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Halo-like Structure of ^{7}He and Transition from Neutron Halo to Neutron Skin

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A study of the reactions induced by stopped pions ^{9}Be(π^{-},d)X was done. The obtained results are consistent with the known data on considerable mixture of configurations "^{6}He in its ground and first excited states plus a neutron" in the ground state of ^{7}He. Comparison of the diffraction components of the differential cross-sections of the charge-exchange reactions (t,^{3}He) measured on ^{6}Li and ^{7}Li allowed extracting the radius of particle-unstable nucleus ^{7}He. The latter occurred to be approximately equal to those of ^{6}He and ^{8}He. The obtained result indicates to existence of the halo-like structure in ^{7}He. One might say about the transition from a neutron halo in ^{6}He to a neutron skin in ^{8}He.

KEYWORDS: Neutron halo, ^{7}He formation in stopped pion absorption, unbound nuclear state, nuclear radius

1. Introduction

In the present paper, we discuss a possible existence of an analog of the neutron halo in the unbound ^{7}He nucleus. The discovery of neutron halos [1] at the end of the last century was one of the most important achievements of nuclear physics.

It is traditionally assumed that only bound neutrons may form a halo. The possibility of appearance of a halo in continuum is not considered, as a rule. A critical parameter that allows speaking about existing of a halo (skin) in a particular unbound state is the ratio of its life time $T \approx \hbar/\Gamma$ to the flight time $t \sim 2R/v$ of the valence neutron required for passing the diameter of a nucleus. This value should be significantly larger than unity and is ~ 7 for ^{7}He. As the latter occupies an intermediate position between ^{6}He(halo) and ^{8}He(skin [2]), both structures are possible.

We analyzed the main possible configurations closest to the ground state of ^{7}He by a novel method using the stopped pions [3]. Secondly, we analyze the existing data on the charge-exchange reactions (t,^{3}He) on ^{6}Li and ^{7}Li in order to compare them and get some information on the radius of ^{7}He. Both approaches are expected to provide some information on possible existence of a halo-like structure in ^{7}He.

2. Results and discussion

We can get information about the most important configurations in ^{7}He by utilizing nuclear absorption of stopped pions [3]. In this case the non-resonant part of the spectrum of the emitted particles would reflect their contribution to the formation of ^{7}He. Here we concentrate on the decays resulting from the ^{9}Be(π^{-}, d)X reaction. The missing mass (MM) spectrum of this reaction obtained in inclusive measurements is shown in Fig. 1.

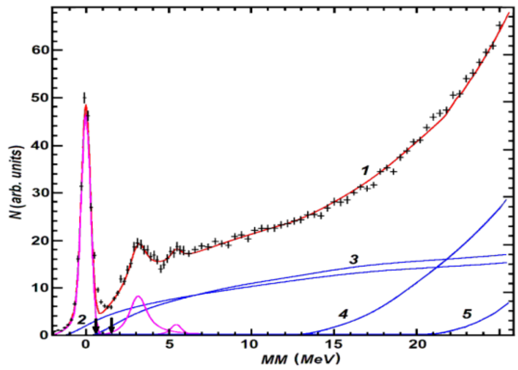

Fig. 1. The MM spectrum of the reaction π^{-}+^{9}Be→ d+X. Points with error bars denote the experimental data. Curve 1 is the summary spectrum; peaks are the Breit–Wigner distributions for the ground and excited states; distributions over phase volumes: 2) π^{-}+^{9}Be→ d+^{6}He+n, 3) π^{-}+ ^{9}Be→d+^{6}He*(1.8MeV)+n, 4) π^{-}+^{9}Be →d+^{5}He+2n, 5) π^{-}+^{9}Be→d+^{4}He + 3n. The thresholds of the 4th and 5th distributions are denoted by arrows.

One of the common features of the spectrum is the dominant contribution to the their continuous part from the final states with the formation of the ground and the first excited states of ^{6}He. The other one is the absence of a significant contribution to the spectrum from the channels with three nucleons in the final state: π^{-} + ^{9}Be → d + ^{4}He + 3n. This observation constitutes one of the most important outcomes of this work. It implies that, in the threshold region, a three-neutron system can be formed only through the creation of the first excited state of ^{6}He and its subsequent decay. This means that the probability to create a halo with three non-interacting neutrons ("true" halo) is very small although this configuration located near emission threshold. The observation of this effect provides grounds to the conclusion that the ^{4}He + 3n structure is not manifested in the ground state of ^{7}He. It must be emphasized that this conclusion does not depend on accurate determination of the ratio of the yields of the channels d + ^{6}He + n and d + ^{6}He*(1.8) + n. This hypothesis has never been proposed before. This observation hints of a possible existence of a complicated "halo-like" configuration in ^{7}He with all three neutrons located outside of the alpha particle core. The structure of this complicated halo-like state would be determined by correlations of neutrons in the $p_{3/2}$ and $p_{1/2}$ shells. This result would be in agreement with the previous works [2, 4] pointing out to a considerable mixing of configurations containing neutrons in the above-mentioned states.

To confirm the existence of the halo-like structure in ^{7}He, it would be necessary to estimate the radius of this nucleus. To do this we propose using the charge-exchange reactions. It is well known that the latter have many common features with the inelastic scattering [5]. The Modified diffraction model (MDM) [6] was successfully applied for measuring of the radii of the excited states of ^{13}N using charge-exchange (^{3}He,t)–reactions [7]. We found only two works for analysis: ^{6}Li(t,^{3}He)^{6}He at E(^{3}He) = 17 MeV [8] and ^{7}Li(t,^{3}He)^{7}He at E(^{3}He) = 22 MeV [9]. Experimental differential cross-sections of these reactions are shown on Fig. 2 and Fig. 3 as a function of linear transferred momentum. DWBA calculations were done for several energies and are presented on Fig. 2, 3.

The result of the performed analysis is that the differential cross sections of the both reactions have minima approximately at the same values of linear transferred momentum. This is a sign of similar diffraction radii in both reactions. The main assumption of MDM is that the difference of the root mean-square radii (RMS) of the states excited in both similar reactions is determined by the difference of the corresponding diffraction radii (see (1)). MDM was verified in many cases of inelastic scattering [6]. Its application to the charge-exchange reactions is still limited, so it is more careful to speak about evaluation of the radius of ^{7}He. Admitting that the linear transferred momentum corresponding to the minimum of the ^{7}Li(t,^{3}He)^{7}He reaction cross section is q(min) = 0.92 ± 0.04 fm^{-1}, we got the RMS radius of ^{7}He equal to 2.40±0.40 fm. Thus in the limit of errors it occurs to be equal to that of ^{6}He (R_{RMS}=2.48±0.03fm) and to ^{8}He (R_{RMS}=2.52± 0.03fm).

$$R_{RMS}(^{7}He) = \langle R_{RMS}(^{6}He)\rangle + \left[R_{dif}(^{7}He) - R_{dif}(^{6}He)\right] \qquad (1)$$

The observed ^{7}He radius is fairly well inscribed in the systematic of the ^{6}He - ^{7}He - ^{8}He radii. The fact that these nuclei have the same radii could only mean that the extra neutrons in ^{7}He and ^{8}He are occupying the same orbitals of the two neutrons in ^{6}He, implying more correlations. Due to the latter, the orbitals are filling up a bit more, thus achieving a region of increased densities without changing significantly the ^{6}He radius.

The single-particle orbit is the same and therefore one is still allowed to speak of a halo-like structure of ^{7}He not specifying whether it is a halo or a skin.

The net result is that the increased number of neutrons outside the ^{4}He core transform a halo into a skin. In Fig. 4 there are shown the neutron density distributions of ^{6}He and ^{8}He taken from [2] and matched for more convenient visualization.

More neutrons on the same orbital imply more correlations and a contraction of the orbital means effective shrinking of ^{8}He. It can see from Fig. 4 where neutron density distributions of ^{6}He and ^{8}He are presented: the density distribution of ^{8}He has a shorter and “thicker” tail.

Naturally, the analogue distribution is unknown for ^{7}He. However,

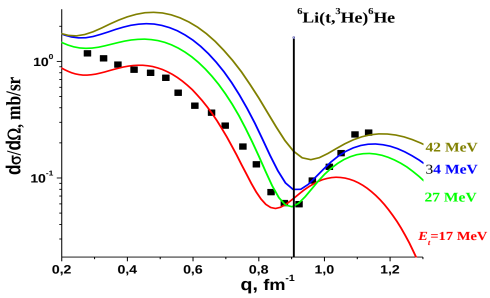

Fig. 2. Differential cross sections of the ^{6}Li(t,^{3}He)^{6}He reaction as functions of the linear transferred momentum q. The curves at different triton energies are calculated by the DWBA. The vertical black line connects with the observed and predicted diffraction minima.

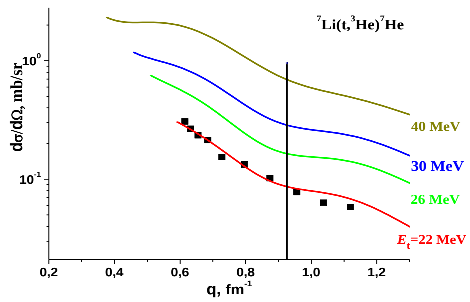

Fig. 3. The same as Fig. 2, only for ^{7}Li(t,^{3}He)^{7}He.

similarity of the radii of all three nuclei allows suggesting that ^{7}He occupies some intermediate position and connects the "halo" and "skin" structures.

The similarity of the radii of ^{6}He - ^{7}He - ^{8}He nuclei provides an additional argument for the absence of difference between halos in discreet spectra and continuum if the proper conditions are fulfilled.

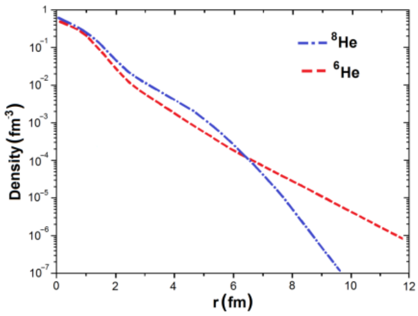

Fig. 4. Neutron density distributions of ^{6}He and ^{8}He taken from [2].

3. Conclusion

The structure of ^{7}He is determined by correlations of two neutrons in the states ^{6}He(0^{+}), ^{6}He(2^{+}) and one neutron in the shell $p_{3/2}$. The ^{4}He+3n structure is not manifested in the ground state of ^{7}He.

The radius of particle – unstable ^{7}He nucleus in its ground state was estimated by the MDM applied to the charge-exchange reactions ^{6}Li(t,^{3}He)^{6}He and ^{7}Li(t,^{3}He)^{7}He. It occurred to be close to the radii of ^{6}He and ^{8}He having two-neutron halo and neutron skin correspondingly indicating to some intermediate three-neutron halo-like structure of ^{7}He.

^{7}He radius is fairly well inscribed in the systematics of the ^{6}He – ^{7}He – ^{8}He radii. For the first time we managed to trace experimentally step by step the transition from neutron halo to neutron skin.

Acknowledgment

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