Neutron Structure of the Ground State of $^7$He

B. A. Chernyshev$^a$, *, A. S. Demyanova$^b$, S. A. Goncharov, Yu. B. Gurov$^a$, S. V. Lapushkin$^a$, A. A. Ogloblin$^b$, V. G. Sandukovsky$^d$, and W. H. Trzaska$^e$

$a$ National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, 115409 Russia
$^b$ National Research Center Kurchatov Institute, Moscow, 123182 Russia
$^c$ Faculty of Physics, Moscow State University, Moscow, 119991 Russia
$^d$ Joint Institute for Nuclear Research, Dubna, Moscow region, 141980 Russia
$^e$ Department of Physics, University of Jyvaskyla, Jyvaskyla, FIN-40014 Finland

* e-mail: chernyshev@mephi.ru

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A study of the neutron structure of the ground state of $^7$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 reactions $^9$Be($\pi^–, d$)$X$ and $^{11}$B($\pi^–, dd$)$X$ have been investigated where $X$ denotes any system with five neutrons and two protons — the constituencies of a $^7$He nucleus. The results point out to the existence of a halo-like configuration of the ground state of $^7$He with all three neutrons outside of the alpha particle core. The structure of this complicated halo-like state is determined by the correlations of neutrons in the $p_{3/2}$ and $p_{1/2}$ shells. The result would be in agreement with the previous works pointing out to a considerable mixing of configurations containing neutrons in the $p_{3/2}$ and $p_{1/2}$ states.

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1. INTRODUCTION

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.

At present, different types of halos are known. After neutron halos, also proton halos were observed [2–6]. Halos were found not only in the ground state, but also in the excited states of nuclei [7, 8]. In addition to halo, the “neutron skin” notion is sometimes used to describe neutron-rich nuclei having neutrons with low binding energies. Although this term is not well defined, the corresponding nuclear structure might also be considered a “halo-like.” For instance, having four neutrons surrounding the $^4$He core, $^8$He is considered to be halo-like. It has neutron density distribution similar to that of $^6$He which is the reference example of a two-neutron halo nucleus, with two neutrons outside of the $^4$He core. However, unlike $^6$He, the density distribution of $^8$He has a shorter and “thicker” tail (see Fig. 3.17 in [9]).

It has been traditionally assumed that only bound neutrons may form a halo. Consequently, halo appearances in continuum are not being considered. 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 $^{11}$Be there is a rotational band that is based on the ground state with $J^P = 1/2^+$. This state is considered to be a classical one-neutron halo and lies in the discrete spectrum. On the other hand, the member-states with higher angular momenta ($5/2^+$ and $3/2^+$) are located already in the continuum [10]. 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 $^9$Be. The latter is entirely located in the continuum and its basic state $1/2^+$ has usual halo characteristics [11–14].

An indication of a possible existence of a halo-like structure in $^7$He is provided by the neighboring isotopes of $^6$He and $^8$He 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 $t = 2R/\nu$ — the flight time of a valence neutron across the diameter of a nucleus. This
The halo structure of $^6\text{He}$ was discussed in a number of theoretical papers, for example in [15–17]. Regarding $^6\text{He}$, it is customary to assume that it has a “neutron skin” in the sense discussed in [9]. It is natural to expect that the three neutrons surrounding the $^4\text{He}$ core in $^7\text{He}$ are similar to the two and four neutrons surrounding the $^4\text{He}$ core in $^6\text{He}$ and $^8\text{He}$, respectively. For $^7\text{He}$, assuming it has the same radius as $^6\text{He}$, $t/\tau \approx 0.1$. The small value of the $t/\tau$ ratio justifies consideration of a halo-like structure in this nucleus. However, the very fact that the valence neutron is located in continuum, may change the structure of $^7\text{He}$. It is conceivable, that it will be completely different from those in $^6\text{He}$ and $^8\text{He}$. For instance, it may be a double-halo with the last neutron forming a halo around the $^6\text{He}$ core, which is a halo nucleus itself.

Figure 1 shows a schematic representation of $^7\text{He}$ configurations closest to the ground state and, therefore, most likely to contribute to its structure.

The two configurations closest to the ground state of $^7\text{He}$ are: $^8\text{He} + n$ and $^4\text{He} + 3n$. For that reason, they should play the dominant role in the formation of the proposed halo-like state. Both configurations are worthy of further investigations. Up to now, a three-neutron halo has never been observed. The case of a double-halo, with one-neutron halo around the halo core of $^6\text{He}$, would be equally exotic. The situation is complicated further by the fact that all of the available data indicate the importance of neutron correlations both in $^6\text{He}$ and $^8\text{He}$.

In this paper we propose a novel method of identifying the most important configurations in $^7\text{He}$ by utilizing nuclear absorption of stopped pions. We assume that $^7\text{He}$ is formed from particles emitted after pion absorption. In this case the non-resonant part of the spectrum of the emitted particles would reflect their contribution to the formation of $^7\text{He}$. If only one configuration were to play a noticeable role, it would be expected that this configuration would also determine the type of the halo-like configuration in $^7\text{He}$. As compared to ion-induced reactions [18–24], pion absorption reactions deliver a larger number of the final states. Here we concentrate on the decays resulting from the $^9\text{Be}(\pi^-,d)X$ and $^{11}\text{B}(\pi^-,dd)X$ reactions. The boron data were published in [25], but the proposed novel approach to study the configuration of the ground state of $^7\text{He}$ is used here for the first time. Also, the results of the measurements on beryllium target are new.

In the future, we intend to extend the analysis of the existing data to the $(t, ^6\text{He})$ charge-exchange reactions on $^6\text{Li}$ and $^7\text{Li}$. This comparison should yield some information on the radius of $^7\text{He}$.

2. EXPERIMENT

The measurements were carried out on a low-energy pion beam from the LANL accelerator in Los Alamos using a multilayer semiconductor spectrometer [26, 27]. A negative pion beam with the energy of 30 MeV passed through a moderator and was stopped in a thin (~25 $\mu$g/cm$^2$) target. The secondary charged particles, produced upon absorption of the stopped pions, were detected by two semiconductor telescopes with silicon detectors. The telescopes were located at the angle of 180° with respect to each other. The total sensitive thickness of each silicon telescope was ~43 mm. This value exceeds the range of all charged particles produced in the absorption reaction on the investigated targets. The achieved energy resolution for single-charged particles throughout the entire energy range was ~0.45 MeV (FWHM) [27]. The error in the absolute energy calibration was below 0.1 MeV and the detection threshold was ~4.5 MeV.

The resolution for the detection of pairs of single-charged particles using the missing mass ($MM$) method depends only weakly on a specific reaction channel and amounts to ~1 MeV [27]. In the correlation measurements the error in the absolute energy calibration did not exceed 0.1 MeV. The spectrometer and the experimental methods are described in more detail in [26, 27].

3. RESULTS

The missing mass spectrum obtained in inclusive measurements of the $^9\text{Be}(\pi^-,d)X$ reaction is shown in Fig. 2. The experimental spectrum was treated as a sum of Breit–Wigner distributions and $N$-particle ($N > 2$) distributions over the phase volumes. The least squares method was used to reveal the $^7\text{He}$ states. A satisfactory description could be achieved by introducing three $^7\text{He}$ states: the ground state with the resonance parameters $E_\nu = 0.410(8)$ MeV and $\Gamma = 0.15(2)$ MeV [20], two excited states with the res-

![Fig. 1. Key configurations expected to be manifested in the decay of $^7\text{He}$.](image-url)

### Table 1: Typical nuclear absorption cross sections for $^9\text{Be}(\pi^-)$ stopped pions on $^7\text{He}$

| Configuration | Cross Section (mb) |
|---------------|-------------------|
| $^8\text{He} + n$ | 2.42 |
| $^4\text{He} + 3n$ | 0.529 |
| $^7\text{He}$ | 0.00 |

The cross sections listed are typical for nuclear absorption of stopped pions. They provide a useful basis for the identification of configurations in $^7\text{He}$. The reported cross sections are normalized to the beam intensity and are therefore independent of the absolute normalization of the incoming pion flux.
The ground state and the two excited states of $^{7}$He appear as discrete peaks in Fig. 2. The intense continuous spectrum is well reproduced throughout the wide energy interval by the phase volumes of the $\pi^{-} + ^{9}$Be $(d + 6^{2}$He n) and $\pi^{-} + ^{9}$Be $(d + 6^{4}$He*$_{1.8}$MeV n) reactions (curves 2 and 3 in Fig. 2). The multibody distributions 4 and 5 start contributing only at higher $MM$ energies. The phase volume contribution to the inclusive spectrum is proportional to $N^{2}$, where $N \geq 3$ is a number of particles in a final state [28, p. 96]. This is the reason why the onsets of curves 2 and 3 in Fig. 2 do not overlap with the relevant threshold values.

The missing mass spectrum obtained on correlation measurements of the $^{11}$B$(\pi^{-}, dd)X$ reaction is shown in Fig. 3. In distinction to [25], the neutron detection threshold was raised up to 20 MeV reducing the contribution from the channels not leading to the formation of helium isotopes.

As in the case of Fig. 2, the intense continuous spectrum is well reproduced by the phase volumes of the $\pi^{-} + ^{11}$B $(d + 6^{2}$He*$_{6}$MeV n) and $\pi^{-} + ^{11}$B $(d + 6^{4}$He*$_{1.8}$MeV n) reactions (curves 2–5 in Fig. 3). The obtained values of the resonance parameters in the region $E_{x} < 7$ MeV are consistent with the results of the other authors [18–24]. The boron results agree, within the error bars, with our previous work [25].

### Table 1. Parameters of the resonance states of $^{7}$He ($E_{x} < 7$ MeV)

| $^{9}$Be$(\pi^{-}, d)X$ | $^{11}$B$(\pi^{-}, dd)X$ |
|-------------------------|----------------------------|
| $E_{x}$, MeV | $\Gamma$, MeV | $E_{x}$, MeV | $\Gamma$, MeV |
| g.s. | 0.15 [20] | g.s. | 0.15 [20] |
| 3.3 $\pm$ 0.1 | 1.1 $\pm$ 0.1 | 2.9 $\pm$ 0.5 | 0.7 $\pm$ 0.3 |
| 5.6 $\pm$ 0.2 | 1.0 $\pm$ 0.4 | 4.6 $\pm$ 0.5 | 0.7 $\pm$ 0.3 |
| | | 6.6 $\pm$ 0.5 | 0.7 $\pm$ 0.3 |
4. DISCUSSION

As can be seen from Figs. 2 and 3, the contributions of different phase volumes differ for the inclusive and correlation spectra. In particular, the channel $d + d + ^3$He + 2$n$ makes the main contribution to the high-energy part of the correlation spectrum for the reaction $\pi^- + ^{11}$B $\rightarrow d + d + X$, while in the inclusive reaction $^9$Be($\pi^-$, $d$)X, it is negligible. Also, as evident from Table 1, the structure of the levels observed in the reactions $^9$Be($\pi^-$, $d$)X and $^{11}$B($\pi^-$, $dd$)X is significantly different.

These differences seem to arise from various mechanisms of the studied reactions. In the two-body channel $^9$Be($\pi^-$, $d$)$^7$He, the studied nucleus has a large momentum. In the three-body channel $^{11}$B($\pi^-$, $dd$)$^7$He, the dominant contribution is made by quasifree absorption, in which $^7$He is a spectator. In this case, the momentum of the residual nucleus is determined by Fermi-motion in the target nucleus. Hence, it can be assumed that the general regularities in the observed spectra do not depend on the reaction mechanism and instead reflect the properties of the investigated system $^7$He.

One of the common features of the spectra is the dominant contribution to the continuous spectrum from the final states with the formation of the ground and the first excited state of $^6$He. The other common feature is the absence of a significant contribution to the spectra from the channels with three nuclei in the final state: $\pi^- + ^9$Be $\rightarrow d + ^4$He + 3$n$ and $\pi^- + ^{11}$B $\rightarrow d + d + ^4$He + 3$n$. 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. The observation of this effect in two different reactions provides grounds to the conclusion that the $^4$He + 3$n$ structure is not manifested in the ground state of $^7$He. This hypothesis has never been proposed before.

The $3/2^-$ spin-parity of the $^7$He ground state conforms with the standard shell model predictions assigning the $p_{3/2}$ state to all three valence neutrons. However, a large deviation of the spectroscopic factor from unity with $S(^6$He gs $+ n) = 0.61 \pm 0.03$ [18, 19] and $S(^6$He gs $+ n) = 0.36 \pm 0.07$ [9] does not support such a simplistic model. The analysis made in [9, 23] showed that, most likely, the $^7$He ground state represents a mixture of two components, including neutrons in the $p_{3/2}$ and $p_{1/2}$ states, coupled to the $^4$He core. This conclusion is in a good agreement with our above-mentioned results on the predominance of the final configuration with formation of the $^6$He gs and the $^6$He*(1.8 MeV) excited state (curves 2 and 3 in Figs. 2 and 3).

5. CONCLUSIONS

For the first time the neutron structure of the ground state of $^7$He has been studied utilizing reactions induced by nuclear absorption of stopped pions. The decay channels of the residual nuclei from the reactions $^9$Be($\pi^-$, $d$)X and $^{11}$B($\pi^-$, $dd$)X have been analyzed, while X denotes the system of five neutrons and two protons constituting $^7$He.

The main outcome of this work is registration of the absence from the spectra of the component corresponding to the decay $\pi^- + ^9$Be $\rightarrow d + ^4$He + 3$n$ and $\pi^- + ^{11}$B $\rightarrow d + d + ^4$He + 3$n$. The spectra covered energies up to 20 and 30 MeV, respectively. This is the first indication that the $^4$He + 3$n$ structure is not present in the ground state of $^7$He.

The main configurations reproducing the sum of partial phase volumes in the near-threshold region are $d + ^6$He + n, and $d + ^6$He* (1.8 MeV) + n for the reaction $^9$Be($\pi^-$, $d$)X, and $d + d + ^6$He + n, and $d + d + ^6$He* (1.8 MeV) + n for the reaction $^{11}$B($\pi^-$, $dd$)X. 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 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. Having this goal in mind, as the next step we intend to analyze the existing data on the $(t, ^3$He) charge-exchange reactions on $^6$Li and $^7$Li.

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