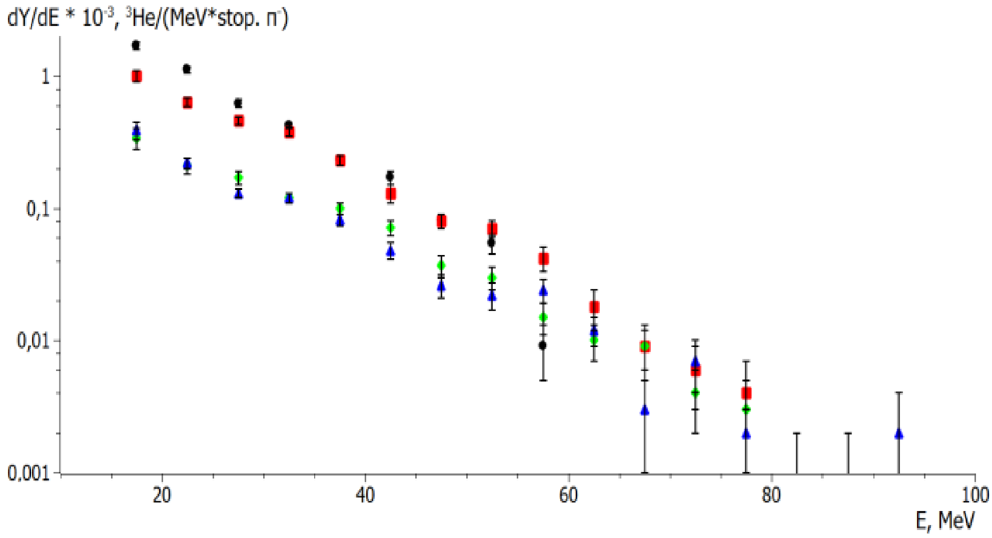

Figure 1. The ^3He spectra at different targets: ●-^6Li, ■-^{40}Ca, ♦-^{117}Sn, ▲-^{181}Ta.

3. Model

We examined the contributions of the two mechanisms in ^3He formation: knock-out and deuteron pick-up. It is assumed that these processes are initiated by the primary nucleons at the nuclear surface. Simulation of these reactions was carried out in the classical approximation taking into account the intranuclear motion of the clusters. The energy spectra of the primary nucleons were determined in the approximation of harmonic oscillator [1].

3.1. The knock-out mechanism

At the pre-equilibrium stage the energetic ^3He are formed as a result of direct knock-out by primary nucleons. The stopped pion absorption occurs on nuclear surface, therefore we consider only ^3He

which immediately leave the nucleus without final state interactions. ^{3}He whose momentum is directed into the nucleus were not taken into account because their mean free path is small (~ 1 fm).

The calculated spectra were normalized to the experimental data at 70 MeV. The errors of the simulation are due to the uncertainties of the primary particle spectra. Their average value is 15% [1]. As can be seen in figure 2 the simulation well describes the experimental spectra in the energy range from 60 MeV to the kinematic limits. For all studied nuclei the contribution of the knock-out process into the ^{3}He yield is about 10%.

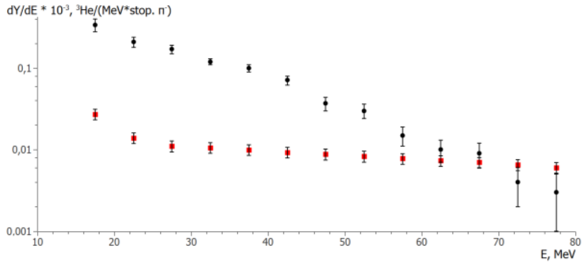

Figure 2. The spectrum of ^{3}He formed on the target of ^{117}Sn. ● – experiment, ■ - simulation of the knock-out process.

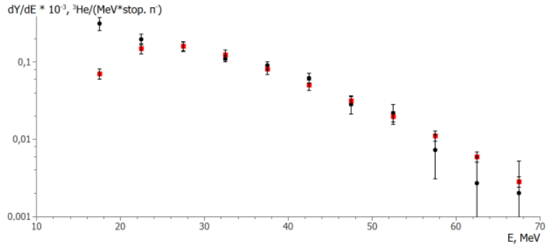

Figure 3. The spectra of ^{3}He formed on the target of ^{117}Sn. ● – the difference spectrum, ■ - simulation of the pick-up process

3.2. The pick-up mechanism

To determine the contribution of the pick-up mechanism in the ^{3}He formation, we studied the spectrum obtained after subtracting from the experimental data the contribution from the knock-out. The difference spectra were described by expression for cumulative particles [1]:

$$\frac{dY_{neq}}{dE} = C\sqrt{E(E_0 - E)}\exp(-\frac{E}{T}),$$

where T is the invariant slope of the spectra.

Table 1. The invariant slope of spectra of nuclei.

Nuclear target	T_τ, MeV	T_t, MeV [3]
^{28}Si	12 ± 1	13 ± 1
^{40}Ca	12 ± 1	14 ± 1
^{59}Co	13 ± 1	15 ± 1
^{93}Nb	14 ± 2	15 ± 1
^{114}Sn	14 ± 2	16 ± 1
^{117}Sn	13 ± 2	15 ± 1
^{120}Sn	15 ± 1	15 ± 2
^{124}Sn	14 ±3	16 ± 1
^{169}Tm	16 ± 2	16 ± 2
^{181}Ta	13 ± 2	16 ± 1
^{209}Bi	16 ±1	16 ± 1

The invariant slope of spectra T_τ obtained in this fitting are presented in table 1. The values T_τ are close to the same values for tritons – T_t [3] (table 1). In the work [3] the evidence was obtained that in the stopped pion absorption the tritons are formed in the pick-up of a deuteron by primary neutron. Therefore we assumed that the difference part of ^{3}He can be produced through the pick-up reaction: π^- + (pp) → p + n, p + d → ^{3}He.

To check this assumption we performed a simulation of the reaction of the pick-up. The shape of the primary proton spectrum was determined using the harmonic oscillator approach [1]. Momentum distribution of the deuterons was determined from Fermi distribution taking into account that pion absorption happened at nuclear surface. The pick-up reaction was treated in the classical approximation.

The calculated spectra were normalized on the difference spectra at the energy 30 MeV. As can be seen in figure 3 on the target of ^{117}Sn the spectra are in reasonably good agreement to one another at energy more than 25 MeV. The same agreement was observed for other medium and heavy nuclei. The difference in spectra observed at low energies indicates the existence of other mechanisms of formation of the ^{3}He nuclei [5].

The simulation allows to determine the yields of the ^{3}He produced in the pick-up process. The obtained results are shown in figure 4. For all studied nuclei the contribution of the pick-up process is about 60%. In order to generalize the obtained results to other nuclei we proposed phenomenological description of ^{3}He formation through the pick-up. It is assumed that this yield is proportional to the probability of pion absorption by (pp) pair, to the relative probability of pick-up pd→^{3}He and to the probability of ^{3}He escape without interaction:

$$Y_{3He} = C_{3He} P_{pp} P_{pick-up} P_{3He} \qquad (1)$$

The probability of pion absorption by a (pp) pair is [1]:

$$P_{pp} = \frac{Z-1}{Z-1+2R'N}$$

where R' is the ratio of elementary widths of the absorption, R'=3.5 [6].

The value $P_{\text{pick-up}}$ was determined by a phenomenological expression:

$$P_{pick-up} = \left(\frac{Z}{N}\right)^{2.1}$$

The value $P_{3\text{He}}$ was determined in the work [6]:

$$P_{3He} = \exp(-0.3A^{1/6})$$

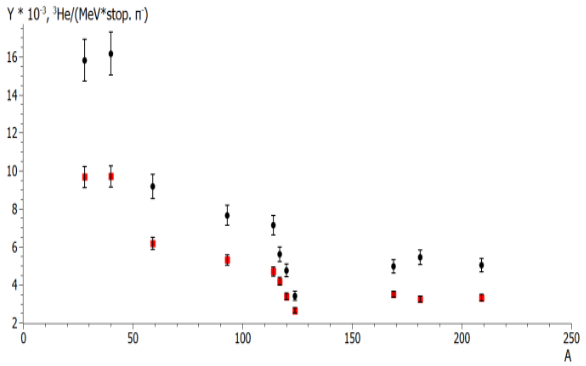

Figure 4. A-dependence of ^{3}He yields. ● – experimental data, ■ – pick-up contribution.

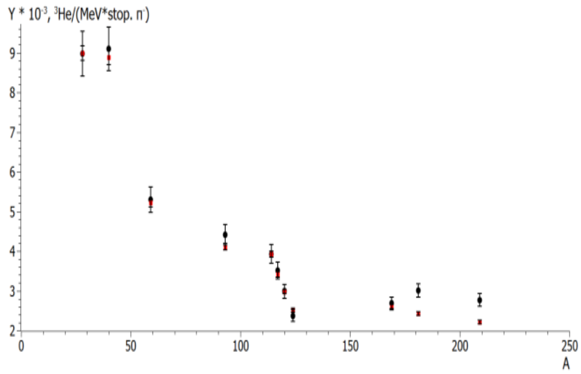

Figure 5. A-dependence of the simulated yield of ^{3}He. ● - simulation of the pick-up, ■ – expression (1).

Thus obtained A-dependence of the yields presented in figure 5. It is seen that the expression well describes the yields of ^{3}He produced by pick-up mechanism.

4. Conclusion
The contributions of the knock-out and pick-up mechanisms in the ^{3}He formation in stopped pion absorption were studied. It is shown that these two mechanisms describe well the spectra and yield of ^{3}He with energies greater than 25 MeV. The contribution of the knock-out process into the formation of ^{3}He is ~ 10%, the pick-up process ~ 60%.

5. Acknowledgements
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