Spectroscopy of $^7$He in the reactions of stopped pion absorption by $^{12,14}$C nuclei

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Abstract. The production of the $^7$He states was studied in the reactions of stopped pion absorption by carbon isotopes: $^{12}$C($\pi^-$, $p^4$He)$^7$He, $^{12}$C($\pi^-$, d$^3$He)$^7$He and $^{14}$C($\pi^-$, t$^3$He)$^7$He. Measurements were performed using two-arm multilayer semiconductor spectrometer. The ground and excited states were observed in all three reactions. Narrow ($\Gamma \leq 2$ MeV) state with the high excitation energy $= 16$ MeV was observed in the $^{14}$C($\pi^-$, t$^3$He)$^7$He reaction.

1. Introduction
Interest in the study of heavy helium isotopes is due to their exotic properties. Information about nucleon-stable isotopes $^6$He and $^8$He is quite extensive. At the same time, experimental results on nucleon-unstable nuclei $^{7,9,10}$He are very limited.

The ground state of $^7$He ($J^P = 3/2^+$) is unbound with respect to decay into $^4$He and a neutron, and has the resonance parameters $E_x = 0.410(8)$ MeV and $\Gamma = 0.15(2)$ MeV [1]. Note that the latest experimental results [2–4] indicate a lower resonance energy $E_{x0} = 0.35 \pm 0.40$ MeV.

For the first time excited state of $^7$He ($J^P = 5/2^+$) with the parameters $E_x = 2.9 \pm 0.3$ MeV, $\Gamma = 2.2 \pm 0.3$ MeV was observed in the $p(^4$He, d)$^7$He reaction at a energy of 50.4 MeV [5]. Note that the excitation energy $E_x$ and the resonance energy $E_r$ are related by the ratio $E_x = E_r - E_{x0}$. This state decays into $^4$He and three neutrons. The observed level was interpreted as a system of $^4$He in the first excited state ($J^P = 2^+$) and a neutron in $1p_{1/2}$ orbit. This state was also observed in works [6, 7]. The more bound excited state with the parameters $E_x = 2.9 \pm 0.3$ MeV, $\Gamma = 2.2 \pm 0.3$ MeV was found in the $d(^4$He, p)$^7$He reaction at a beam energy of 69 MeV [8]. This state ($J^P = 1/2^+$) decays into ground state of $^4$He and neutron.

The more excited states were observed in the ion reaction [6, 7, 9-11] (see table 1). All these states have large widths ($\Gamma \geq 5$ MeV) and these results have insufficient statistics.

Recently, the level structure of $^7$He was studied by us in the reactions of stopped pion absorption by boron isotopes B: $^{11}$B($\pi^-$, p)$^7$He, $^{12}$B($\pi^-$, dd)$^7$He and $^{10}$B($\pi^-$, pd)$^7$He [12]. The existence of three narrow states with excitation energies $E_x = 3.1(1)$, 4.90(15), and 6.65(15) MeV has been proven. Highly excited states with $E_x = 16.9(5)$ MeV, $\Gamma = 1.0(3)$ MeV, $E_x = 19.8(3)$ MeV, $\Gamma = 1.5(3)$ MeV, and $E_x = 24.8(4)$ MeV, $\Gamma = 4.6(7)$ MeV have been identified. The widths of these levels are much narrower than the results obtained in the ion reactions.

Thus the experimental information on the level structure of $^7$He is quite limited and contradictory. In this paper, the excitation spectra of this isotope are studied in the reactions of stopped pion absorption carbon isotopes: $^{12}$C($\pi^-$, $p^4$He)$^7$He, $^{12}$C($\pi^-$, d$^3$He)$^7$He and $^{14}$C($\pi^-$, t$^3$He)$^7$He.
2. Experiment
Experiment was performed with a low energy pion beam from LANL accelerator using the two arm semiconductor spectrometer [13].

The beam of negatively charged pions with energy of 30 MeV passed through the beryllium moderator and stopped in the thin target (≈ 24 mg·cm⁻²).

In one experimental run the measurements were carried out on the isotope-pure targets ⁹Be and ¹²C, targets ¹⁰B (contribution of the ¹¹B impurity was 15%), ¹¹B (contribution of the ¹²C impurity was 8%) and ¹⁴C “radioactive” target (76% is ¹³C, 23% is ¹²C). The contribution of uncontrolled impurities in all targets was ≤ 1%.

Charged particles emitted after pion absorption in the targets were detected by two multi-layer semiconductor telescopes located at an angle of 180° with respect to each other. The energy resolution (FWHM) was better than 0.5 MeV for single-charged particles (p, d, t) and about 2 MeV for double-charged particles (³He) [13]. The error of absolute energy calibration did not exceed 100 keV [14].

A search for the ³He excited states was carried out on the peaks in the missing mass spectrum (MM). In detecting the pairs of single- and double-charged particles the MM resolution amounts to 3 MeV [13]. The error of the MM absolute calibration (δMM) did not exceed 100 keV [14].

The spectrometer and experimental technique are described in more detail in [13, 14].

3. Results
A missing mass (MM) spectrum in the ¹²C(π⁻, p⁴He)X reaction is shown in figure 1. Missing masses were measured from the sum of the masses of the ground state of ⁴He and a neutron.

![Figure 1](image_url)

**Figure 1.** The MM spectrum for the π⁻ + ¹²C → p + ⁴He + X reaction. Histogram denotes the experimental data. 1 – the summary spectrum; peaks are the Breit – Wigner distributions for the ground and excited states. Distributions over phase volumes: 2 – π⁻ + ¹²C → p + ⁴He + ⁵He₂⁺ + n, 3 – π⁻ + ¹²C → p + ⁴He + ⁶He₃⁺ + 2n, 4 – π⁻ + ¹²C → p + ⁴He + ⁴He + 3n.
The method of least squares was used to separate the $^7$He states in describing the experimental spectrum by a sum of Breit–Wigner distributions and n-particle ($n > 3$) distributions over phase volumes. A satisfactory description can be achieved by introducing three $^7$He states: the ground state with resonance parameters $E_{r0} = 0.410(8) \text{ MeV}$ and $\Gamma = 0.15(2) \text{ MeV}$ [1] and two excited states with parameters $(E_r, \Gamma): (2.9 \pm 0.3 \text{ MeV}, < 2 \text{ MeV})$ and ($\approx 7 \text{ MeV}, < 1 \text{ MeV}$). However, it should be noted that in these measurements insufficient $MM$ resolution does not allow to distinguish reliably the states with resonance energy 2.6 and 2.9 MeV.

A missing mass ($MM$) spectrum in the $^{12}$C($^\pi^-$, $^3$He)$X$ reaction is shown in figure 2. 

Figure 2. The $MM$ spectrum for the $^\pi^- + ^{12}$C $\rightarrow d + ^3$He$+X$ reaction. Histogram denotes the experimental data. 1 – the 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 +$^4$He$_{g.s.} +n$, 3 – $^\pi^- + ^{12}$C $\rightarrow d + ^3$He +$^4$He +3n. The arrow indicates the position of the level with $E_r = 7 \text{ MeV}$.

The method of description of spectrum is similar to the previous case. Due to the low statistics of measurements, only two states could be identified in this reaction: ground state and excited state with $E_r \approx 2.9 \text{ MeV}$, $\Gamma < 2 \text{ MeV}$. The structure in the spectrum indicated by the arrow could not be interpreted.

The $MM$ spectrum obtained in the correlation measurements of $^t$He pairs on the radioactive target $^{14}$C is shown in figure 3a. The contribution of $^{14}$C impurity is clearly seen. We note that the spectrum was calculated in the kinematics of the reaction $^{14}$C($^\pi^-$, $^t$He)$X$, therefore peaks due to three-body channels of $^{12}$C($^\pi^-$, $^t$He)$^5$He reaction are in the region of negative $MM$.

The contribution of the background caused by $^{12}$C impurity was determined using the results from correlation measurements $^t$He pairs on the $^{12}$C target. $MM$ spectrum for the reaction $^{12}$C($^\pi^-$, $^t$He)$X$ was normalized to the relative impurity contribution (23%) and was subtracted from the spectra in figure 3a. The subtracted contribution is shown by shaded histogram. The spectrum after impurity subtraction is shown in figure. 3. The small background in the region of negative $MM$ is due to several
causes, i.e., the statistical errors of the subtraction procedure, accidental coincidence background and the contribution of uncontrolled impurities.

Figure 3. The MM spectrum obtained in the correlation measurements of \(^4\)He pairs on the radioactive target \(^{14}\)C (a). Dots with error bars are the experimental data. Shaded histogram is MM spectrum obtained in measurements on target \(^{12}\)C and normalized to 23\%. The spectrum after impurity subtraction (b). Histogram denotes the experimental data. 1 – the summary spectrum; peaks are the Breit – Wigner distributions for the ground and excited states. Distributions over phase volumes: 2 – \(\pi^+\)^{14}\)C \(\rightarrow t + ^4\)He + \(^6\)He, + \(n\), 3 – \(\pi^+\)^{14}\)C \(\rightarrow t + ^4\)He + \(^4\)He + \(3n\).

A statistically satisfactory description of the experimental spectrum can be achieved by introducing ground and two excited states of \(^7\)He with the following resonance parameters \((E_x, \Gamma)\): \((\approx 2.9\) MeV, \(< 2\) MeV) and \((16\) MeV, \(< 2\) MeV). The bump observed in the spectrum near 7 MeV (marked by an arrow) can be an indication on the existence of a level with \(E_x \approx 7\) MeV.

### 4. Discussion

The results for the \(^7\)He level structure obtained in the present work presented in table 1 together with the data obtained in the reactions of stopped pion absorption by boron isotopes [12] and the results of other authors.

In the energy region \(E_x \approx 3\) MeV, we observed excited state in all studied reactions. Unfortunately, the insufficient energy resolution does not allow us to make an unambiguous conclusion that this state has energy \(E_x \approx 2.9\) MeV. The hypothesis that this state has energy \(E_x \approx 2.6\) or \(3.1\) MeV (see table 1) can't be excluded.

The excited state with \(E_x \approx 7\) MeV is close to narrow state with \(E_x \approx 6.8\) MeV. This coincidence confirms the existence of narrow highly excited states in \(^7\)He. Also, the states with \(E_x \approx 16\) MeV and 16.8 MeV are close in energy. These coincidences confirm the existence of narrow highly excited states in \(^7\)He. The nature of the observed states is unclear. Note that the second of the observed levels is above the decay threshold \(^7\)He into \(t + t + n\) (12.3 MeV). Therefore, it is possible that this state is a cluster resonance \(t + ^4\)H. Similar resonances in the system of two tritons are observed in the excited states of \(^6\)He [15]. At the same time, in the reactions with stopped pions there are not observed the wide states (\(\Gamma > 7\) MeV), information about the existence of which was obtained in the reactions on ion beams (see table 1).
Table 1. Energies and widths of the excited states of $^7\text{He}$.

| $E_x$, MeV | $\Gamma$, MeV | Our measur. | Work |
|------------|---------------|-------------|------|
| $\approx2.6$ | $\approx2$ | | [8] |
| 2.9$^a$ | 2.0$^a$ | this work | [5–7] |
| 3.1(1) | $\leq0.5$ | | [12] |
| 4.9(2) | $\leq0.5$ | | [12] |
| $\approx5.3$ | ~5 | | [11] |
| 5.8(3) | 4(1) | | [6] |
| 6.7(2) | $\leq0.5$ | | [12] |
| $\approx7$ | $\leq2$ | this work | |
| $\approx8.0$ | ~7 | | [11] |
| $\approx16$ | $\leq2$ | this work | |
| 16.9(5) | 1.0(3) | | [12] |
| $\approx18^a$ | ~8$^a$ | | [10, 11] |
| 19.8(3) | 1.5(3) | | [12] |
| 20(1) | 9(2) | | [9] |
| 24.8(4) | 4.6(7) | | [12] |

$^a$ – Average values.

5. Conclusion

The excited states of heavy helium isotope $^7\text{He}$ were studied in stopped pion absorption on $^{12,14}\text{C}$ nuclei. Narrow highly excited states were observed with $E_x \approx 6$ MeV in reaction $^{12}\text{C}(\pi^- , p)^7\text{He}$, and $E_x \approx 18$ MeV in reaction $^{14}\text{C}(\pi^- , t)^7\text{He}$.

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