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Halo-like structure in ${}^7\text{He}$ nucleus

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Abstract. A study of the neutron structure of the ground state of ${}^7\text{He}$ has been performed by means of registration and analysis of the decay channels of the residual nuclei following absorption of stopped pions. In particular, the reaction ${}^9\text{Be}(\pi^-,d)X$ have been investigated where X denotes any system with five neutrons and two protons – the constituencies of a ${}^7\text{He}$ nucleus. It was shown that the structure of ${}^7\text{He}$ is determined by correlations of two neutrons in the states ${}^6\text{He}(0^+)$, ${}^6\text{He}(2^+)$ and one neutron in the shell $p_{3/2}$. The ${}^4\text{He}+3n$ structure is not manifested in the ground state of ${}^7\text{He}$. The obtained results are consistent with the known data on considerable mixture of configurations “ ${}^6\text{He}$ in its ground and first excited states plus a neutron” in the ground state of ${}^7\text{He}$. Comparison of the diffraction components of the differential cross-sections of the charge-exchange reactions ($t, {}^3\text{He}$) measured on ${}^6\text{Li}$ and ${}^7\text{Li}$ allowed extracting the radius of particle-unstable nucleus ${}^7\text{He}$. The latter occurred to be approximately equal to those of ${}^6\text{He}$ and ${}^8\text{He}$. The obtained result indicates to existence of the halo-like structure in ${}^7\text{He}$.

1. Introduction

In the present paper, we discuss a possible existence of an analog of the neutron halo in the unbound ${}^7\text{He}$ nucleus. The discovery of neutron halos [1] was one of the most important achievements of nuclear physics at the end of the 20th century. The observed halo nuclei consist of two components: the diffusive part (halo of neutrons) and the core with a normal nuclear density. The neutron density distribution in the diffusive component has a long tail. As a result, the radii of halo nuclei are much larger than those of ordinary nuclei with the same mass number. In addition to a halo the “neutron skin” notion is sometimes used to describe neutron-rich nuclei having neutrons with low binding energy. Although this term is not well defined, the corresponding nuclear structure might also be considered a “halo-like.”

However, unlike ${}^6\text{He}$, the density distribution of ${}^8\text{He}$ has a shorter and “thicker” tail (see Fig. 3.17 in [2]). Question is to what group applies to the intermediate nucleus ${}^7\text{He}$.

Another point of interest is the fact that ${}^7\text{He}$ is a particle – unstable nucleus. It has been traditionally assumed that only bound neutrons may form a halo. However, there are cases when the structure of states in the discrete spectrum is the same below and above the threshold. In particular, this refers to the members of some rotational bands in light nuclei. Thus, for example, in ${}^{11}\text{Be}$ there is a rotational band that is based on the ground state with $J^\pi = 1/2^+$. This state is considered as the classical



one-neutron halo and lies in the discrete spectrum. On the other hand, the member-states with higher angular moments ($5/2^+$ and $3/2^+$) are located in the continuum [3]. Judging by its parameters (moment of inertia, inversion of parity), the band in ^{11}Be is very similar to the well known positive parity rotational band in ^9Be . The latter is entirely located in the continuum and its basic state $1/2^+$ has usual halo characteristics [4-7]. An indication of a possible existence of a halo-like structure in ^7He is provided by the neighboring isotopes of ^6He and ^8He in which such structures are pronounced. To determine the conditions for a possible existence of a halo-like structure in an unbound state, we have introduced the concept of a characteristic time. It is defined as —the flight time of a valence neutron across the diameter of a nucleus. This value should be significantly smaller than the life time of an unbound state.

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 so one may expect formation of some “analog of halo” in this nucleus. For ^7He the ratio T/t is ~ 7 .

We looked for data which could provide some information on the halo-like structure of ^7He . Information on the ^7He structure can be obtained by two independent methods: First, we analyzed the main possible configurations closest to the ground state of ^7He , and therefore, capable of giving the largest contribution to its structure. The novel method using the stopped pions [8] was applied. Secondly, we analyze the existing data on the charge-exchange reactions ($t, ^3\text{He}$) on ^6Li and ^7Li in order to compare them and get some information on the radius of ^7He . Both approaches are expected to provide some information on possible existence of a halo-like structure in ^7He .

2. Results and discussion

2.1. Structure of the Ground State of ^7He from reactions induced by stopped pions

We can get information about the most important configurations in ^7He by utilizing nuclear absorption of stopped pions [8]. In this case the non-resonant part of the spectrum of the emitted particles would reflect their contribution to the formation of ^7He . Here we concentrate on the decays resulting from the $^9\text{Be}(\pi^-,d)X$ reaction. The missing mass (MM) spectrum of this reaction obtained in inclusive measurements [8] is shown in Fig. 1.

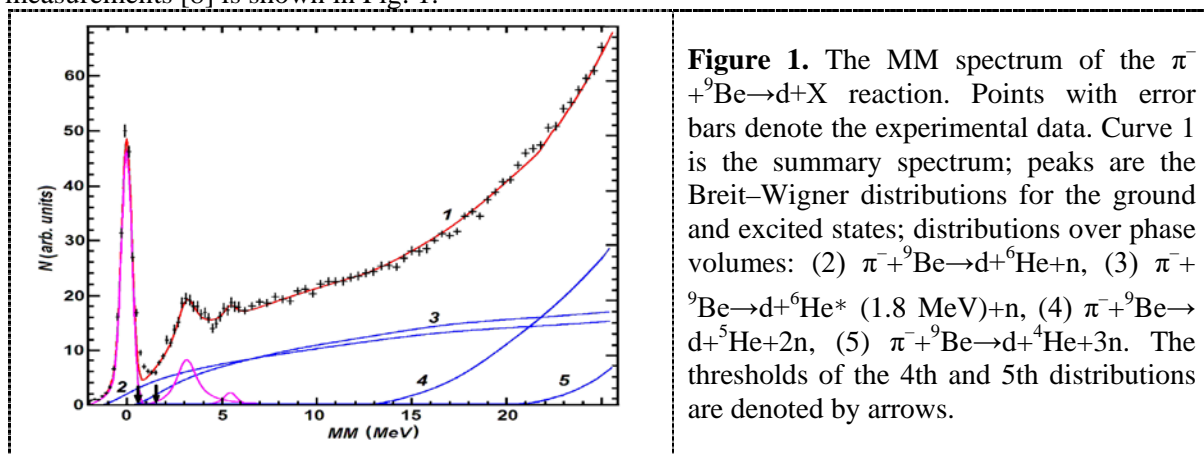


Figure 1. The MM spectrum of the $\pi^- + ^9\text{Be} \rightarrow d + X$ reaction. Points with error bars denote the experimental data. Curve 1 is the summary spectrum; peaks are the Breit-Wigner distributions for the ground and excited states; distributions over phase volumes: (2) $\pi^- + ^9\text{Be} \rightarrow d + ^6\text{He} + n$, (3) $\pi^- + ^9\text{Be} \rightarrow d + ^6\text{He}^* (1.8 \text{ MeV}) + n$, (4) $\pi^- + ^9\text{Be} \rightarrow d + ^5\text{He} + 2n$, (5) $\pi^- + ^9\text{Be} \rightarrow d + ^4\text{He} + 3n$. 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 their continuous part from the final states with the formation of the ground and the first excited states of ^6He . The other one is the absence of a significant contribution to the spectrum from the channels with three nucleons in the final state: $\pi^- + ^9\text{Be} \rightarrow d + ^4\text{He} + 3n$. 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 ^6He 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 ${}^4\text{He} + 3n$ structure is not manifested in the ground state of ${}^7\text{He}$. It must be emphasized that this conclusion does not depend on accurate determination of the ratio of the yields of the channels $d + {}^6\text{He} + n$ and $d + {}^6\text{He}^*(1.8) + n$. This hypothesis has never been proposed before. These observation hints of a possible existence of a complicated “halo-like” configuration in ${}^7\text{He}$ 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, 9] pointing out to a considerable mixing of configurations containing neutrons in the above-mentioned states.

2.2. Root mean square radius of ${}^7\text{He}$

To confirm the existence of the halo-like structure in ${}^7\text{He}$, it would be necessary to estimate the radius of this nucleus. As mentioned previously, we can speak about the radius of ${}^7\text{He}$ due to fact that its life time T is much larger than the characteristic time t , in simplest case equal to the flight time of the neutron across diameter of the nucleus. It is fulfilled in this case. We have two methods that can be used for measuring the radii of short-lived excited states: Modified Diffraction Model (MDM) [10] and Asymptotic Normalization Coefficients (ANC) method [11]. The ANC method is the most adequate method to measure a halo radius. Unfortunately, the ANC method is applicable only to bound states. In case of unbound states, we propose to use MDM. MDM is operating with experimental data on scattering. As ${}^7\text{He}$ can't be obtained in scattering, we propose to use charge-exchange reactions. It is well known that the latter have many common features with the inelastic scattering [12]. The method using charge-exchange reactions was proposed in [13] and later developed in [14]. This method represents some modification of MDM. Main aspects of it are present below.

In case of charge-exchange reactions, in the plane wave approximation, the cross sections are described by spherical (rather than by cylindrical in case of scattering) Bessel function, so:

$$\frac{d\sigma}{d\Omega} \sim [j_L(qR)]^2 \quad (1)$$

where q is the linear transferred momentum and R is the radial parameter. In accordance with (1), extrema of experimental angular distributions are associated with squared extrema of a Bessel function of the corresponding order depending on the transferred linear momentum. On base of this, diffraction radius is determined, which is the only parameter of the model.

Direct application of the MDM would involve a comparison of the inelastic and elastic scattering. In analogy with the scattering, for the proposed method the RMS radius of the excited state is estimated using practically the same formula

$$R_{RMS}^* = \langle R_0 \rangle + [R_{dif}^* - R_{dif}(0)] \quad (2)$$

where $\langle R_0 \rangle$ is the presumably known root-mean square radius of the nucleus in the ground state, R_{dif}^* and $R_{dif}(0)$ are the diffraction radii determined from the positions of the minima and maxima of experimental angular distributions of charge-exchange reaction with excitation of corresponding states.

There are convincing arguments to apply the method to charge-exchange reactions for the study of isobar-analogue states. We have successfully applied this approach to determine the proton halo in an unbound state of ${}^{13}\text{N}$ [13].

In case of heavy helium isotopes (${}^6\text{He}$, ${}^7\text{He}$), there is a problem with existing experimental data on angular distributions of the charge-exchange reactions. We found only two works for analysis by proposed method: ${}^6\text{Li}(t, {}^3\text{He}){}^6\text{He}$ at $E({}^3\text{He}) = 17$ MeV [15] and ${}^7\text{Li}(t, {}^3\text{He}){}^7\text{He}$ at $E({}^3\text{He}) = 22$ MeV [16]. 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.

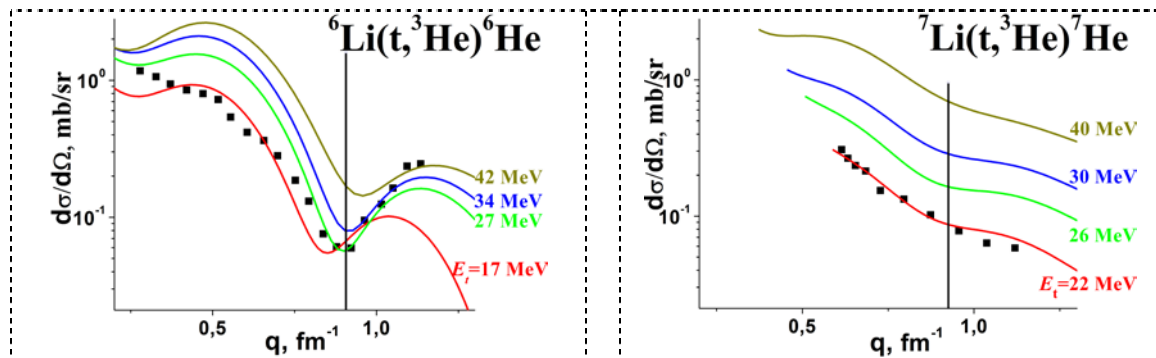


Figure 2. Differential cross sections of the ${}^6\text{Li}(t, {}^3\text{He}){}^6\text{He}$ reaction as functions of the linear transferred momentum q . The curves at different triton energies are calculated by the DWBA. The vertical black line connects with the observed and predicted diffraction minima.

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

In our DWBA analysis of these charge-exchange reactions, we used global optical potentials [16] for input and output channels of both reactions, which satisfactorily describe available elastic scattering data in these channels. Imaginary parts of the potentials effectively take into account dynamical part of interaction. As the used potential parameters appeared to be practically similar for both reactions, we can suppose that contributions of dynamical parts of diffraction radii for both reactions are close.

These considerations allow us, besides direct application of proposed method, compare the data of two reactions ${}^6\text{Li}(t, {}^3\text{He}){}^6\text{He}$ and ${}^7\text{Li}(t, {}^3\text{He}){}^7\text{He}$. In such a case ${}^7\text{He}$ radius would be determined relatively the known radius of the ${}^6\text{He}$ participating in the reference reaction. As a matter of fact, we transformed the relation (2) into

$$R_{RMS}({}^7\text{He}) = \langle R_{RMS}({}^6\text{He}) \rangle + [R_{dif}({}^7\text{He}) - R_{dif}({}^6\text{He})] \quad (3)$$

The result of the performed DWBA 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. As application of the method to the charge-exchange reactions is still limited, it is more careful to speak about some evaluation of the radius of ${}^7\text{He}$. Admitting that the linear transferred momentum corresponding to the minimum of the ${}^7\text{Li}(t, {}^3\text{He}){}^7\text{He}$ reaction cross section is $q(\text{min}) = 0.92 \pm 0.04 \text{ fm}^{-1}$, in accordance with (3), we got the RMS radius of ${}^7\text{He}$ equal to $2.40 \pm 0.40 \text{ fm}$. Thus in the limit of errors it occurs to be equal to that of ${}^6\text{He}$ ($R_{RMS} = 2.48 \pm 0.03 \text{ fm}$) and to ${}^8\text{He}$ ($R_{RMS} = 2.52 \pm 0.03 \text{ fm}$).

The observed ${}^7\text{He}$ radius is fairly well inscribed in the systematic of the ${}^6\text{He}$ - ${}^7\text{He}$ - ${}^8\text{He}$ radii. The fact that these nuclei have the same radii could only mean that the extra neutrons in ${}^7\text{He}$ and ${}^8\text{He}$ are occupying the same orbitals of the two neutrons in ${}^6\text{He}$, 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 ${}^6\text{He}$ radius.

${}^6\text{He}$ is a typical halo with long tail. ${}^8\text{He}$ is proposed to be example of skin in [2]. As one can see from Fig. 4, the density distribution of ${}^8\text{He}$ has a shorter tail. Due to the facts that the single-particle orbit is the same for all three nuclei ${}^6\text{He}$, ${}^7\text{He}$ and ${}^8\text{He}$ and rms radii coincide within error, it is quite natural to suggest that ${}^7\text{He}$ is characterized by halo-like structure and occupies some intermediate position. It connects the “halo” and “skin” structures, not specifying whether it is a halo or a skin.

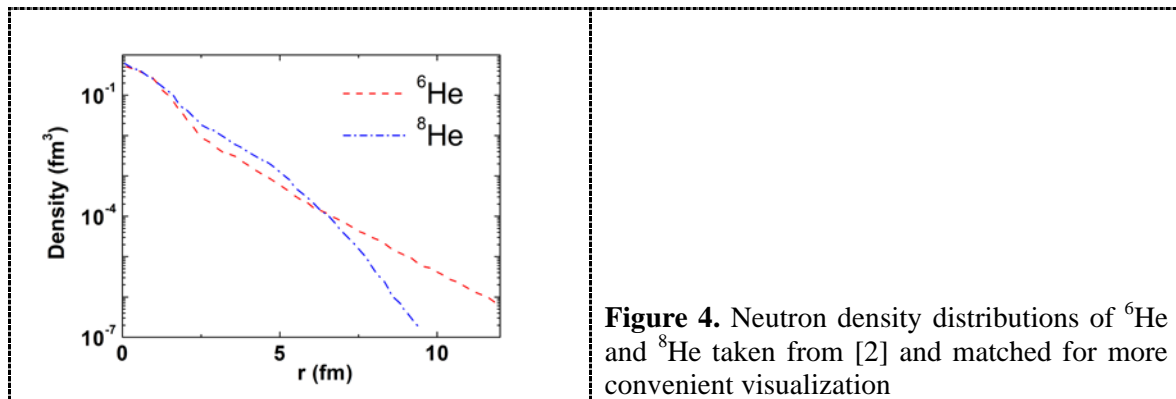


Figure 4. Neutron density distributions of ${}^6\text{He}$ and ${}^8\text{He}$ taken from [2] and matched for more convenient visualization

More neutrons on the same orbital imply more correlations and the contraction of the orbital means effective shrinking of ${}^8\text{He}$. The density distribution is unknown for ${}^7\text{He}$.

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

3. Conclusions

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

The radius of particle-unstable ${}^7\text{He}$ nucleus in its ground state was estimated using charge-exchange reactions ${}^6\text{Li}(t, {}^3\text{He}){}^6\text{He}$ and ${}^7\text{Li}(t, {}^3\text{He}){}^7\text{He}$. The ${}^7\text{He}$ radius is fairly well inscribed in the systematics of the ${}^6\text{He}$ - ${}^7\text{He}$ - ${}^8\text{He}$ radii. It occurred to be close to the radii of ${}^6\text{He}$ and ${}^8\text{He}$ having two-neutron halo and neutron skin correspondingly indicating to some intermediate three-neutron halo-like structure of ${}^7\text{He}$

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