Study of hydrogen and helium isotopes with A=5,6,7

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The level structure of superheavy hydrogen and heavy helium isotopes with A = 5, 6, 7 was studied in stopped pion absorption by light nuclei. The measurements were performed at low energy pion channel of LANL with two-arm multilayer semiconductor spectrometer. Excited states of the $^5$H and $^6$He were observed in several reaction channels on the $^9$Be and $^{10,11}$B nuclei. Several excited levels were found only in our measurements. Candidate on isobar-analog state of the $^6$H ground states with $E_x \sim 5.5$ MeV was observed in the reaction $^{10}$B(π$^-$,pt)X.

1. Introduction
Experimental investigation of neutron-rich nuclei near the drip line is mainstream in the development of nuclear physics [1]. Superheavy hydrogen isotopes $^n$H (n $\geq$ 4) and heavy helium isotopes $^n$He (n $\geq$ 5) are the most interesting ones due to extremely large neutron–to–proton ratio. A relatively small number of nucleons makes possible to find a correct microscopic description of their properties and, therefore, to verify existing nuclear models as well as nucleon–nucleon potentials.

The search for these exotic nuclei and investigation of their level structure have been continued for a long time, but there are still many open questions, especially for superheavy hydrogen isotopes [1–4]. Most of the results have been obtained in the measurements with ion beams, including radioactive beams [1–4].

Another way of the studying is associated with particle ($\gamma$, e$^-$, π) beams. Stopped pion absorption is most suitable to the search for light neutron-rich nuclei. Among other things the first observations of the superheavy hydrogen isotope $^3$H [5] and ground state of lithium isotope $^{10}$Li [6] were obtained in this type of reactions.

An opportunity to effectively exploit stopped π-meson absorption by nuclei in order to form neutron-rich nuclear states is based on the peculiarities of this reaction: a charge reduction of the produced nuclear system and a large energy release (~m$\pi$c$^2$), which leads to the formation of fast nuclear particles (n, p, d, t, $^3$He, …). For channels in which one or two charged particles are detected, a residual nucleus will be a neutron-rich one. Production of studied nuclei in two- and three-body channels appears as a peak in the missing mass spectra for one or two registered particles.
respectively. The important advantage of using the stopped pion absorption is the possibility to obtain the information on the wide range of exotic nuclei in one experimental run. Data on the known nuclear states permit to resolve such problems as the energy calibration, the determination of the energy resolution, and the stability of the parameters of the experimental setup during data collecting [7].

In this work experimental results on the level structure of helium isotope with A = 5, 6, 7 obtained in the stopped pion absorption are analyzed with the aim of funding isobar-analog states (IAS) of superheavy hydrogen isotopes ^5^7H. Search for the helium states was performed in the following channels of the stopped pion absorption $^{10}\text{B}(\pi^- ,dt)\text{X}$ and $^{11}\text{B}(\pi^- ,tt)\text{X}$ – for ^3^He, $^{11}\text{B}(\pi^- ,dt)\text{X}$, $^{10}\text{B}(\pi^- ,pt)\text{X}$, and $^{10}\text{B}(\pi^- ,dd)\text{X}$ – for ^6^He, $^{10}\text{B}(\pi^- ,pd)\text{X}$, $^{11}\text{B}(\pi^- ,pt)\text{X}$ and $^{11}\text{B}(\pi^- ,dd)\text{X}$ – for ^3^He.

2. Experiment details

The experiment was performed on the meson factory LAMPF in Los Alamos, USA using the two arm semiconductor spectrometer [6]. Layout of the setup is presented in Fig. 1. The beam of negatively charged pions with energy of 30 MeV passed through the beryllium moderator and stopped in a thin target (≈ 24 mg·cm$^{-2}$). The measurements were carried out on the targets $^9\text{Be}$, $^{10,11}\text{B}$ and $^{12,14}\text{C}$. The pion stopping rate in the target was ~ 6 × 10$^4$ s$^{-1}$. The collimators $C_1$ and $C_2$ were used to suppress the background from secondary particles emitted by the moderator and chamber walls.

Charged particles emitted after pion absorption were detected by two semiconductor telescopes located at the angle 180° with respect to each other. Each telescope included two Si(Au) semiconductor detectors (s.c.d.) with thicknesses of 100 and 450 μm and 14 Si(Li) s.c.d. with thickness of ~ 3 mm. The diameter of the sensitive area of all detectors was 32 mm (the working area – 8 cm$^2$). The total sensitive thickness of each telescope was 43 mm. This thickness permitted to measure the total absorption of charged particles up to kinematical limits of the reaction. As a result, a high energy resolution was achieved throughout a whole range of measured energies of detected particles. The energy resolution (FWHM) for single-charged particles (p, d, t) was better than 0.5 MeV [7]. The error of absolute energy calibration did not exceed 100 keV [7].

A search for the neutron-rich states was carried out in the peaks of the missing mass spectrum (MM). In the measurements of any pairs of singly charged particles the MM resolution was 1 MeV [7]. The error of the MM absolute calibration ($\delta$MM) did not exceed 100 keV [7].

The spectrometer and experimental technique are described in more detail in [7, 8].

3. Results and discussion
Search for $^5\text{He}$ states was carried out in the reactions: $^{10}\text{B}(\pi^- ,dt)X$ and $^{11}\text{B}(\pi^- ,tt)X$. The $MM$ spectra measured in these reactions are shown in Figs. 2 and 3. The sum of $\alpha$-particle and neutron masses is taken to be a reference point. To separate $^5\text{H}$ states and determine its parameters we used the least square approximation while fitting of the experimental spectra by the sum of the Breit–Wigner shaped resonances and $n$–particle distributions over phase space ($n \geq 4$). We used the Breit-Wigner distributions with energy-dependent widths parameterized for states near the threshold [9].

In both spectra peaks due to three-body channels with $^5\text{He}$ in the final states are observed. The peak in Fig.2 is due to the $^5\text{He}$ ground state. The peak in Fig.3 is due to the superposition of the ground and the first excited states. Values of resonance parameters of these states ($E_r$ – resonance energy, $\Gamma$ – level width): (0.80(3) MeV, 0.7(1) MeV) and (2.1(1) MeV, 5.6(3) MeV) are in a coincident with data of the compilation [3].

We did not obtained statistically significant evidence on high excited states of $^5\text{He}$. In the Fig. 2 some excess of the experimental events exists in the range from 22 MeV to 28 MeV. This range corresponds to resonance energies of $^4\text{H}$ ground state: 1 MeV $\leq E_r(^4\text{H}) \leq 5$ MeV. The results of direct measurements of this value in ion reactions lay on the same interval [10, 11] and stopped pion absorption [7]. However it is necessary to point out that several states with isospin $T = 1/2$ lie in the region 21 MeV $\leq E_r(^4\text{H}) \leq 24$ MeV [3]. Thus, we did not obtain reliable indication on the existence of IAS of $^5\text{H}$ with $T = 3/2$.

Search for $^6\text{He}$ excited states was carried out in the following reactions: $^{11}\text{B}(\pi^- ,dt)X$, $^{10}\text{B}(\pi^- ,pt)X$, $^{10}\text{B}(\pi^- ,dd)X$. The $MM$ spectra for these reactions are shown in Fig. 4. The mass of $^6\text{He}$ ground state is taken to be a reference point. Description of the spectra was carried out similarly to the case of $^5\text{He}$. Peaks formed due to the appearance of the ground state and the excited states in the three-body reaction channels are well seen. Average values of parameters of $^6\text{He}$ excited states ($E_r$ – excitation energy, $\Gamma$ -width), obtained in this paper are presented in the table 1.

Two high excited states with $E_r > 20$ MeV are observed in $^{10}\text{B}(\pi^- ,pt)X$ channel only. The parameters of level with $E_r = 22.1(1.0)$ MeV coincide within the limits of experimental error with the parameters of the resonance in the $t + t$ system ($E_r = 20.9(3)$ MeV, $\Gamma = 3.2(1.5)$ MeV) formed in the reaction $^7\text{Be}(\pi^-, tt)$ [12]. The last one has an isospin $T = 1$, and therefore it is not IAS of $^6\text{H}$. The highest excited $^6\text{He}$ state with $E_r = 27.0(8)$ MeV may have $T = 1$ or 2. In the latter case this state is isobar-analog states of $^8\text{H}$ with resonance energy $E_r \approx 5.5$ MeV. This value is close to resonance energy of $^8\text{H}$ ground state (6.67(7) MeV) obtained in measurements of stopped pion absorption [7]. These magnitudes are considerably higher than the results obtained in reaction with heavy ions.
In these measurements the resonance energy was \( \approx 2.6 \text{ MeV} \). Also, it should be underlined that statistics of the data obtained in this work and in [7] is much more than statistics in works [13, 14]. In our measurements, there were no indications on the existence states with \( E_x > 30 \text{ MeV} \) observed in [15]. These states may be IAS of the excited states of \(^6\text{He}\).

![Image]

**Fig. 4. MM spectrum for the reaction**

- \( ^{11}\text{B}(\pi^-,\text{dt})X \)
- \( ^{10}\text{B}(\pi^-,\text{pt})X \)
- \( ^{10}\text{B}(\pi^-,\text{dd})X \)

Dots with error bars are the experimental data. The solid lines are the Breit–Wigner distributions, 1 – fit, 2 – sum of phase-space distributions and 3 – background coming from random coincidences.

**Table 1. Parameters of excited states of \(^6\text{He}\) and \(^7\text{He}\) measured in this work**

| \( E_x \) (MeV) | \( \Gamma \) (MeV) | reaction | \( E_x \) (MeV) | \( \Gamma \) (MeV) | reaction |
|-----------------|------------------|----------|-----------------|------------------|----------|
| 1.80(3)         | 0.11(2)          | 1,2,3    | 3.1(1)          | \( \leq 0.5 \)    | 4,5,6    |
| 3.5(2)          | 3.1(4)           | 1,2,3,4  | 4.9(2)          | \( \leq 0.5 \)    | 4,5,6    |
| 9.3(2)          | 1.0(4)           | 1,2      | 6.7(2)          | \( \leq 0.5 \)    | 4,5      |
| 15.9(9)         | 3.2(7)           | 1        | 16.9(5)         | 1.0(3)           | 5,6      |
| 22.1(1.0)       | 2.7(1.4)         | 2        | 19.8(3)         | 1.5(3)           | 4,5,6    |
| 27.0(8)         | 2.5(1.1)         | 2        | 24.8(4)         | 4.6(7)           | 4,5,6    |

1 – \( ^{11}\text{B}(\pi^-,\text{dt})X \), 2 – \( ^{10}\text{B}(\pi^-,\text{pt})X \), 3 – \( ^{10}\text{B}(\pi^-,\text{dd})X \), 4 – \( ^{11}\text{B}(\pi^-,\text{pt})X \), 5 – \( ^{11}\text{B}(\pi^-,\text{dd})X \), 6 – \( ^{10}\text{B}(\pi^-,\text{dd})X \).

Search for \(^7\text{He}\) excited states was carried out in the following reactions: \( ^{11}\text{B}(\pi^-,\text{pt})X \), \( ^{11}\text{B}(\pi^-,\text{dd})X \), \( ^{10}\text{B}(\pi^-,\text{pd})X \). The MM spectra for these reactions are shown in Fig. 5. The sum of \(^6\text{He}\) and neutron masses is taken to be a reference point. Peaks formed due to the appearance of the ground state and the excited states in the three-body reaction channels are well seen. Average values of parameters of \(^6\text{He}\) excited states, obtained in this paper, are presented in the table 1. High excited state with \( E_x = 24.8 \text{ MeV} \) is observed in the all studied channels.
Fig. 5. MM spectrum for the reaction a – $^{11}$B($\pi^-$,pt)X; b – $^{11}$B($\pi^-$,dd)X; c – $^{10}$B($\pi^-$,pd)X. Dots with error bars are the experimental data. The solid lines are the Breit–Wigner distributions, 1 – fit, 2 – sum of phase-space distributions and 3 – background coming from random coincidences.

In the region of high excitation energies above the threshold of the decay $^7$He → t + t + n ($E_x = 11.9$ MeV), relatively narrow states of $^7$He were detected in our measurements for the first time. The nature of the observed states is unclear. It only can be noted that the level with $E_x = 19.8(3)$ MeV lies near the threshold of the decay $^7$He → t + p + 3n (18.56 MeV). However, this state is not an IAS of the superheavy hydrogen isotope $^7$H, because the isospin of the final state of the $^{11}$B($\pi^-$, dd)$^7$He reaction can be only $T = 3/2$.

4. Conclusions
Excited states of $^5$-$^7$He were observed in three-body channels of stopped pion absorption by boron isotopes $^{10,11}$B. $^6$He excited state with $E_x = 27.0(8)$ MeV observed in $^{10}$B($\pi^-$,pt)X channel is an IAS candidate for $^8$H with $E_r \sim 5.5$ MeV.

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