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Spectroscopy of superheavy hydrogen isotopes ^{4}H and ^{5}H

Yu.B. Gurov[1,a], M.N. Behr[1], D.V. Aleshkin[1], B.A. Chernyshev[1], S.V. Lapushkin[1], P.V. Morokhov[1], V.A. Pechkurov[1], N.O. Poroshin[1], V.G. Sandukovsky[2], and M.V. Tel'kushev[1]

[1] Moscow Engineering Physics Institute (State University), 115409 Moscow, Russia
[2] Join Institute for Nuclear Research, 141980 Dubna, Russia

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Abstract. The superheavy hydrogen isotopes ^{4}H and ^{5}H have been investigated in the stopped pion absorption on ^{9}Be. Three states of ^{4}H were proposed in the reaction channel ^{9}Be(π^-, dt)X. Four states of ^{5}H were proposed in the reaction channels ^{9}Be(π^-, pt)X and ^{9}Be(π^-, dt)X. The excited states of ^{5}H can decay into free nucleons.

PACS. 27.10.+h Properties of specific nuclei listed by mass ranges: $A \leq 5$ – 25.80.Ls Pion inclusive scattering and absorption

1 Introduction

The study of neutron-rich light nuclei near the drip line has attracted considerable attention as they exhibit a particular nuclear structure. The precise spectroscopy of these nuclei is the subject of considerable interest now because the small number of nucleons involved and a realistic theoretical description of their structure can be obtained. Among all nuclei near the drip line only the low-lying states of the superheavy hydrogen isotopes contain a not completely occupied proton 1s shell. Therefore, the parameters of these nuclei make it possible to verify theoretical models based on spectroscopy data for helium and lithium isotopes.

Up to now the existence of the ^{4}H isotope is established reliably [1–11] (for the earlier works see [12,13]). It was shown experimentally in different types of nuclear reactions that the ground state of the ^{4}H is nucleon-unstable. However, data on the energy and width of this resonance state are not always consistent to each other. The excited states of the ^{4}H were observed in several works [1,8,14,15].

For a long time the problem of the existence of the ^{5}H isotope remained unsolved. The evidence for the formation of the ^{5}H isotope in the ^{9}Be(π^-, pt)^{5}H reaction was found in our earlier work [5]. Assuming that the observed features in the missing-mass spectra are caused by only one resonance state, we obtained the following parameters: $E_{\rm r}(^5{\rm H}) = 7.4 \pm 0.7$ MeV, $\Gamma(^5{\rm H}) = 8 \pm 3$ MeV ($E_{\rm r}$ is the resonance energy above the unbound $2{\rm n} + {\rm t}$ mass). Later on, we observed the ^{5}H production in the two-body channel of pion absorption by lithium isotopes [6]. The following parameters were obtained: $E_{\rm r}(^5{\rm H}) = 11.8 \pm 0.7$ MeV, $\Gamma(^5{\rm H}) = 5.6 \pm 0.9$ MeV (^{6}Li(π^-, p)X channel) and $E_{\rm r}(^5{\rm H}) = 9.1 \pm 0.7$ MeV, $\Gamma(^5{\rm H}) = 7.4 \pm 0.6$ MeV (^{7}Li(π^-, d)X channel). The results of the two experiments are rather close, but the statistics under peaks on the lithium targets is essentially worse.

In heavy-ion reactions the ^{5}H production was long observed only in the ^{7}Li(^{6}Li,^{8}B)^{5}H reaction where the resonance with $E_{\rm r} \approx 5.2$ MeV and $\Gamma \approx 4$ MeV was identified [8].

Recently, radioactive ion beams have been used for the study of the ^{5}H. A resonance state with $E_{\rm r} = 1.7 \pm 0.3$ MeV and $\Gamma = 1.9 \pm 0.4$ MeV was observed in the ^{6}He(p, 2p)X reaction [16]. More recently the ^{5}H resonance at the same energy, but with a width less than 0.5 MeV, was observed in the t(t, p)^{5}H and d(^{6}He, ^{3}He)^{5}H reactions [11,17]. The peak in the missing-mass energy spectrum from the t(t, ptn) reaction was a certain indication for a second ^{5}H resonance at 2.7 MeV [17], but it was ascertained with a low statistical significance. Whereas a broad structure peaked at 3 MeV with about 6 MeV as a full width at half-maximum (FWHM) was observed in the C(^{6}He,2nt)X reaction [10].

Thus, the situation is not completely clear with the spectroscopy of the ^{4}H and, especially, ^{5}H isotopes. The binding energies obtained in various experiments differ more strongly than the reported experimental errors. It is conceivable that these discrepancies are due to the selectivity in the occupation of different levels of the isotopes in each specific reaction. More experimental data are needed.

[a] e-mail: gurov@axpk40.mephi.ru

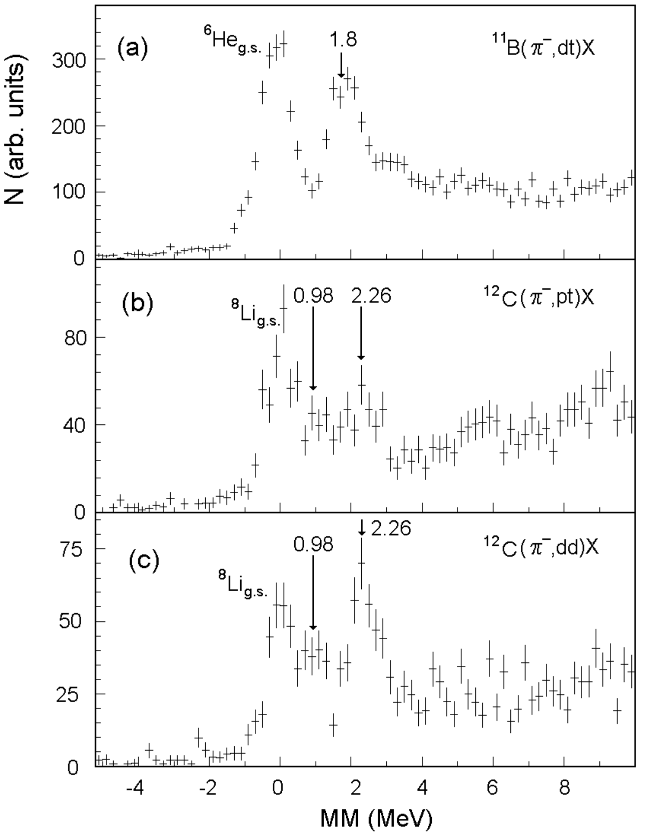

Fig. 1. Missing-mass spectra for the reactions: (a) ^{11}B(π^-, dt)X, the mass of the ^{6}He$_{g.s.}$ was used as a zero point, (b) ^{12}C(π^-, pt)X and (c) ^{12}C(π^-, dd)X the mass of the ^{8}Li$_{g.s.}$ was used as a zero point. Excited energies are indicated with arrows.

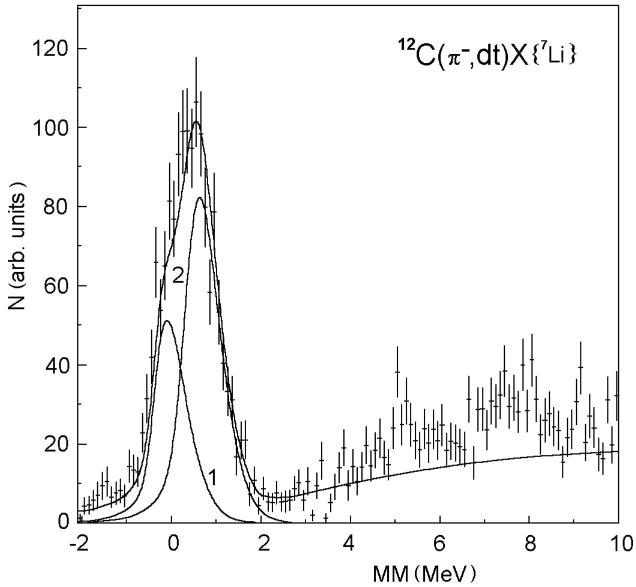

Fig. 2. Missing-mass spectrum for the ^{12}C(π^-, dt)X reaction. The solid lines are the fit and Gaussian distributions (1: ground state , 2: first-excited state of the ^{7}Li).

In the present work the spectroscopy of hydrogen isotopes ^{4,5}H is investigated in the reaction of stopped negative pion absorption on the ^{9}Be nuclei. The measurements were carried out in the framework of the joint MEPhI-Northwestern University experiment on the neutron-rich isotope production in absorption reactions of negative pions by 1p shell nuclei. New measurements on the ^{9}Be target are motivated by the opportunity to obtain much higher energy resolution and statistics.

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 spectrometer [18]. The pion beam with the energy $E = 30$ MeV was slowed down by the beryllium moderator and was stopped by a thin (~ 24 mg/cm^2) target. Measurements were carried out with ^{9}Be, ^{10,11}B, and ^{12,14}C targets. The ^{9}Be target had less than 1% of uncontrolled impurities. The pion stopping rate was $\sim 6 \cdot 10^4$ s^{-1}. The resulting charged particles were detected and identified by two semiconductor telescopes located under 180° to each other. Each telescope comprised two thin surface barrier Si(Au) detectors (100 and 400 μm in thickness) and a series of Si(Li) detectors, with a thickness of about 3 mm each. The active area of each detector was 8 cm^2. The total sensitive thickness of each telescope was $\sim$ 44 mm. This thickness permitted to measure the total absorption energy of charged particles up to the kinematical limits of the reaction.

The energy calibration of the detectors was carried out by means of an alpha source ^{238}Pu and the precise pulse generator. The absolute energy calibration and energy resolution were obtained by using peaks in inclusive spectra of p, d and t in the following reactions: ^{9}Be(π^-, p)X, ^{12}C(π^-, d)X and ^{12}C(π^-, t)X. These spectra show the sharp peaks resulted from two-body reaction channels (p^{8}He$_{g.s.}$, d^{10}Be$_{g.s.}$ and t^{9}Be$_{g.s.}$). The ground states of residual nuclei are bound and separated from excited ones. Systematic errors in the calibration were less than 100 keV. The energy resolution for single charged particles (p, d, t) was better than 0.5 MeV [18].

In order to determine the missing-mass resolution of the spectrometer the correlation data obtained on the ^{10,11}B and ^{12}C targets were used: ^{11}B(π^-, dt)^{6}He [18,19], ^{10}B(π^-, pt)^{6}He, ^{10}B(π^-, dd)^{6}He and ^{12}N(π^-, pd)^{9}Li [20]. The analysis of the results showed that the missing-mass resolution is about 1.0 MeV and the systematic error in the calibration is less than 100 keV. As an illustration the missing-mass spectra for the (π^-, dt), (π^-, pt) and (π^-, dd) reactions are shown in fig. 1. As can be seen, ground and low-lying excited states of ^{6}He and ^{8}Li are separated.

In this work the parameters of the superheavy hydrogen isotopes are determined using the least square approximation in the fitting of the experimental spectra (sect. 3). As an illustration we used this approach for the ^{12}C(π^-, dt)X reaction. The ground and first-excited states of ^{7}Li lie off the continuum ($\Delta \cong 2$ MeV). In consequence of

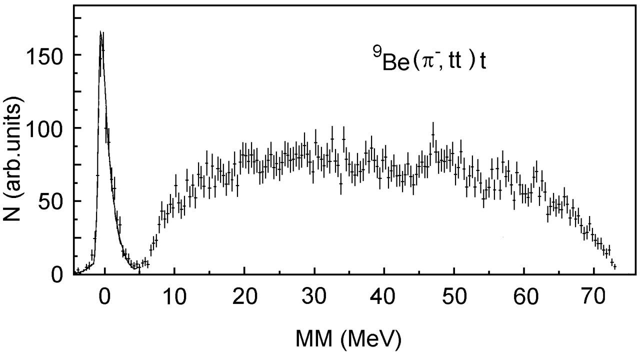

Fig. 3. Missing-mass spectrum for the ^{9}Be(π^-, tt)X reaction.

small excited energy (E_x = 0.48 MeV) these levels are seen as single peak (fig. 2). The fit using two Gaussians is in close agreement with the experimental spectrum between −2 MeV and 2 MeV (χ^2 is 32.8 for $N_{DF} = 31$).

The energy resolution and calibration as well as the time variation of its magnitudes for the ^{9}Be target experiment were controlled by the measurements of tt-events. The missing-mass spectrum for this channel is shown in fig. 3. The triton mass was used as a zero point. The observed peak is associated with the three-body reaction channel ^{9}Be(π^-, tt)t. The fit describes this peak adequately (χ^2 is 13.2 for $N_{DF} = 11$). The peak position ($MM_t = 0.0 \pm 0.1$ MeV) and its width ($\Delta_t = 1.2 \pm 0.1$ MeV) are consistent with the results obtained on the other targets. The increase in the peak width is caused by the angle acceptance of the spectrometer. As a result, the width of the spectrometer response grows with the reduction of the residual mass. The stability of the spectrometer parameters was controlled by the shape of the spectrum for various parts of the statistics.

The spectrometer and experimental procedure are described in more detail in our work [18].

3 Results

3.1 The ^{4}H case

The missing-mass spectra for the ^{9}Be(π^-, dt)^{4}H reaction are shown in fig. 4. The mass of triton plus neutron was used as a zero point. The spectrum in fig. 4a shows clearly a peak at low missing mass. This part of the spectrum is shown in more detail in fig. 5. As seen from the figure, the peak is a superposition of several states of ^{4}H. To separate these states and determine their parameters, we 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 ($n \geqslant 4$). The following parameterization of the resonances was used [21]:

$$\frac{\mathrm{d}Y}{\mathrm{d}E} \propto \frac{\Gamma}{(E_\lambda - \Delta_l - E)^2 + (\Gamma/2)^2}\,, \quad (1)$$

$$\Gamma = 2\gamma^2 P_l(E)\,, \quad (2)$$

$$\Delta_l = \gamma^2 S_l(E)\,. \quad (3)$$

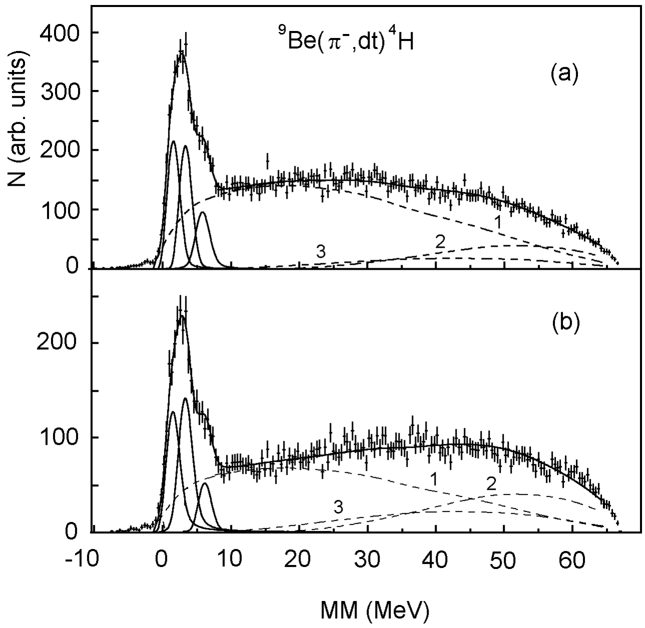

Fig. 4. Missing-mass spectra for the ^{9}Be(π^-, dt)X reaction without (a) and with (b) restriction on the momentum of residual nuclei. The solid lines are the fit and Breit-Wigner distributions. Curve 1 is the phase space distribution for the breakup of ^{9}Be into d + t + t + n; curve 2: d + t + p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

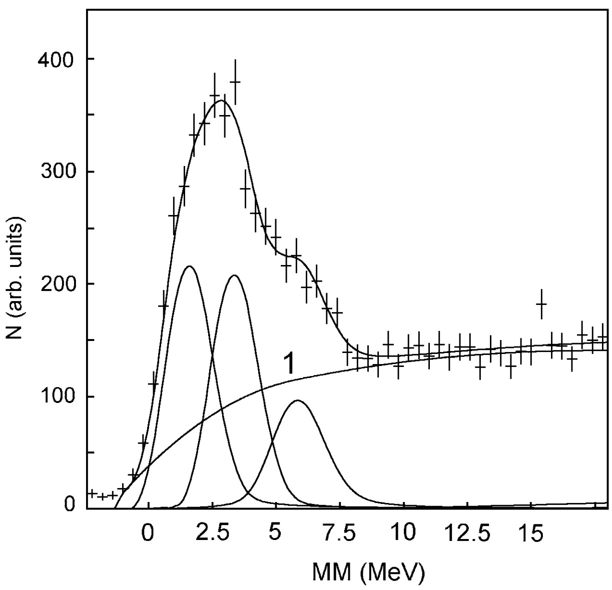

Fig. 5. Missing-mass spectra for the ^{9}Be(π^-, dt)X reaction over a bounded range. The solid lines are the fit and Breit-Wigner distributions. Curve 1 is the phase space distribution for the breakup of ^{9}Be into d + t + t + n.

Here, E_λ is formal energy of the resonance and Γ is its width, γ^2 is the reduced width. $S_l(E)$ is the channel shift width and $P_l(E)$ is the channel penetrability function, E is the relative energy between neutron and triton. The resonance energy $E_r = E_\lambda - \Delta_l$. The channel radius was chosen to be 4 fm [14]. For the fit only P-wave resonances were included.

The angular and energy resolutions of the spectrometer, and the background of accidental coincidence, were taken into account in the Monte Carlo calculations.

As seen from fig. 4a, the experimental spectrum at MM over 8 MeV can adequately be fitted by using a superposition of the n-particle phase space distributions. The four-particle channel t + d + t + n is dominant in the range MM from 8 MeV to 25 MeV. This channel constitutes a "physical" background under the peak, with value determined by the large MM.

First the peak was fitted with one state of ^{4}H. In this case the resonance parameters are $E_r = 3.1 \pm 0.1$ MeV and $\gamma^2 = 3.2 \pm 0.1$ MeV; however this hypothesis can be rejected at a 2% significance level (χ^2 is 50.4 for $N_{DF} = 32$). Nevertheless, it should be pointed out that these resonance parameters agree closely with recent results of refs. [10,11]. In these works experimental data were fitted by using a single Breit-Wigner shaped resonance. A hypothesis of two levels ($E_{r_{g.s.}} = 2.4 \pm 0.1$ MeV, $\gamma^2_{g.s.} = 1.4 \pm 0.1$ MeV and $E_{r_1} = 5.0 \pm 0.2$ MeV, $\gamma_1^2 = 2.6 \pm 0.2$ MeV) also can be rejected at a 2% significance level ^{4}H (χ^2 is 46.8 for $N_{DF} = 29$). The experimental spectrum shown in fig. 5 is adequately fitted (χ^2 is 23.0 for $N_{DF} = 26$) by using three states of ^{4}H with the following resonance parameters:

$$E_{r_{g.s.}} = 1.6 \pm 0.1\,\text{MeV}, \qquad \gamma^2_{g.s.} = 0.4 \pm 0.1\,\text{MeV},$$

$$E_{r_1} = 3.4 \pm 0.1\,\text{MeV}, \qquad \gamma^2_1 = 0.4 \pm 0.1\,\text{MeV},$$

$$E_{r_2} = 6.0 \pm 0.1\,\text{MeV}, \qquad \gamma^2_2 = 0.5 \pm 0.1\,\text{MeV}.$$

The quasifree processes, in which nucleons of residual nuclei are not involved in the reaction, make a considerable contribution to the three-body channels of pion absorption. This provides a possibility of checking the ^{4}H parameters. For a greater enrichment of the measured spectra by such events, we impose a restriction on the momentum of the residual ($P_x < 100$ MeV/c). This quantity does not exceed an expected value of the Fermi momentum for the intranuclear cluster motion. The missing-mass spectrum thus obtained is shown in fig. 4b. This spectrum was fitted by using the Breit-Wigner distribution with the resonance parameters presented above. As is seen from the figure, the fitting is consistent with the existence of the three states of ^{4}H isotope.

When these results are compared with the data obtained in other experiments, it is apparent that:

- the ^{4}H ground state is found to be more bound. The level with $E_r = 2.0 \pm 0.3$ MeV observed in ref. [8] agrees closely with our result;
- the three ^{4}H states were first observed in one reaction. Note that the four states reported in the review [13] are obtained from charge-symmetric reflection of the R-matrix parameters for ^{4}Li;
- reduced widths γ^2 are significantly less than is generally appreciated.

The study of the ^{4}H spectroscopy must definitely be continued. It is possible that improvement in energy resolution and statistics provides a means for the observation of new states.

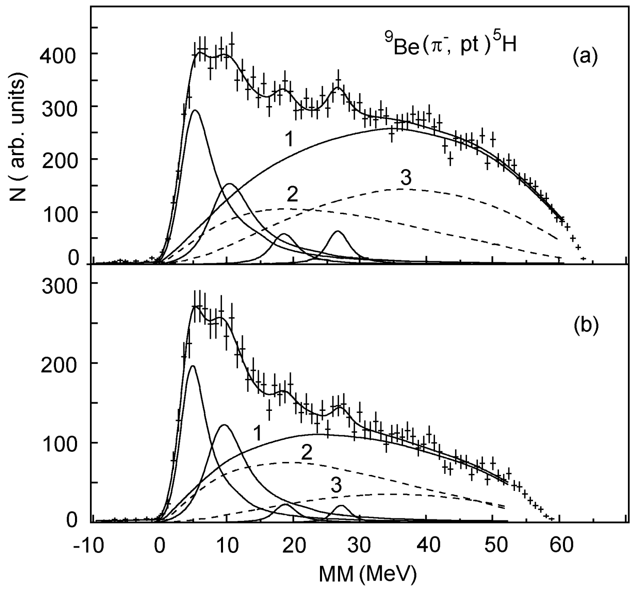

Fig. 6. Missing-mass spectra for the ^{9}Be(π^-, pt)X reaction without (a) and with (b) restriction on the momentum of residual nuclei. The solid lines are the fit and Breit-Wigner distributions. Curve 1 is the sum of phase space distributions for all open channels, curve 2 is the phase space distribution for the breakup of ^{9}Be into p + t + ^{4}H + n; curve 3: p + t + t + n + n; curve 4: p + t + d + n + n + n.

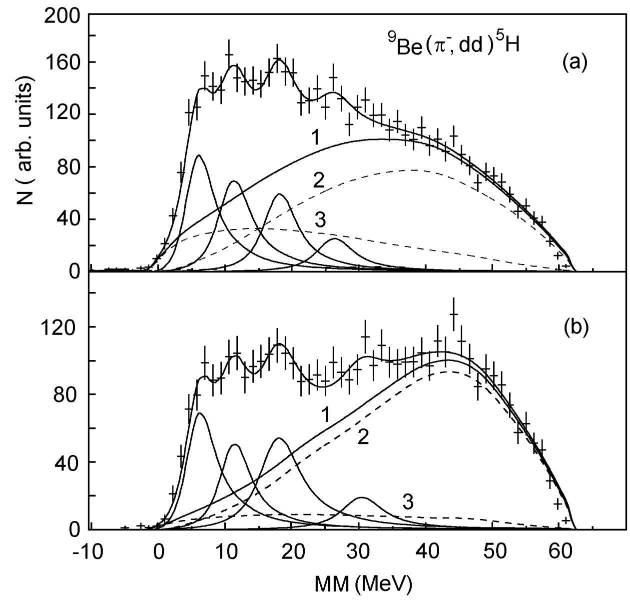

Fig. 7. Missing-mass spectra for the ^{9}Be(π^-, dd)X reaction without (a) and with (b) restriction on the momentum of residual nuclei. The solid lines are the fit and Breit-Wigner distributions. Curve 1 is the sum of phase space distributions for all open channels, curve 2 is the phase space distribution for the breakup of ^{9}Be into d + d + ^{4}H + n; curve 3: d + d + t + n + n.

3.2 The ^{5}H case

The missing-mass spectra for the ^{9}Be(π^-, pt)X and ^{9}Be(π^-, dd)X reactions are shown in figs. 6, 7. The mass

Table 1. States in ^{5}H relative to the t + n + n threshold (energies and widths of the states are given in MeV).

Reaction channel				Average weighting values	
^{9}Be(π^-, pt)^{5}H		^{9}Be(π^-, dd)^{5}H			
E_r	Γ	E_r	Γ	E_r	Γ
5.2 ± 0.3	5.5 ± 0.5	6.1 ± 0.4	4.5 ± 1.2	5.5 ± 0.2	5.4 ± 0.6
10.4 ± 0.3	7.4 ± 0.6	11.4 ± 0.7	5 ± 1	10.6 ± 0.3	6.8 ± 0.5
18.7 ± 0.5	3.9 ± 2.0	18.3 ± 0.5	5.5 ± 1.7	18.5 ± 0.4	4.8 ± 1.3
26.8 ± 0.4	3.0 ± 1.4	26.5 ± 1.0	6 ± 3	26.7 ± 0.4	3.6 ± 1.3

of triton plus two neutrons was used as a zero point. As seen from figs. 6, 7, n-particle phase space distributions ($n \geqslant 4$) give no way of fitting the experimental data.The fittings of the spectra were made in a manner like the ^{4}H case. A simple Breit-Wigner form was used for ^{5}H states. The reason is the very complicated experimental and theoretical situation on the ^{5}H system [22]. In such a situation the Breit-Wigner distribution is a suitable form of description of the observed peaks only. We suppose that this approach provides a way of correlation with other experimental data.

The spectra shown in figs. 6a, 7a are described well enough (the $\chi^2/N_{\rm DF}$ is equal to 1.05 and 0.94, respectively) with four resonances. The parameters of the ^{5}H isotope are presented in table 1. The Γ is the full width at half-maximum (FWHM) of the peaks. It should be pointed out that an adequate fitting cannot be obtained without the ^{2}n (di-neutron) or ^{4}H resonance in the final state.

It should be noted that the spectra shown in figs. 6, 7 have different forms and yields for different states in the pt- and dd-channels differ noticeably. This might be the indication that various mechanisms are responsible for the formation of these channels. In ref. [22] it has been suggested that the observed properties of broad states can be strongly influenced by the reaction mechanism. Nevertheless, the parameters of the ^{5}H states fall in the range of experimental errors.

The spectra obtained with the constraint $P_{\rm x} < 100$ MeV/c (figs. 6b, 7b) were described using the resonance parameters listed in table 1. The values of the $\chi^2/N_{\rm DF}$ (1.2 and 1.1 for pt- and dd-events, respectively) are consistent with the proposal for the existence of four states of the ^{5}H isotope.

The two highly excited states of ^{5}H ($E_{\rm r} = 18.7$ and 26.8 MeV) are less visible than the others. Therefore, we used the χ^2 criterion for checking the following hypotheses. The spectra were fitted with three states of ^{5}H by sequentially eliminating the levels with $E_{\rm r} = 18.5$ MeV and $E_{\rm r} = 26.7$ MeV from consideration. Both the hypotheses were rejected at the 10% significance level.

The resonance energy of the ^{5}H ground state obtained in the present work is in agreement with the experimental result of ref. [23] and the theoretical result of ref. [24], but is a bit higher (ΔE = 2–4 MeV) than the data obtained in refs. [10,11,17] and the theoretical calculations of refs. [25–27]. In our opinion, the discrepancies between the experimental data of various authors are rather great. An important point is that in our measurements the binding energy of the ^{5}H isotope is substantially less as compared to the ^{4}H isotope. It seems reasonable to say that the binding energy of the superheavy hydrogen isotopes depends less on neutron pairing in comparison with helium and lithium isotopes.

An important result of our measurements is the observation of several excited levels of the ^{5}H isotope. Up to now the experimental information on the excited states of nuclei near the drip line is very limited. As for ^{5}H, an experimental indication for the excited state at $E_{\rm r}$ about 2.7 MeV has been obtained in refs. [11,17]. While recent theoretical calculations predict at least two excited levels with resonance energies $E_{\rm r}$ in the range of 4.5–7.5 MeV [25]. The excited energies of these states ($\sim$ 2–5 MeV) are close to our value for the first-excited level. It is possible that the peak observed is a superposition of the two states predicted.

The resonance energies of the excited states are above the threshold of the ^{5}H decay into five nucleons. The excitation of this system of the free nucleons is as much as 18 MeV (or 3.6 MeV/nucleon). The structure and the production mechanism of these states are unclear. From the compilations of the energy levels of light nuclei [28,29] it is seen that such high excitations were observed only in the case of the ^{5}He and the ^{5}Li isotopes [2]. The ^{5}He level with $E_{\rm x} = 35.7$ MeV and the ^{5}Li level with $E_{\rm x} = 34$ MeV are probably isobar analog of ^{5}H with $E_{\rm r} = 18.7$ MeV.

4 Conclusion

The states of superheavy hydrogen isotopes ^{4}H and ^{5}H were searched for in the stopped pion absorption on ^{9}Be nuclei. Three states of the ^{4}H were proposed in the reaction channel ^{9}Be(π^-, dt)X. The ground state with $E_{\rm r} = 1.6 \pm 0.1$ MeV is found to be more bound than is generally appreciated. Four states of the ^{5}H were proposed in the reaction channels ^{9}Be(π^-, pt)X and ^{9}Be(π^-, dt)X. All states are broad. The ^{4}H isotope is more bound than the ^{5}H one.

The present results differ essentially from the recent data on ^{4}H and ^{5}H spectroscopy obtained in works [10, 11,16,17]. It should be pointed out that there are some arguments in favour of our results. First, the experiment statistics is higher in comparison with other data. Second, a large region of missing mass under study reduces any impact of phase space effects. On the other hand, the study of the effects of the structure of the initial nuclei and reaction mechanisms can resolve the contradiction between experimental results obtained by various authors [22].

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