Search for isobar-analog states of superheavy hydrogen isotopes $^{5-7}\text{He}$

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Abstract. Search for isobar-analog states (IAS) of superheavy hydrogen isotopes $^{5-7}\text{H}$ was performed among the high-excited states of helium isotopes $^{5-7}\text{He}$. The excited spectra were measured in stopped pion absorption by light nuclei. The experiment was performed at low energy pion channel of LANL with two-arm multilayer semiconductor spectrometer. Excited states of $^{5}\text{He}$ were observed in three-body reaction channels on $^{10,11}\text{B}$ nuclei. Several excited levels were observed for the first time. $^{6}\text{He}$ excited state with $E_x = 27.0(8)$ MeV observed in $^{10}\text{B}(\pi^-,pt)X$ channel is an IAS candidate for $^{6}\text{H}$ with $E_r \sim 5.5$ MeV. $^{7}\text{He}$ excited state with $E_x = 24.8(4)$ MeV observed in $^{10}\text{B}(\pi^-,pd)X$, $^{11}\text{B}(\pi^-,pt)X$ and $^{11}\text{B}(\pi^-,dd)X$ channels is an IAS candidate for $^{7}\text{H}$ with $E_r \sim 3$ MeV.

Introduction
Study of light neutron-rich nuclei is one of the main current subjects of nuclear physics and is a field of great experimental activity [1]. 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.

Superheavy hydrogen isotopes $^n\text{H} (n \geq 4)$ are the most interesting ones due to extremely large neutron–to–proton ratio and a proton 1s–shell being open, unlike that of other elements. The experimental search for these exotic nuclei and investigation of their level structure has been continued for a long time. Nevertheless, the available experimental information is still contradictory and is extremely limited, except for $^4\text{H}$ [1]. Superheavy hydrogen isotopes are nucleon-unstable ones. $^{5,6}\text{H}$ isotopes were observed in stopped pion absorption by light nuclei [2]. Other results on $^7\text{H}$ were obtained in measurements on radioactive ion beams (references to these works are reviewed in [1]). The resonance energy of $^7\text{H}$ ground state measured in these experiments falls in the range 1.7 MeV [3] to 5.4 MeV [2]. At first time, $^6\text{H}$ was observed in the experiments on heavy ion beams [4, 5]. The resonance energy ($\approx 2.7$ MeV) obtained in these measurements differs significantly from value (6.6(7) MeV) obtained in the stopped pion absorption [2]. The observation of $^7\text{H}$ nucleus is still under examinations since the cross sections of its production are very low [1, 2].

In such situation investigations of new reaction channels of the superheavy hydrogen isotope formation are of great interest. For this purpose we attempted to find isobar analog states (IAS) of superheavy hydrogen isotopes $^{5-7}\text{H}$ among the high-excited states of the helium isotopes $^{5-7}\text{He}$. Search for the helium states was performed in the following channels of the stopped pion absorption
$^{10}$B$(\pi^- , dt)X$ and $^{11}$B$(\pi^- , tt)X$ – for $^5$He, $^{11}$B$(\pi^- , dt)X$, $^{10}$B$(\pi^- , pt)X$, and $^{10}$B$(\pi^- , dd)X$ – for $^6$He, $^{10}$B$(\pi^- , pd)X$, $^{11}$B$(\pi^- , pt)X$ and $^{11}$B$(\pi^- , dd)X$ – for $^7$He.

**Experiment details**

The experiment was performed on the meson factory LAMPF using the two arm semiconductor spectrometer [6]. The $\pi$ beam with the energy of 30 MeV passed through the beryllium moderator and stopped in a thin target (≈ 24 mg·cm$^{-2}$). In one experimental run the measurements were carried out on the targets $^9$Be, $^{10,11}$B and $^{12,14}$C.

Charged particles emitted after pion absorption were detected by two semiconductor telescopes located at an angle of 180° with respect to each other. The energy resolution (FWHM) for single-charged particles (p, d, t) was better than 0.5 MeV [6]. The error of absolute energy calibration did not exceed 100 keV [2].

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 [2]. The error of the $MM$ absolute calibration ($\delta MM$) did not exceed 100 keV [2].

The spectrometer and experimental technique are described in more detail in [2, 6].

**Results and discussion**

Search for $^5$He states was carried out in the reactions: $^{10}$B$(\pi^- , dt)X$ and $^{11}$B$(\pi^- , tt)X$. The $MM$ spectra measured in these reactions are shown in figures 1 and 2. The sum of $\alpha$-particle and neutron masses is taken to be a reference point. To resolve $^5$H states we used the method of least squares in describing the experimental spectra by the sum of $n$–particle distributions over phase space ($n \geq 4$) and Breit–Wigner distributions [7].

**Figure 1.** $MM$ spectrum for the reaction $^{10}$B$(\pi^- , dt)X$. Dots with error bars are the experimental data. The solid lines are: 1 – the fit, 2 – Breit–Wigner distribution for ground state, 3 – sum of phase-space distributions.

**Figure 2.** $MM$ spectrum for the reaction $^{11}$B$(\pi^- , tt)X$. Dots with error bars are the experimental data. The solid lines are: 1 – the fit, 2 (3) – Breit–Wigner distribution for ground (first excited) state, 4 – sum of phase-space distributions.

In both spectra peaks due to three-body channels with $^5$He in the final states are observed. The peak in figure 1 is due to the $^5$He ground state. The peak in figure 2 is due to the superposition of the ground and 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 [8].

We did not obtained statistically significant evidence on high excited states of $^5$He. In the figure 1 some excess of the experimental events exists in the range from 22 MeV to 28 MeV. Several states
with isospin $T = 1/2$ lie in this region \cite{8}. Thus we did not obtain any indication on the existence of IAS of $^3H$ with $T = 3/2$.

Search for $^6He$ excited states was carried out in the following reactions: $^{11}B(\pi, dt)X$, $^{10}B(\pi, pt)X$, $^{10}B(\pi, dd)X$. The $MM$ spectra for these reactions are shown in figure 3. The mass of $^6He$ ground state 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 $^6He$ excited states, obtained in this paper are presented in the table 1. High excited states with $E_x > 20$ MeV are observed in $^{10}B(\pi, pt)X$ channel only. These states may have a spin equals to 1 or 2. In last case these states are isobar-analog states of $^6H$ with resonance energy $E_r \approx 0$ MeV and $5.5$ MeV. The first value is inconsistent with results of the works on search for $^6H$ \cite{2, 4, 5}. The second value is close to resonance energy of $^6H$ ground state ($6.6(7)$ MeV) obtained in measurements of stopped pion absorption \cite{2}.

Search for $^7He$ excited states was carried out in the following reactions: $^{11}B(\pi, pt)X$, $^{11}B(\pi, dd)X$, $^{10}B(\pi, pd)X$. The $MM$ spectra for these reactions are shown in figure 4. The sum of $^6He$ 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 $^6He$ excited states, obtained in this paper, are presented in the table 1. High excited state with $E_x = 24.8$ MeV is observed in all studied channels. This state is the candidate on isobar-analog of $^7He$ with resonance energy $E_r \approx 3$ MeV. From the experimental data on spectroscopy of helium, lithium, and beryllium isotopes it follows that the number of neutrons $N = 6$ becomes magic rather than $N = 8$ \cite{1}. Based on the latter, it is reasonable to expect that among superheavy hydrogen isotopes, $^7H$ should be the most bounded one. However, until now any reliable evidence for the existence of this isotope in a
stable state and in a resonance state has not been received. Thus, our result for IAS is important for future experimental search for the $^7$H.

### Table 1. Parameters of excited states of $^6$He and $^7$He measured in this work.

| $^6$He | $^7$He |
|-------|-------|
| $E_x$ | $\Gamma$ | Reaction | $E_r$ | $\Gamma$ | Reaction |
| MeV | MeV | | MeV | MeV | |
| 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 | 4.9(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 |

Reactions in columns 3 and 6: $1^{11}$B(π,dt)X; $2^{10}$B(π,pt)X; $3^{10}$B(π,dd)X; $4^{11}$B(π,pt)X; $5^{11}$B(π,dd)X; $6^{10}$B(π,dd)X.

### Conclusion

Excited states of $^{5,7}$He were observed in three-body channels of stopped pion absorption by boron isotopes $^{10,11}$B. We found the two candidate on IAS of superheavy hydrogen isotopes. $^6$He excited state with $E_x = 27.0(8)$ MeV observed in $^{10}$B(π,pt)X channel is an IAS candidate for $^6$H with $E_r \sim 5.5$ MeV. $^7$He excited state with $E_x = 24.8(4)$ MeV observed in $^{10}$B(π,pd)X, $^{11}$B(π,pt)X and $^{11}$B(π,dd)X channels is an IAS candidate for $^7$H with $E_r \sim 3$ MeV.

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