Spectroscopy of $^7$He in stopped pion absorption

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Abstract. Formation of the $^7$He heavy isotope was studied in the reactions of stopped pion absorption by light nuclei $^6$Be, $^{10,11}$B and $^{12,14}$C. Measurements were performed using the two-arm multilayer semiconductor spectrometer. Contrary to the results of other studies, we observed several narrow highly excited states ($E_x > 16$ MeV) of $^7$He. From the analysis of the continuous excitation spectrum in reactions $^6$Be$(\pi^-, d)X$ and $^{11}$B$(\pi^-, dd)X$ it was obtained first indication that the $^7$He+3n structure is not present in the ground state of $^7$He.

1. Introduction

Studies of the level structure of light neutron-rich isotopes near drip line are currently a field of great experimental activity. This information allows us to extend our understanding of the properties of nuclear matter under conditions of anomalously high $N/Z$ ratios ($N$ – neutron number, $Z$ – proton number in nucleus).

The ground state (g.s.) of $^7$He ($J^P = 3/2^+$) is unbound with respect to decay into $^6$He$_{g.s.}$ ($J^P = 0^+$) and neutron in the $1p_{3/2}$ orbital and has the following values of resonance parameters – $E_x = 0.410(8)$ MeV and $\Gamma = 0.15(2)$ MeV [1].

An excited state $E_x = 2.93(3)$ MeV and $\Gamma = 2.23(3)$ MeV was observed for the first time in the p($^7$He,$d$)$^7$He reaction at energy 50.4 MeV [2]. This level was also observed in other works (see table 1, references to earlier works are in compilation [1]). For other levels the experimental situation with the determination of their resonance parameters remains controversial (see table 1). Thus, indications of $^7$He state with $E_x \sim 1$ MeV were obtained in three works [3–5], while in other work this state was not observed. Note that no more than two low-lying excited states of $^7$He were observed in any experiments. In the region of high excitations ($E_x \geq 8$ MeV) only wide levels ($\Gamma \sim 10$ MeV) were observed.

Theoretical predictions of level structure of $^7$He are equally contradictory (see review [12]). Most of the models predict the same order of low lying levels: $J^P = 3/2^+$ (ground state), 1/2$, 5/2$, 3/2$. However, the values of resonance parameters in these models are quite different. Theoretical calculations of highly excited states are unknown to us.

Thus information on the level structure of $^7$He is fragmented and contradictory. To improve this situation we conducted an experimental search for $^7$He in the reactions of stopped pion absorption by light nuclei $^6$Be, $^{10,11}$B, $^{12,14}$C. This paper presents an overview of these results. Note that some of these results were presented in paper [13].
Table 1. Parameters of excitation levels of \(^7\)He.

| \(E_x, \text{MeV}\) | \(\Gamma, \text{MeV}\) | Work |
|----------------|-----------------|------|
| 0.6(1)         | 0.75(8)         | [3]  |
| 0.9(5)         | 1.0(9)          | [4]  |
| \(\approx 1.45\) | \(\approx 2\) | [5]  |
| 2.22(8)        | 2.34(7)         | [6]  |
| \(\approx 2.6\) | \(\approx 2\) | [7]  |
| 2.9(3)         | 2.2(3)          | [1, 2, 4, 5, 8] |
| 5.8(1)         | 4(1)            | [1]  |
| \(\approx 8.0\) | \~7             | [8]  |
| \(\approx 18.0\) | \~7             | [8, 9] |
| 18.0(1.5)      | \~10            | [10] |
| 20(1)          | 9(2)            | [5, 11] |

2. Experiment

Measurements were carried out in the low energy pion channel of LAMPF with a two-arm multilayer semiconductor spectrometer [14]. The beam of negatively charged pions with an energy of 30 MeV was slowed down by the beryllium moderator and was then stopped in a thin target. The rate of pion stop in the target was about 6\(\cdot\)10\(^4\) s\(^{-1}\). Measurements were made on targets Measurements were made on targets \(^9\)Be, \(^{10},^{11}\)B, \(^{12},^{14}\)C. The \(^{14}\)C enriched radioactive target consisted of \(^7\)% \(^{14}\)C and 2\% \(^{14}\)C.

Charged particles (p, d, t, \(^{3,4}\)He) emitted after pion absorption in the targets were detected by two semiconductor telescopes oriented at an angle of 180\(^\circ\) with respect to each other. The total sensitive thickness of each telescope was \~43\, mm. This thickness permitted one to measure the total absorption of charged particles up to kinematical limits of the reaction.

The energy resolution (FWHM) was better than 0.5 MeV for single charged particles (p, d, t) and 2 MeV for double charged particles (\(^{3,4}\)He). The error of absolute energy calibration did not exceed 100 keV. In correlation measurements the missing mass (\(MM\)) resolution was 1 MeV for pairs of single charged pairs and 3 MeV for pairs hydrogen and helium isotopes.

The spectrometer and experimental techniques are described more detail in [14, 15].

3. Results and discussion

A missing mass spectrum in the \(^9\)Be(\(\pi^-,d\))X reaction is shown in fig. 1. The sum of neutron and \(^4\)He masses is taken as a reference point. To separate \(^7\)He states and determine their parameters, we used the least square approximation in the fitting of the experimental spectrum by the sum of the Breit-Wigner resonances and \(N\)-particle phase-space distributions \((N \geq 3)\).

A satisfactory description could be achieved by introducing three \(^7\)He states: the ground state with the resonance parameters \(E_r = 0.410(8)\) MeV and \(\Gamma = 0.15(2)\) MeV [1], two excited states with the parameters listed in table 2, and four distributions over the phase volumes. Note that the absence of highly excited levels in these data may be due to the rapid growth of the continuous part of the inclusive spectrum. The obtained excitation energies coincide with the data of compilation [1] (see table 1) within the errors of the measurements. At the same time, in our measurements, the width of the levels is noticeably narrower.

In the correlation measurements on the boron isotopes search for \(^7\)He was carried out in the reactions \(^{11}\)B(\(\pi^-,dd\))X (fig. 2), \(^{11}\)B(\(\pi^-,pt\))X (fig. 3) and \(^{10}\)B(\(\pi^-,pd\))X (fig. 4). The sum of neutron and \(^9\)He masses is taken as a reference point. All spectra show structures associated with three-body channels involving \(^7\)He in the ground and excited states. The spectra were described in the same way.
as in case $^9\text{Be}$ ($N$-particle phase-space distributions with $N \geq 4$ were considered). Parameters of excited states are presented in the table 2.

![Figure 1. MM spectrum for the reaction $^9\text{Be}(\pi^-,d)X$. Points with error bars denote the experimental data. Curve 1 — summary spectrum; peaks are the Breit – Wigner distributions for the ground and excited states; distributions over phase volumes: $2 - \pi^- + ^9\text{Be} \rightarrow d + ^6\text{He} + n$, $3 - \pi^- + ^9\text{Be} \rightarrow d + ^6\text{He}(1.8 \text{ MeV}) + n$, $4 - \pi^- + ^9\text{Be} \rightarrow d + ^5\text{He} + 2n$, $5 - \pi^- + ^9\text{Be} \rightarrow d + ^4\text{He} + 3n$.](image)

In our measurements the $^{11}\text{B}(\pi^-,dd)X$ and $^{11}\text{B}(\pi^-,pt)X$ reaction channels have the highest statistics. The spectra of levels observed in these reactions have almost the same structure. Three narrow states are observed in the range of low excitation. The existence of three states in the region $2.5 \leq E_x \leq 7$ MeV was predicted in several theoretical works [16–19]. Our data are close to the results of [19]: $(E_x$, $\Gamma) = (3.27 \text{ MeV}, 2.7 \text{ MeV})$, $(3.9 \text{ MeV}, 0.94 \text{ MeV})$ and $(5.2 \text{ MeV}, 1.2 \text{ MeV})$. The value $E_x$ of the first excited state is close to the results of other works (table 1) and our value obtained on the $^9\text{Be}$ target (table 2). The parameters of two other levels are noticeable different from results of other authors and $^9\text{Be}$ data. This probably is evidence for existence of more than three low lying excited states of $^7\text{He}$.

In the region of high excitation energies above the threshold of the decay $^7\text{He} \rightarrow t+t+n$ ($E_x = 11.9$ MeV), three rather narrow states of $^7\text{He}$ are observed in both channels. In other experiments only wide states have been observed in this region (table 1). The nature of the observed us states is unclear.

The MM spectrum measured in the $^{10}\text{B}(\pi^-,pd)X$ reaction (fig. 4) has the lower statistics in comparison with data on the $^{11}\text{B}$. A satisfactory description is obtained by the inclusion of the three excited levels of $^7\text{He}$ (table 2). The parameters of these states are close to the corresponding values obtained on the $^{11}\text{B}$. The absence of other levels in the description is due to insufficient statistics of the data.

Indications of the existence of a low-lying excited state of $^7\text{He}$ with $E_x \approx 1$ MeV were not obtained in any of the channels in the measurements on $^9\text{Be}$, $^{10}\text{B}$ and $^{11}\text{B}$. Nevertheless to test the hypothesis of existence this state, we carried out an alternative description of the experimental spectra (figs. 1–4) including the level with the parameters $E_x = 0.6$ MeV and $\Gamma = 0.75$ MeV, which was found in [3]. The upper bound for the contribution of this state is $\sim 10\%$.

In addition to the discrete peaks corresponding to the formation of $^7\text{He}$ states one can see in figs. 1–4 the intensive continuous spectra. The common feature of these spectra is the absence of a significant contribution from the channels with three nucleons in the final state. This means that the probability to create a halo with three non-interacting neutrons ("true" halo) is very small.
Figure 2. MM spectrum for the reaction $^{11}$B$(\pi^-,$dd$)X$. Points with error bars denote the experimental data. Curve 1 – summary spectrum; peaks are the Breit – Wigner distributions for the ground and excited states; distributions over phase volumes: $2 - \pi^- + ^{11}$B $\rightarrow$ d + d + $^6$He + n, $3 - \pi^- + ^{11}$B $\rightarrow$ d + d + $^5$He + 2n, $4 - \pi^- + ^{11}$B $\rightarrow$ d + d + 2d + 3n. The inset shows the spectrum obtained after the subtraction the sum of phase-space distributions.

Figure 3. MM spectrum for the reaction $^{11}$B$(\pi^-,$pt$)X$. Points with error bars denote the experimental data. Curve 1 – summary spectrum; peaks are the Breit – Wigner distributions for the ground and excited states; distributions over phase volumes: $2 - \pi^- + ^{11}$B $\rightarrow$ p + t + $^6$He + n, $3 - \pi^- + ^{11}$B $\rightarrow$ p + t + $^5$He + 2n, $4 - \pi^- + ^{11}$B $\rightarrow$ p + t + $^4$He + 3n, $5 - \pi^- + ^{11}$B $\rightarrow$ p + t + 2d + 3n. The inset shows the spectrum obtained after the subtraction the sum of phase-space distributions.

Figure 4. MM spectrum for the reaction $^{10}$B$(\pi^-,$pd$)X$. Points with error bars denote the experimental data. Curve 1 – summary spectrum; peaks are the Breit – Wigner distributions for the ground and excited states; distributions over phase volumes: $2 - \pi^- + ^{10}$B $\rightarrow$ p + t + $^6$He + n, $3 - \pi^- + ^{10}$B $\rightarrow$ p + t + $^5$He + 2n. The inset shows the spectrum obtained after the subtraction the sum of phase-space distributions.
Table 2. Parameters of excitation levels of $^7$He obtained in the reactions of stopped pion absorption.

|                  | $^9$Be($\pi$,d)$X$ | $^{11}$B($\pi$,dd)$X$ | $^{11}$B($\pi$,pt)$X$ | $^{10}$B($\pi$,pd)$X$ |
|------------------|---------------------|------------------------|------------------------|------------------------|
| $E_x$, MeV       | $\Gamma$, MeV       | $E_x$, MeV              | $\Gamma$, MeV          | $E_x$, MeV              |
| 3.3(1)           | 0.7(3)              | 3.0(2)                  | 0.5(2)                 | 3.0(2)                  | 0.5(4)                  |
| 5.6(2)           | 0.7(3)              | 4.9(2)                  | 0.5(2)                 | 4.9(3)                  | 0.5(4)                  |
| 6.6(5)           | 0.7(3)              | 7.0(2)                  | 0.5(2)                 |                        |                        |
| 17.2(5)          | 1.0                 | 16.3(5)                 | 2.0                    |                        |                        |
| 20.7(5)          | 1.5                 | 19.3(5)                 | 1.5                    |                        |                        |
| 24.5(5)          | 2.0                 | 24.5(5)                 | 4.5                    | 23.0(6)                 | 5.0(7)                  |

The $MM$ spectra obtained in the measurements on $^{12}$C and $^{14}$C are shown in figs. 5–7. Unfortunately due to insufficient energy resolution and low data statistics in these measurements only limited information on the level structure of $^7$He could be obtained. In the reaction $^{12}$C($\pi^-$,p$^4$He)$X$ there are observed two excited states with parameters ($E_x$, $\Gamma$) = (3.0(5) MeV, 1.0 MeV) and (6.7(5) MeV, 1.0 MeV). In the reaction $^{12}$C($\pi^-$,d$^3$He)$X$ there is observed excited state with parameters ($E_x$, $\Gamma$) = (3.0(5) MeV, 1.0 MeV). These values are close to the data obtained on boron isotopes.

Figure 5. $MM$ spectrum for the reaction $^{12}$C($\pi^-$,p$^4$He)$X$. Points with error bars denote the experimental data. Curve 1 – summary spectrum; peaks are the Breit – Wigner distributions for the ground and excited states; distributions over phase volumes: $2 - \pi^- + ^{12}$C $\rightarrow$ p + $^4$He + $^4$He + n, $3 - \pi^- + ^{12}$C $\rightarrow$ p + $^4$He + $^5$He + 2n, $4 - \pi^- + ^{11}$B $\rightarrow$ p + $^4$He + $^4$He + 3n.

Figure 6. $MM$ spectrum for the reaction $^{12}$C($\pi^-$,d$^3$He)$X$. Points with error bars denote the experimental data. Curve 1 – summary spectrum; peaks are the Breit – Wigner distributions for the ground and excited states; distributions over phase volumes: $2 - \pi^- + ^{12}$C $\rightarrow$ d + $^3$He + $^6$He + n, $3 - \pi^- + ^{12}$C $\rightarrow$ d + $^3$He + $^5$He + 2n.
Figure 7. a – $MM$ spectrum for the reaction $(\pi^-, p^4\text{He})$ on the radioactive target $^{14}\text{C}$ (points with error bars) and on $^{12}\text{C}$ target (shaded histogram); b – $MM$ spectrum for the reaction $^{14}\text{C}(\pi^-, t^4\text{He})X$. Dots with error bars were obtained after the subtraction of $^{12}\text{C}$ background. Curve 1 – summary spectrum; peaks are the Breit – Wigner distributions for the ground and excited states; distributions over phase volumes: $2 - \pi^- + ^{14}\text{C} \rightarrow t + ^6\text{He} + n$, $3 - \pi^- + ^{14}\text{C} \rightarrow t + ^4\text{He} + ^3\text{He} + 2n$.

The $MM$ spectrum obtained on the radioactive target $^{14}\text{C}$ is shown in fig. 7. The contribution of $^{12}\text{C}$ impurity is clear seen. The contribution of $^{12}\text{C}$ impurity was determined using the results from correlation measurements of $^p\text{He}$-pairs on the $^{12}\text{C}$ target. The $MM$ spectrum for the reaction $^{12}\text{C}(\pi^-, p^4\text{He})X$ was normalized to the relative impurity contribution (23%) and was subtracted from the spectra in fig. 7a. The subtracted contribution is shown by the shaded histogram. The spectrum after impurity subtraction is shown in fig. 7b. In the obtained spectrum there are observed two excited states with parameters $(E_x, \Gamma) = (3.0(5) \text{ MeV}, \sim 1 \text{ MeV})$ and $(\sim 16 \text{ MeV}, \sim 1.5 \text{ MeV})$. Note that the highly excited state with similar parameters was observed in the reaction $^{11}\text{B}(\pi^-, pt)X$.

4. Conclusion
The overview of the data on the level structure of heavy helium isotope $^7\text{He}$ obtained in stopped pion absorption by light nuclei $^8\text{Be}$, $^{10,11}\text{B}$, $^{12,14}\text{C}$ is presented. In the region of low excitation energies, the existence of three States was observed simultaneously for the first time. The formation of narrow highly excited states was observed for the first time in four reaction channels.

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References
[1] Tilley D, Cheves C M, Godwin J L, Hale H M, Hofmann H M, Kelley J H, Sheu H R and Weller H R 2002 Nucl. Phys. A, 708 3
[2] Korsheninnikov A A et al 1999 Phys. Rev. Lett. 82 3581–3
[3] Meister M et al 2002 Phys. Rev. Lett. 88 102501
[4] Scaza F et al 2006 Phys. Rev. C 73 044301
[5] Ryezayeva N et al 2006 Phys. Lett. B. 639 623–8
[6] Renzi F et al 2016 Phys. Rev. C 94 024619
[7] Wuosma A H et al 2005 Phys. Rev. C 72 061301(R)
[8] Wuosma A H et al 2008 Phys. Rev. C 78 041302(R)
[9] Frekers D 2004 Nucl. Phys. A 731 76–93
[10] Yamagata T et al 2004 Phys. Rev. C 94 044313
[11] Brady F, Needham G A, Romero J L, Kastenada C M, Ford T D, Ullmann J L and Webb M L 1999 Phys. Rev. Lett. 51 1320–3
[12] Tanihata I, Savajols H and Kanungo R 2013 Prog. Part. Nucl. Phys. 68 215–313
[13] Gurov Yu B, Korotkova L Yu, Lapushkin S V, Pritula R V, Sandukovsky V G, Tel’kushev M V and Chernyshev B A 2015 JETP Lett. 101 69–73
[14] Gornov M G, Gurov Yu B, Morokhov P V, Lapushkin S V, Pechkurov V A, Chernyshev B A, Sandukovsky V G and Pasyuk E A 20 Nucl. Instr. Meth. Phys. Res. A 446 461–8
[15] Gurov Yu B, Lapushkin S V, Chernyshev B A and Sandukovsky V G 2009 Phys. Part. Nucl. 40 558
[16] Wolters A A, van Hees A G M and Glaudemans P W M 1990 Phys. Rev. C 42 2062–78
[17] Navratil P and Barrett B R 1998 Phys. Rev. C 57 3119–28
[18] Pieper S C, Wiringa R B and Carlson J 2004 Phys. Rev. C 70 054325
[19] Volya A and Zelevinsky V 2005 Phys. Rev. Lett. 94 052501