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Search for superheavy hydrogen isotopes ^{6}H and ^{7}H in stopped π^--absorption reactions

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Abstract. Experimental search for superheavy hydrogen isotopes ^{6}H and ^{7}H was performed in the stopped pion absorption on ^{9}Be and ^{11}B nuclei. The structures in the missing-mass spectra were observed in the reaction channels $^9\mathrm{Be}(\pi^-,\mathrm{pd})\mathrm{X}$ and $^{11}\mathrm{B}(\pi^-,\mathrm{p}^4\mathrm{He})\mathrm{X}$. Four states of ^{6}H were proposed. Evidences for ^{7}H formation were obtained in the reaction channels $^9\mathrm{Be}(\pi^-,\mathrm{pp})\mathrm{X}$ and $^{11}\mathrm{B}(\pi^-,\mathrm{p}^3\mathrm{He})\mathrm{X}$.

PACS. 27.20.+n $6 \le A \le 19$ – 25.80.Ls Pion inclusive scattering and absorption

1 Introduction

In [1] we presented the results on the spectroscopy of superheavy hydrogen isotopes ^{4}H and ^{5}H produced in the stopped pion absorption on ^{9}Be. Three states of ^{4}H were proposed in the reaction channel $^9\mathrm{Be}(\pi^-,\mathrm{dt})\mathrm{X}$. The ground state with $E_r = 1.6 \pm 0.1\,\mathrm{MeV}$ (E_r is the resonance energy above the unbound n+t mass) was found to be more bound than is generally accepted. Four states of ^{5}H were proposed in the reaction channels $^9\mathrm{Be}(\pi^-,\mathrm{pt})\mathrm{X}$ and $^9\mathrm{Be}(\pi^-,\mathrm{dd})\mathrm{X}$. Other recent experimental studies of ^{4}H and ^{5}H may be found in refs. [2–7]. In this paper, the results of the search for superheavy hydrogen isotopes with a large number of neutrons ^{6}H and ^{7}H in stopped π^--absorption are presented.

Up to now indications of the existence of the ^{6}H isotope were obtained only in heavy-ion reactions [8]. A resonance state of ^{6}H with $E_r = 2.7 \pm 0.4\,\mathrm{MeV}$, $\Gamma = 1.8 \pm 0.5\,\mathrm{MeV}$ (E_r is the resonance energy above the unbound t+3n mass) was identified in the $^7\mathrm{Li}(^7\mathrm{Li},{}^8\mathrm{B})\mathrm{X}$ reaction at the energy $E(^7\mathrm{Li}) = 82\,\mathrm{MeV}$ [9]. In the $^9\mathrm{Be}(^{11}\mathrm{B},{}^{14}\mathrm{O})\mathrm{X}$ reaction a resonance state of ^{6}H with $E_r = 2.6 \pm 0.5\,\mathrm{MeV}$, $\Gamma = 1.3 \pm 0.5\,\mathrm{MeV}$ was observed at the energy $E(^{11}\mathrm{B}) = 88\,\mathrm{MeV}$ [10]. The results are in close agreement, but data suffer from high background [9] and poor statistics [10]. In the double charge exchange reaction $^6\mathrm{Li}(\pi^-,\pi^+)\mathrm{X}$ at $E_\pi = 220\,\mathrm{MeV}$ the ^{6}H isotope was not observed [11]. In our previous papers, there was no evidence for the formation of ^{6}H in two reaction channels $^9\mathrm{Be}(\pi^-,\mathrm{pd})\mathrm{X}$ [12] and $^7\mathrm{Li}(\pi^-,\mathrm{p})\mathrm{X}$ [13], as the statistics and energy resolution in those measurements were insufficient.

Special interest in the search for ^{7}H stems from the evidence thus far obtained that traditional magic numbers disappear and new ones appear for light nuclei near the drip line [14–16]. In particular, it follows from the experimental data on the spectroscopy of helium, lithium, and beryllium isotopes that the number of neutrons $N = 6$ becomes magic instead of $N = 8$. In this connection one can expect that among superheavy hydrogen isotopes the most bound is ^{7}H.

The only experimental indication of the ^{7}H existence has recently been obtained in the $\mathrm{p}(^8\mathrm{He},\mathrm{pp})\mathrm{X}$ reaction with the ^{8}He beam at 61.3 A MeV [17]. The authors demonstrated an abnormal behavior of the ^{7}H missing-mass spectrum just above the t+4n threshold. However, a considerable background in the measurements does not allow one to determine the parameters of this state.

Thus, one can conclude that the experimental situation with ^{6}H and ^{7}H is more uncertain as compared to ^{4}H and ^{5}H.

In the present paper a search for the ^{6,7}H isotopes was conducted in the reactions of stopped π^--meson absorption on ^{9}Be and ^{11}B.

2 Experiment

The experiment was carried out at the Low-Energy Pion (LEP) channel of the Los Alamos Meson Physics Facility (LAMPF) with a multilayer semiconductor

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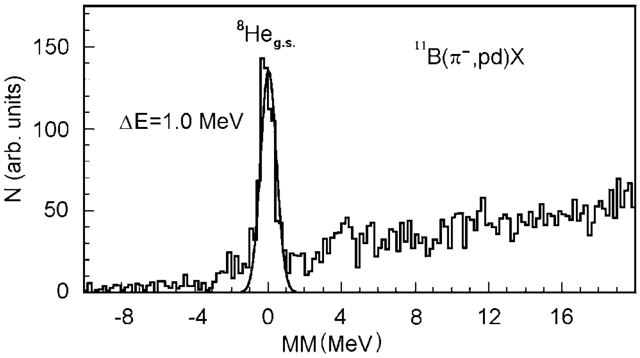

Fig. 1. Missing-mass spectrum for the $^{11}B(\pi^-, pd)X$ reaction, the mass of $^8He_{g.s.}$ was used as a zero point. The solid line is the Gaussian distribution.

spectrometer [18]. The pion beam with the energy $E =$ 30 MeV was slowed down by beryllium moderator and was stopped by a thin ($\sim 24\,mg/cm^2$) target. Measurements were performed with ^9Be, $^{10,11}B$, and $^{12,14}C$ targets within one experimental run. The pion stopping rate was $\sim 6 \times 10^4\,s^{-1}$.

Resulting charged particles, after pion absorption by nuclei, were detected and identified by two silicon telescopes located under $180\,^\circ$ to each other. Each telescope made it possible to identify charged particles and measure their energies up to the kinematic limits of the reaction. The energy resolution (FWHM) for single charged particles (p,d,t) was better than 0.5 MeV and for double charged particle ($^{3,4}He$) amounted to 2.0 MeV [18].

In order to determine the missing-mass (MM) resolution in the correlation measurements of the pd-pairs, the reaction $^{11}B(\pi^-, pd)X$ was used. The measured MM spectrum is shown in fig. 1. The peak, corresponding to the production of the ^8He ground state, is pronounced. The analysis of the results showed, that the MM resolution (FWHM) in these measurements amounts to 1.0 MeV. A systematic error in the calibration was less than 100 keV. The ^8He peak parameters were also used for control of time stability of the spectrometer characteristics for measurements on the ^{11}B target. Correlation measurements of tt-pairs were used with the same aim on the ^9Be target [1].

A more complicated situation takes place for pp-pairs. In our experiment, ground and first excited states of a residual nucleus, produced in the $A(\pi^-, pp)X$ channel, are widely spaced only on the ^{10}B target. However, as it is seen from fig. 2, the yield of the reaction $^{10}B(\pi^-, pp)^8He_{g.s.}$, is strongly suppressed. In this situation the energy resolution ~ 1 MeV and calibration error ~ 200 keV were determined from the Monte Carlo simulation and comparison with the data for other pairs of registered particles.

In order to determine the MM resolution in correlation measurements of helium isotopes and single charged particles, we have used data obtained in the $^{10}B(\pi^-, t^4He)X$ reaction. In this channel, statistics of data is much more to others. The missing-mass spectrum is shown in fig. 3. The peak, corresponding to the production of the ^3H, is pronounced. The MM resolution amounts to 3.0 MeV. A calibration error was less than 200 keV. The simulation shows

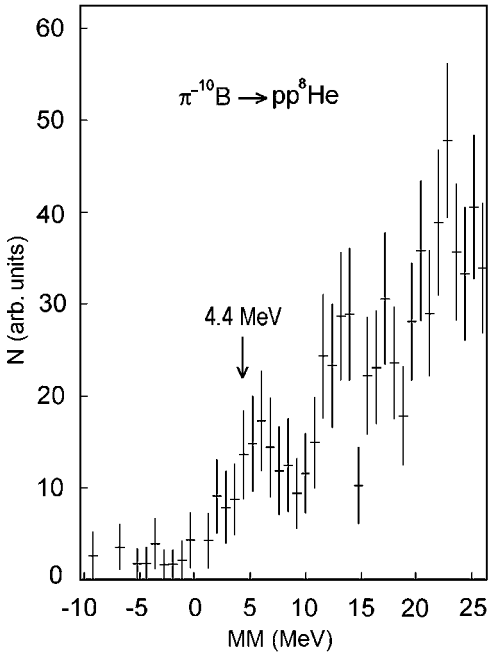

Fig. 2. Missing-mass spectrum for the $^{10}B(\pi^-, pp)X$ reaction, the mass of $^8He_{g.s.}$ was used as a zero point.

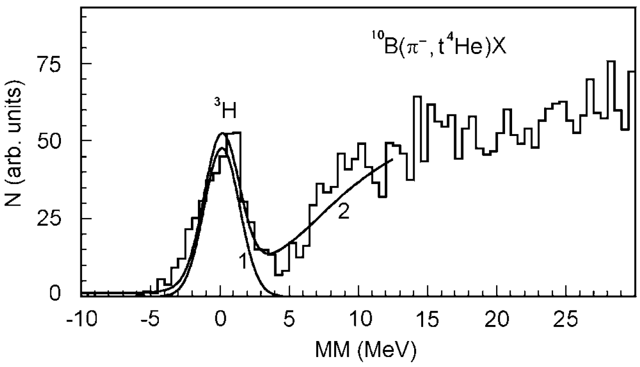

Fig. 3. Missing-mass spectrum for the $^{10}B(\pi^-, t^4He)X$ reaction, the mass of the ^3H was used as a zero point. The solid line is the fit, curve 1 is the Gaussian distribution for the $^{10}B(\pi^-, t^4He)^3H$ channel; curve 2 is the fit.

that these values do not change in measurements of p^3He- and p^4He-pairs. The worsening of the resolution for events with the $^{3,4}He$ ions was caused by an increase of their ionization losses in the target, as compared to p, d.

A quantitative estimation of possible impurities in the targets was conducted by separating the peaks corresponding to the known two-body reactions on the impurity nuclei. For the ^{11}B target, the main impurity is ^{12}C (8%). The contribution of uncontrolled impurities in the ^9Be and ^{11}B targets do not exceed 1%.

The spectrometer and experimental methods are described in more detail in [1, 18].

3 Results

3.1 The ^{6}H case

The missing-mass spectrum for the ^{9}Be(π^-, pd) X reaction is shown in fig. 4a. The mass of triton plus three neutrons was used as a zero point. No indications of the existence of bound states of ^{6}H were observed. A weak background in the negative MM region is due to random coincidences in the correlation measurements. In the positive MM region one can see some structures that may be caused by the formation of resonance states. To separate these states of ^{6}H and to determine their parameters, we have used the least-square approximation in the fitting of the experimental spectrum by the sum of Breit-Wigner shaped resonances and N-particle phase-space distributions. All possible channels with $N \geq 4$, including the reactions with formation of singlet neutron pairs ^{2}n (dineutron) and superheavy hydrogen isotopes ^{4}H and ^{5}H, were taken into account. The angular and energy resolutions of the spectrometer and the background of accidental coincidences were taken into consideration in the Monte Carlo calculations.

Nowadays the problem of the effective mass spectrum form of such exotic states as heavy hydrogen isotopes remains open. In default of any theoretical description of ^{6}H states a simple Breit-Wigner form was used for fitting the observed peaks

$$\frac{\mathrm{d}Y}{\mathrm{dMM}} \propto \frac{\Gamma}{\left(\mathrm{MM} - E_r\right)^2 + (\Gamma/2)^2}\,.$$

We suppose that this approach provides a way of correlation with other experimental data.

As can be seen from fig. 4a, phase space distributions cannot reproduce the structure observed at MM < 25 MeV. Notice that the main contribution to the total distribution comes from the five-body phase space with dineutron in the final state ($\mathrm{d} + \mathrm{p} + {}^2\mathrm{n} + \mathrm{t} + \mathrm{n}$). A satisfactory description ($\chi^2/N_{\mathrm{DF}} = 0.95$) of the experimental spectrum can be achieved only by introducing four states of ^{6}H with the parameters shown in table 1. The Γ is the full width at half-maximum (FWHM) of the peaks. The errors of the parameters are due to both statistical and systematic errors of the measurements.

The final-state interaction (FSI) is of considerable importance in the stopped pion absorption by light nuclei [19]. The FSI between particles of the nuclear residue was taken into account by including into the fitting the reaction channels with ^{2}n, ^{4}H and ^{5}H in the final state. However, one should take into account the FSI between one of the detected particles and neutron in the following channels: $\pi^- + {}^9\mathrm{Be} \rightarrow \mathrm{p} + (\mathrm{dn})_{\mathrm{FSI}} + R$ and $\pi^- + {}^9\mathrm{Be} \rightarrow (\mathrm{pn})_{\mathrm{FSI}} + \mathrm{d} + R$ (where R denotes a residue). The unbound states of the "quasitriton" $(\mathrm{dn})_{\mathrm{FSI}}$ and the "quasideuteron" $(\mathrm{pn})_{\mathrm{FSI}}$ result from correlations of particle velocities. Below we consider the method that allows to strongly suppress the contribution of these channels in the case of quasi-free pion absorption.

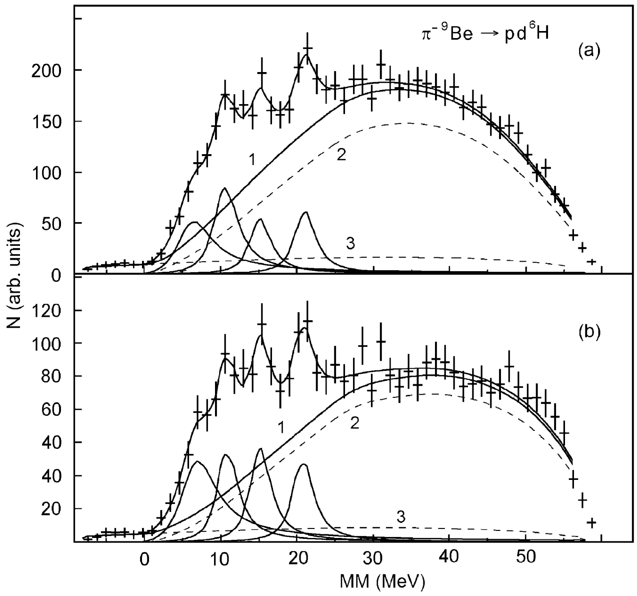

Fig. 4. Missing-mass spectra for the ^{9}Be(π^-, pd)X reaction: (a) without and (b) with restriction on the momentum of residual nuclei. The solid lines are the fit and the Breit-Wigner distributions. Curve 1 is the sum of space phase distributions; curve 2 is the phase space distribution for the breakup of ^{9}Be into $\mathrm{p} + \mathrm{d} + {}^4\mathrm{H} + {}^2\mathrm{n}$; curve 3 is the background from accidental coincidences.

Table 1. States in ^{6}H relative to the t+3n threshold (the energies and widths of the states are given in MeV).

Reaction channel			
^{9}Be(π^-, pd)^{6}H		^{11}B(π^-, p^{4}He)^{6}H	
E_r	Γ	E_r	Γ
6.6 ± 0.7	5.5 ± 2.0	7.3 ± 1.0	5.8 ± 2.0
10.7 ± 0.7	4 ± 2	–	–
15.3 ± 0.7	3 ± 2	14.5 ± 1.0	5.5 ± 2.0
21.3 ± 0.4	3.5 ± 1.0	22.0 ± 1.0	5.5 ± 2.0

In the quasi-free processes the nucleons of residual nuclear state are not involved in the pion absorption. The residual nucleus momentum P_R is determined by the intranuclear Fermi motion. Then, for example, for the reaction with the "quasitriton" we have

$$P_{(\mathrm{dn})_{\mathrm{FSI}}} \approx P_{\mathrm{p}} \text{ and } T_{(\mathrm{dn})_{\mathrm{FSI}}} + T_{\mathrm{p}} \approx Q,$$

where Q is the total kinetic energy of particles produced in the reaction; P and T are the momentum and kinetic energy of these particles, respectively.

Assuming that the neutron and deuteron velocities in the "quasitriton" are the same, one can estimate the neutron momentum (in the non-relativistic approximation):

$$P_{\mathrm{n}} = \frac{m_{\mathrm{n}}}{m_{\mathrm{n}} + m_{\mathrm{d}}} \sqrt{2\frac{m_{\mathrm{p}}(m_{\mathrm{n}} + m_{\mathrm{d}})}{m_{\mathrm{p}} + m_{\mathrm{n}} + m_{\mathrm{d}}} Q} \approx 120\,\mathrm{MeV}/c\,.$$

It should be noted that the neutron momentum in the reaction channel with the "quasideuteron" is much higher ($P'_{\rm n} \approx 200\,{\rm MeV}/c$).

In our experiment the energy of these neutrons is not registered. Owing to this, in the analysis of experimental data the momentum $P_{\rm n}$ ($P'_{\rm n}$) will be assigned to the nuclear residue. By imposing a restriction on the residual nucleus momentum one can essentially suppress the contribution of the reaction channels with FSI.

Figure 4b shows the missing-mass spectrum with a restriction on the value of $P_R < 100\,{\rm MeV}/c$. As this value does not exceed the expected one for the Fermi momentum of the intra-nuclear cluster, the restriction made it possible to increase a relative contribution of quasi-free absorption in the spectrum observed. The description of the spectrum by using the Breit-Wigner distributions with the parameters listed in table 1 led to the value of $\chi^2/N_{\rm DF} = 1.01$. It justifies the assumption of the existence of ^{6}H states. However, it is not improbable that these resonance parameters may be changed if in the future a more advanced theoretical approach will be used for the description of our data.

On the ^{11}B target the formation of ^{6}H has been observed in the missing-mass spectrum in the $^{11}{\rm B}(\pi^-, {\rm p}^4{\rm He}){\rm X}$ channel (fig. 5). The ^{11}B target contains the impurity ^{12}C. Therefore, the relevant contribution of the $^{12}{\rm C}(\pi^-, {\rm p}^4{\rm He}){\rm X}$ reaction was subtracted from the measured spectrum (fig. 5a). This contribution, shown in fig. 5b, was determined by normalizing the spectrum measured on the ^{12}C target to a relative portion of impurity (8%). The resulting spectrum is shown in fig. 5c.

The spectrum obtained on ^{11}B, has been analyzed in two ways. First, to describe the spectrum we used the ^{6}H resonance parameters obtained on the ^{9}Be target. In this case, $\chi^2/N_{\rm DF}$ is equal to 0.88. This result does not contradict the assumption about the existence of four levels of the ^{6}H isotope. Then, the position and width of levels as well as their yields were thought to be free parameters. In this case, the spectrum is fitted ($\chi^2/N_{\rm DF} = 0.87$) if only three resonance states with the parameters, listed in table 1, are included (fig. 5c). The results obtained in the two channels agree within the limits of experimental errors.

The missing-mass spectrum, obtained for the $^{11}{\rm B}(\pi^-, {\rm d}^3{\rm He}){\rm X}$ channel, was analyzed in the same way [20]. Note that the statistics of these data was poor. The MM spectrum does not contradict the assumption of ^{6}H existence. However, the spectrum may be fitted without this assumption. A satisfactory value of $\chi^2/N_{\rm DF} = 1.0$ can be achieved if the phase space of the ${\rm d} + {}^3{\rm He} + {\rm n} + {}^5{\rm H}$ channel is included in the fitting.

According to the data analysis, there are no discrepancies between the results obtained on both the targets. However, as compared to measurements on ^{9}Be, the energy resolution and data statistics for ^{11}B are worse, which hinders the observation of the ^{6}H states. One can assume that the results obtained in the $^9{\rm Be}(\pi^-, {\rm pd}){\rm X}$ reaction reproduce the level structure of the ^{6}H isotope more adequately.

The resonance energy of the lowest-lying state of the ^{6}H isotope derived in this paper is much higher than experimental results obtained earlier [9,10]. It should be emphasized that the statistics of our data is more than an order of magnitude higher, compared to statistics in these experiments. Our result is in agreement with the theoretical prediction of [21]. Note that the same good agreement was also for ^{5}H [1,21]. At the same time, our data do not agree with the ^{6}H level structure, which was obtained by the shell mode in ref. [22].

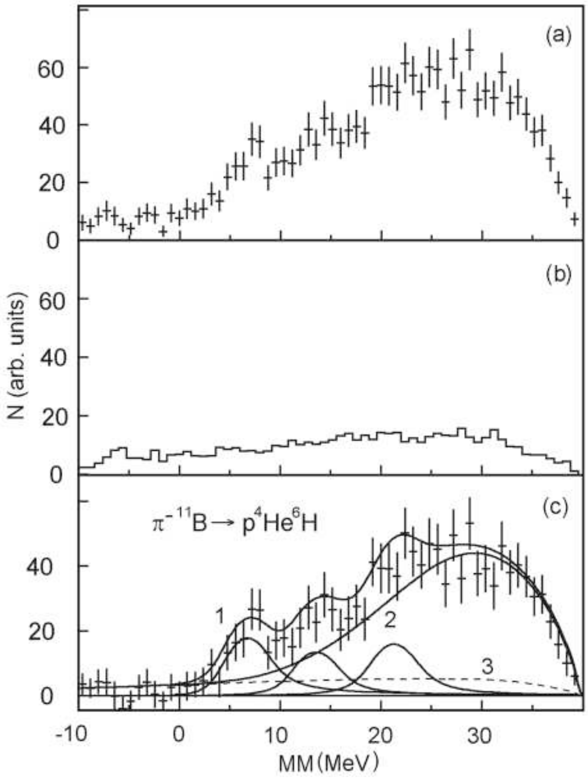

Fig. 5. Missing-mass spectra for the $^{11}{\rm B}(\pi^-, {\rm p}^4{\rm He}){\rm X}$ reaction: (a) spectrum measured on the ^{11}B target; (b) spectrum for the $^{12}{\rm C}(\pi^-, {\rm p}^4{\rm He}){\rm X}$ reaction (the spectrum is normalized to the content of impurity ^{12}C in the ^{11}B target); (c) spectrum resulting on subtraction of the impurity contribution. The solid lines are the Breit-Wigner distributions, curve 1 is the fit; curve 2 is the sum of phase space distributions; curve 3 is the background from accidental coincidences.

Additional confirmation of the existence of the levels with $E_r = 10.7$ and $15.3\,{\rm MeV}$ can be derived from the data on the spectroscopy of the ^{6}He isotope [23]. In the missing-mass spectrum measured in the $^7{\rm Li}(^3{\rm He}, {\rm p}^3{\rm He})$ reaction at $E(^3{\rm He}) = 120\,{\rm MeV}$, two rather narrow ($\Gamma \le 2\,{\rm MeV}$) states of ^{6}He with excitation energies $E_x \cong 32.0$ and $35.7\,{\rm MeV}$ were identified [23]. The binding energy of these states (the quantity B is positive for bound states) is $B(^6{\rm H}) = -2.2 \pm 0.7\,{\rm MeV}$ and $-6.8 \pm 0.7\,{\rm MeV}$, $B(^6{\rm He}) \cong -2.7\,{\rm MeV}$ and $-6.4\,{\rm MeV}$, respectively. The Coulomb energy of ^{6}He does not exceed $0.7\,{\rm MeV}$ [24]; therefore, it can be assumed that the observed levels are isobar-analog states.

An important feature of the level structure of the ^{5}H [1] and ^{6}H isotopes is the existence of levels above the breakup threshold of the nuclei into free nucleons. The nature of these states is still an open problem. Giant resonances observed in different nuclear processes are related to collective states in bound nuclei, and their excitation energies are distinctly lower. In particular, for ^{6}He and ^{6}Li the maximum energies of the GDR are at ~ 5 MeV below the breakup threshold [25].

Large nuclear excitations may be due to the formation of two holes in the 1s shell. These states of light nuclei were earlier searched for in pion absorption reactions by the 1p shell nuclei in the correlation spectra of two nucleons. There is clear evidence that the $(1s)^{-2}$ states are produced only in reactions on the lithium isotopes ^{6,7}Li$(\pi^-, \mathrm{nn})^{4,5}$He [26]. The interpretation of experimental data for heavier residual nuclei remains uncertain [19]. Nevertheless, we should like to emphasize the results of the measurement of the excitation spectrum of a residual nucleus in the ^{9}Be$(\pi^-, \mathrm{nn})^7$Li reaction [27]. In the region $E_x = 42$–46 MeV a certain structure was identified. It may be due to a manifestation of the isobar-analog of ^{7}H with $E_{r1} = 16 \pm 1$ MeV observed in our paper (see below).

3.2 The ^{7}H case

Figure 6 shows the missing-mass spectrum for the ^{11}B$(\pi^-, \mathrm{p}^3\mathrm{He})$X reaction. The sum of the masses of triton and four neutrons is taken as a zero point. It should be noted that events in the region of negative MM are caused by the admixture of ^{12}C in the ^{11}B target, the contribution of which was determined in a similar way for the ^{6}H case. Large statistical uncertainties preclude any firm conclusions. Nevertheless, a structure near the threshold should be indicated. One of the nonresonant reaction channel is present in fig. 6. Curve 1 was obtained when only the $\mathrm{p} + {}^3\mathrm{He} + \mathrm{t} + {}^2\mathrm{n} + {}^2\mathrm{n}$ channel was taken into account. For simplicity, the relative motion in both the pairs of neutrons was described by delta functions. It is seen that near the threshold the experimental spectrum does not correspond to the phase space distribution. We suppose that this result is an indication of the possible existence of the ^{7}H state near the threshold. Further studies of the ^{11}B$(\pi^-, \mathrm{p}^3\mathrm{He})$X reaction seem to be promising on condition that experimental statistics is at least several times larger.

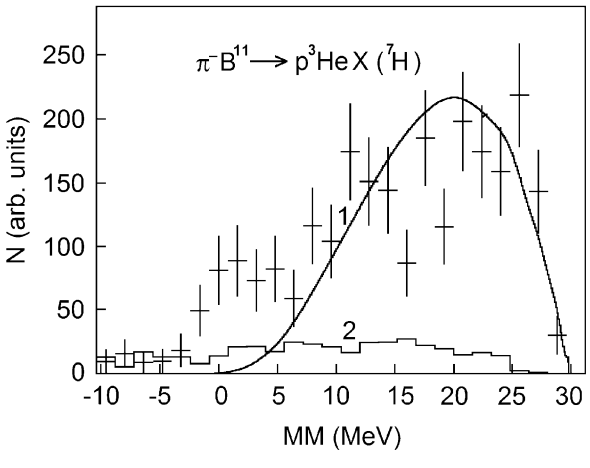

Fig. 6. Missing-mass spectra for the ^{11}B$(\pi^-, \mathrm{p}^3\mathrm{He})$X reaction. Curve 1 is the phase space distribution for the breakup of ^{11}B into $\mathrm{p} + {}^3\mathrm{He} + \mathrm{t} + {}^2\mathrm{n} + {}^2\mathrm{n}$, curve 2 is the spectrum for the ^{12}C$(\pi^-, \mathrm{p}^3\mathrm{He})$X reaction (the spectrum is normalized to the content of impurity ^{12}C in the ^{11}B target).

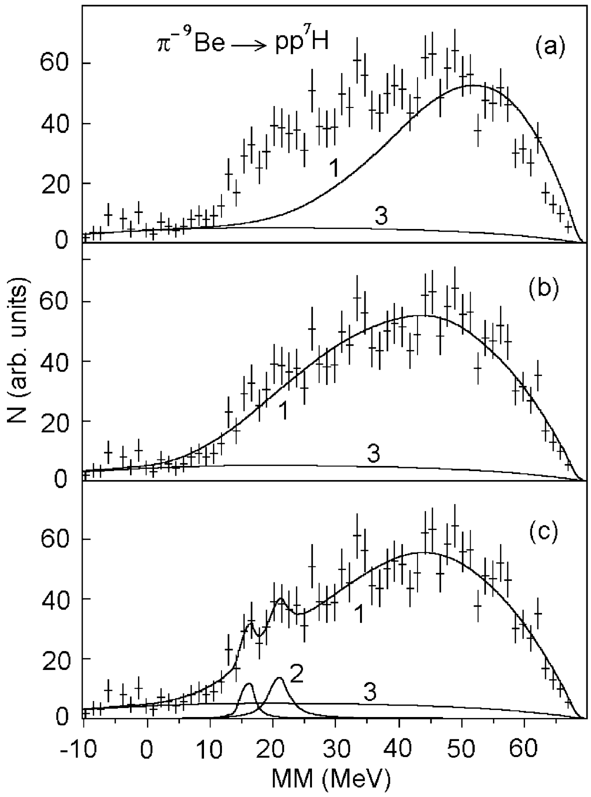

Fig. 7. Missing-mass spectra for the ^{9}Be(π^-, pp)X reaction: (a) the sum of phase space distributions with nucleon-stable nuclei and nucleons in the final states; (b) sum of the phase space distributions including singlet neutron pairs; (c) fit including the ^{7}H states. Solid lines are: curve 1 is the fit (all panels), curves 2 are the Breit-Wigner distributions (panel (c)), curve 3 is the background from accidental coincidences (all panels).

Figure 7 shows the missing-mass spectrum for the ^{9}Be(π^-, pp)X reaction. Pronounced resonance states in the spectrum are not observed, which is probably due to insufficient statistics. Therefore, an attempt was made to describe this spectrum by the sum of distributions over the phase space with the inclusion of only those reaction channels that produce nucleon-stable nuclei and nucleons.

The obtained spectrum is shown in fig. 7a. The description is seen to be unsatisfactory ($\chi^2/N_{\mathrm{DF}} = 6.3$). The 2p+t+4n reaction channel contributes significantly to the description. The comparison with the experimental spectrum indicates the necessity of including the channels with a less number of particles in the final state.

To this end, the reaction channels, in which FSI of a singlet neutron pair is taken into account, were included in the description. The result is shown in fig. 7b. The

$2p + t + {}^2n + {}^2n$ reaction channel contributes significantly to the description. The value $\chi^2/N_{DF} = 1.14$ does not permit us to reject this hypothesis. Nevertheless, we should point out an increase in the experimental spectrum in the range $10\,\text{MeV} \leq \text{MM} \leq 30\,\text{MeV}$.

The situation almost does not change if multi-particle channels with superheavy hydrogen isotopes ^{4}H, ^{5}H, and ^{6}H are taken into account. In this case, strong correlations occur in the channel yields having the same number of particles in the final state, as the shapes of these distributions are rather similar.

In the range of $10\,\text{MeV} \leq \text{MM} \leq 30\,\text{MeV}$ the fitting can be improved by including two states of ^{7}H with the following Breit-Wigner parameters:

$$E_{r1} = 16 \pm 1\,\text{MeV}, \qquad \Gamma_1 \cong 2\,\text{MeV};$$
$$E_{r2} = 21 \pm 1\,\text{MeV}, \qquad \Gamma_2 \cong 5\,\text{MeV}.$$

Within the errors these resonance energies are conserved when the channels with $^{4-6}$H are included in the fitting.

One of the reasons for the absence of any evidence for the ^{7}H states near the t + 4n threshold may be due to the mechanism of the $\text{A}(\pi^-, \text{pp})\,\text{X}$ reaction. The absolute yields of pairs of singly charged nuclei (p,d,t) produced in the absorption of stopped π^--mesons by light nuclei ^{6,7}Li [28], ^{9}Be [29], and ^{12}C [30] and measured at an angle of 180° demonstrate that the yields of pp-pairs are more than an order of magnitude lower than the yields of the remaining pairs. In addition, selectivity in the level occupancy in the (π^-,pp) channel is observed. As noted above, the yield of the ^{8}He ground state in the $^{10}\text{B}(\pi^-, \text{pp})\text{X}$ reaction is strongly suppressed, whereas the peak related to the level excitation near $E_x \cong 4.5\,\text{MeV}$ is clearly seen (fig. 2). Note that in our measurements of the missing-mass spectra for the $^9\text{Be}(\pi^-, \text{p})\text{X}$ and $^{11}\text{B}(\pi^-, \text{pd})\text{X}$ reactions the yield of the ^{8}He ground state is several times as large as the yields of excited states [31]. One of the conceivable mechanisms of the (π^-,pp) reaction was considered in more detail in [32].

In the present paper, evidence has been deduced for the existence of highly excited states of ^{7}H lying above the breakup threshold into free nucleons (7.5 and 12.5 MeV, respectively). The analysis of compilation with respect to energy levels of nuclei $A = 7$ [8] shows that such highly excited states were identified only in [23] where the ^{7}Li level with $E_x = 40.5 \pm 0.5\,\text{MeV}$ was observed in the $^7\text{Li}(^3\text{He}, \text{pd})\,\text{X}$ reaction; however, by virtue of the isotopic invariance this level cannot be an isobar analog of ^{7}H.

4 Conclusion

This paper and ref. [1] present the data on the spectroscopy of superheavy hydrogen isotopes $^{4-7}$H produced in the stopped pion absorption by light nuclei. These results are based on the data of one experimental run, which essentially decreases systematic errors.

The results of our measurements are: the level structures of ^{5}H and ^{6}H are similar and differ noticeably from the level structure of ^{4}H; the binding energies of the most low-lying levels decrease with increasing neutron number: $B(^4\text{H}_{\text{g.s.}}) = 6.9 \pm 0.2\,\text{MeV}$, $B(^5\text{H}_{\text{g.s.}}) = 3.0 \pm 0.2\,\text{MeV}$, and $B(^6\text{H}_{\text{g.s.}}) = 1.9 \pm 0.7\,\text{MeV}$.

The ^{7}H issue remains open, but it seems quite possible that ^{7}H is most bound among the superheavy hydrogen isotopes. New experimental information is obviously needed.

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