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SEARCH FOR ^{4}H, ^{5}H AND ^{6}H NUCLEI IN THE ^{11}B-INDUCED REACTION ON ^{9}Be

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Abstract: In the reaction ^{11}B(88.0 MeV)+^{9}Be the energy spectra of the ^{14}O, ^{15}O and ^{16}O nuclei have been measured to obtain some information about their partners in the exit channel - the neutron-rich hydrogen isotopes ^{4}H, ^{5}H and ^{6}H. The unbound levels in the ^{4}H and ^{6}H systems have been observed at excitation energies of 3.5 ± 0.5 MeV ($\Gamma \sim 1$ MeV) and 2.6 ± 0.5 MeV ($\Gamma = 1.5 \pm 0.3$ MeV), respectively. No evidence for the existence of any bound or unbound state in ^{5}H has been found.

E NUCLEAR REACTIONS ^{9}Be(^{11}B, ^{46}O), $E = 54$–80 MeV; ^{9}Be(^{11}B, ^{15}O), $E = 58$–70 MeV; ^{9}Be(^{11}B, ^{14}O), $E = 52$–58 MeV; measured $\sigma(E(^{16}\mathrm{O}))$, $\sigma(E(^{15}\mathrm{O}))$, $\sigma(E(^{14}\mathrm{O}))$, ^{4,6}H deduced levels, Γ.

1. Introduction

Heavy ion reactions have been widely used to synthesize new isotopes. The fusion reactions, having become already traditional [1]), lead mainly to the formation of neutron-deficient isotopes in a wide range of masses with relatively high cross sections. The use of the deep inelastic [2]) as well as fragmentation [3]) reactions has allowed one to extend the investigations to the region of neutron-rich nuclei far from the β-stability line. In addition to the production of new isotopes, the aim of the majority of previous works has been to measure the mass excess of these nuclei as it constitutes the first quantitative information on their structure. Such information serves to test the predictions of different models whose parameters have been determined from nuclei lying closer to the valley of stability, and, in turn, permits the upgrading of these parameters to allow a more accurate prediction of the masses farther from the β-stability line, and thus a more precise definition of the limits of nuclear stability. In these studies very light elements play a special role as they may serve as a good test for different theoretical calculations. However, the above mentioned reactions enable us to study only those nuclei which are stable against nucleon decay.

On the other hand, the use of the few-nucleon transfer reactions and the single as well as double charge exchange reactions opens up new possibilities for measuring the mass excess. These reactions yield two products in the exit channel and this fact allows one to draw conclusions about one product from the measurement of the energy spectrum of the other. This approach becomes particularly important, when the product under study is weakly bound or even unbound. In this case the other product which has to be a particle stable nucleus is measured and its spectrum gives us accurate information about the ground state mass and the low-lying excited states of the product under study.

In recent years, a good deal of work [4]) has been reported on using these so-called "two-body" heavy ion reactions to study neutron-rich light nuclei with $Z = 6$–20. On the contrary, the very light nuclei ($Z < 6$) have been studied only scarcely and the main source of information has come from light-particle and pion beams [5]). Moreover, this information is sometimes contradictory: for example, the broad levels of ^4H observed in three different works [6-8]) do not agree with each other. The search for levels in ^5H has been performed in refs. [9-11]) in which no evidence for either bound or unbound state of ^5H has been found. Only Seth [12]) claims to have observed a bump at 11 MeV in the reaction $^6Li(\pi^-, p)^5H$. Recently, the $^7Li(^7Li, ^8B)^6H$ reaction has been investigated [13]) which is the first attempt to synthesize the ^6H isotope by a heavy ion reaction. The cross section for ^6H formation turned out to be high enough to support the idea that heavy ion reactions may be a promising tool for the studies of light exotic nuclei.

Up to now, information about the neutron-rich hydrogen isotopes has come from reactions of different kinds. The aim of the present work was to study these neutron-rich isotopes of hydrogen in one single reaction $^{11}B + ^9Be$ using its different exit channels. For this purpose, the energy spectra of ^{16}O, ^{15}O and ^{14}O have been measured and this gives information about the corresponding products - ^4H, ^5H and ^6H, respectively.

2. Experimental

The schematic view of our experimental set-up is shown in fig. 1; it has been described in detail elsewhere [14]). The $^{11}B^{2+}$ (88.0 MeV) beam delivered by the Dubna U-300 cyclotron, after being collimated by three carbon slits, reached a Be target with an intensity of up to 1.5 μA. The thickness of the ^9Be target was 230 $\mu g/cm^2$. The reaction products emitted within a 0.6 msr solid angle were analyzed by a magnetic spectrograph. A position-sensitive double ionization chamber served as a focal plane detector. The ionization chamber measured three parameters (energy losses dE, position x, residual energy E) in order to identify and determine the energy of the reaction products. The energy resolution of the dE and E sectors of the ionization chamber was 3.2% and 2%, respectively. These values were determined mainly by the angular dispersion (about $\pm 1.5°$) at the entrance to the ionization

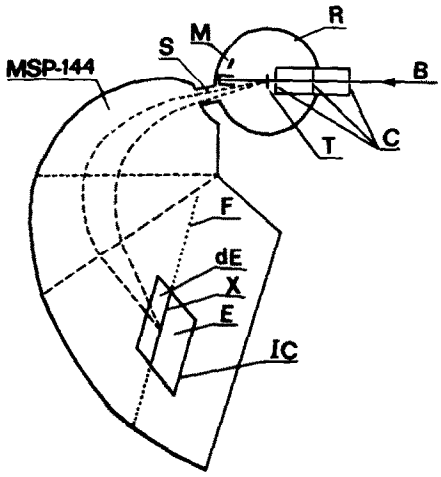

Fig. 1. The experimental set-up. B - beam, R - reaction chamber, C - collimators, M - monitor, T - target, S - entrance slit of the MSP-144 magnetic spectrograph, F - focal plane of the spectrograph, IC - ionization chamber.

chamber, which caused different energy-losses due to unequal trajectory lengths in the detectors. The position resolution at the focal plane was about 0.7 mm, this being equivalent to an energy resolution $\Delta E/E \approx 7 \times 10^{-4}$.

The elastic scattering of ^{11}B on a Ag target was used to measure the beam energy. To test the possibilities of our experimental apparatus the reaction $^{9}Be(^{11}B, ^{12}C)^{8}Li$ was measured. In fig. 2 we present the position spectrum of the ^{12}C nuclei measured at an angle of $(8 \pm 0.5)°$. From this spectrum, with the help of the previously done calibration of the magnetic spectrometer (by means of a ^{226}Ra α-source), the corresponding energy spectrum was obtained in a straightforward manner. Taking into account the energy shift due to the target thickness, the resulting energy values at the peak centroids were found to correspond to the formation of ^{8}Li nuclei in

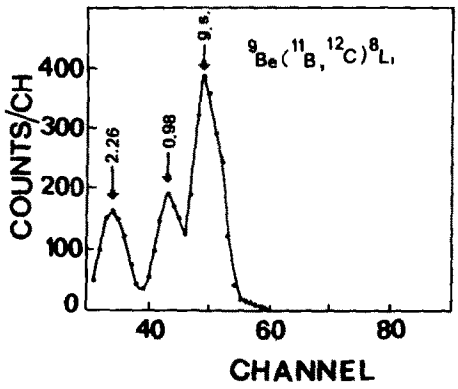

Fig. 2. The ^{12}C spectrum along the focal plane (x-coordinate) from the $^{9}Be(^{11}B, ^{12}C)^{8}Li$ reaction.

the ground and two low-lying excited states at 0.98 and 2.26 MeV, respectively. The mass of ^{8}Li could be obtained with an accuracy of ±280 keV. In this value uncertainties due to the cyclotron beam energy drift during the experiment, the target thickness, the scattering angles as well as the uncertainties in the peak centroids were included. Of these the most significant was the uncertainty due to the beam energy drift.

It is obvious that as a result of poor statistics the experimental accuracy of mass determination may worsen.

3. Results and discussion

3.1. THE ^{9}Be(^{11}B, ^{16}O)^{4}H REACTION

The energy spectrum of the ^{16}O ions is presented in fig. 3. The arrow at 79.3 MeV indicates the energy of ^{16}O ions, corresponding to the formation of the ^{4}H unbound system at zero excitation energy. As can be seen, the absence of any events of higher energies indicates the non-existence of any bound states in ^{4}H. In such a case the energy spectrum of ^{16}O, in principle, should be described by the sum of the phase-space distributions from different multi-body exit channels. As the starting point of each distribution (the maximum energy of ^{16}O available in the given decay mode) depends on the threshold of the corresponding break-up, there is some possibility to distinguish among different phase-space contributions. Starting at zero excitation energy the only contributing channel is the three-body break-up ^{16}O + ^{3}H + n with ^{16}O being emitted in its ground state. At 6.05 MeV, where the first excited level of ^{16}O lies, another three-body break-up had to be taken into account. The other multi-body break-up channels, such as the four-body break-up ^{16}O + ^{2}H + n + n as well as the five-body break-up ^{16}O + H + n + n + n start at excitation energies of 6.28 MeV and 8.49 MeV, respectively. Thus only the above-mentioned exit channels may contribute to the total phase space distribution in the studied energy region. The contribution of each channel was considered as a varying parameter in order to obtain a best fit to the experimental data. In the procedure the experimental resolution was taken into account. The resulting total phase space distribution is presented in fig. 3 by a full line.

One can see that the agreement with the experimental data is rather good. However, at 77.5 MeV, an enhancement over the phase space distribution is clearly seen. The difference between the experimental points and the phase space distribution is shown in the inset. The observed peak lies at 3.5 ± 0.5 MeV above the mass of ^{3}H + n and its width is about 1 MeV. The area under the peak implies a cross section of 150 ± 50 nb/sr and can be attributed to the ^{3}H + n final-state interaction corresponding to transitions to the ground state of unbound ^{4}H. A similar level has been observed in the reaction ^{6}Li(^{6}Li, ^{8}B)^{4}H [ref. [9])] and in the π^{-}-induced reactions on ^{6}Li [ref. [15])] and on ^{7}Li [ref. [7])]. The evidence for the existence of a strong resonant

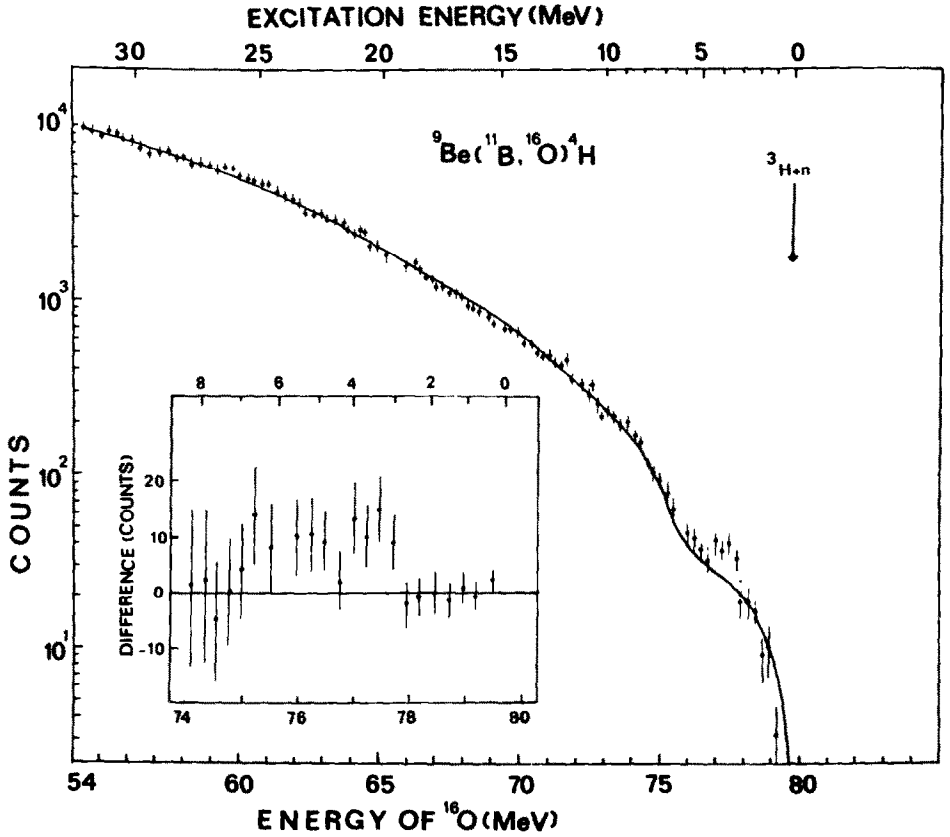

Fig. 3. Energy spectrum of ^{16}O ions from the $^{9}Be(^{11}B, ^{16}O)^{4}H$ reaction. The full line represents the sum of phase space contributions of $^{16}O+^{3}H+n$, $^{16}O^{*}_{0.05}+^{3}H+n$, $^{16}O+^{2}H+n+n$ and $^{16}O+H+n+n+n$ exit channels. The difference between experimental points and full line is shown on linear scale in the inset.

behaviour at 3.4 MeV in the $^{3}H+n$ system follows from a phase-shift analysis [6]) and also from the total cross section data of Phillips [16]) for n-t scattering. All the above mentioned data on the unbound levels of the ^{4}H system are presented for convenience in the table.

As for the enhancement at an excitation energy of about 5 MeV our experimental counting rate does not allow one to draw any positive conclusion about a statistically significant peak at this energy despite the fact that the authors of refs. [6,8,17]) claim to have observed levels in this region.

3.2. THE $^{9}Be(^{11}B, ^{15}O)^{5}H$ REACTION

Fig. 4 shows the energy spectrum of ^{15}O. Over a wide energy range no sharp states are evident in the data. Instead, the spectrum rises rather smoothly above the threshold for ^{5}H particle stability (relative to decay into $^{3}H+n+n$). A theoretical

TABLE 1

Parameters of the unbound states in the ^4H system deduced in different reactions

Reaction	Level energy (MeV)	Width (MeV)	Ref.
$n+{}^3H \rightarrow n+{}^3H$	3.4	5.5 [a])	
	5.1	5.5 [a])	[6])
$\pi^-+{}^7Li \rightarrow t+{}^4H$	2.7 ± 0.6	2.3 ± 0.6 [a])	[7])
$^4H \rightarrow t+n$			
$^6Li+{}^6Li \rightarrow {}^8B+{}^4H$	~3.6	~2.2 [b])	[9])
$\pi^-+{}^6Li \rightarrow {}^2H+{}^4H$	3.3 ± 1.5	≤ 3	[15])
$\pi^-+{}^7Li \rightarrow {}^3H+{}^4H$	0.3 ± 1.5	≤ 5	[15])
$n+{}^3H \rightarrow n+{}^3H$	~3.5	~3 [b])	[16])
$^{11}B+{}^9Be \rightarrow {}^{14}O+{}^4H$	3.5 ± 0.5	~1	present work

[a]) Reduced width γ^2.

[b]) Deduced from the figure in the given reference.

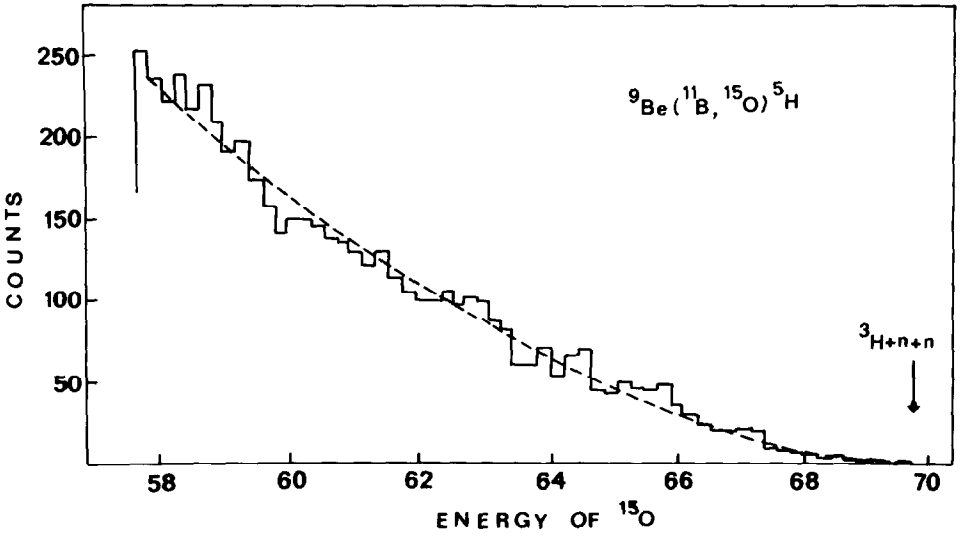

Fig. 4. Energy spectrum of ^{15}O ions from the $^9Be(^{11}B, ^{15}O)^5H$ reaction. The four-body phase space distribution $^{15}O+{}^3H+n+n$ is shown by a dashed line.

fit to the experimental spectrum in the shown energy region was performed as in the ^4H case. It was found that the contribution of the four-body break-up channel $^{15}O+{}^3H+n+n$ dominated, while those of channels other than $^{15}O+{}^3H+n+n$ were negligibly small and gave no significant improvement in describing the measured energy spectrum of ^{15}O. The dashed line in fig. 4 represents the phase space contribution from the four-body break-up $^{15}O+{}^3H+n+n$. As one can see, the agreement with the experimental data is quite good. The spectrum is rather smooth

and presents no evidence for bound or unbound levels of the ^{5}H system. This result is in agreement with other attempts to study the ^{5}H nucleus in the $^{7}Li(^{6}Li, ^{8}B)$ [ref. [9])], $^{3}H(t, p)$ [ref. [10])] and $^{9}Be(\alpha, ^{8}B)$ [ref. [18])] reactions where no sharp states have been observed either. The broad unbound level at 11 MeV seen in the $^{6}Li(\pi^{-}, p)^{5}H$ reaction [12]) has not been observed in the present experiment.

3.3. THE $^{9}Be(^{11}B, ^{14}O)^{6}H$ REACTION

The resulting spectrum of ^{14}O measured in ten independent runs is shown in fig. 5. Despite the rather low number of counts, the enhancement at 53 MeV is clearly observed. We have attempted to fit the spectrum with the five-body $^{14}O+^{3}H+n+n+n$ phase space contribution (dashed line) but with little success. In order to explain the experimental data which cannot be reproduced by either five- or four-body phase space we had to include the three-body exit channel $^{14}O+^{5}H+n$, though neither bound nor unbound levels have been observed in the $^{9}Be(^{11}B, ^{15}O)^{5}H$ reaction. A similar situation has appeared in the $^{7}Li(\pi^{-}, \pi^{+})^{7}H$ reaction [12]), where the contribution from the $^{7}H \rightarrow ^{5}H+n+n$ exit channel had to be included. This fact can only be understood as a consequence of the final state interaction in the ^{5}H system with a very large width ($\Gamma \sim 10$ MeV), that makes it very difficult to observe this interaction as a peak in the reactions leading directly to the ^{5}H nucleus.

The three-body phase space normalized to the experimental spectrum in the vicinity of 52 MeV is shown by a solid curve. The enhancement above the phase space distribution is still seen.

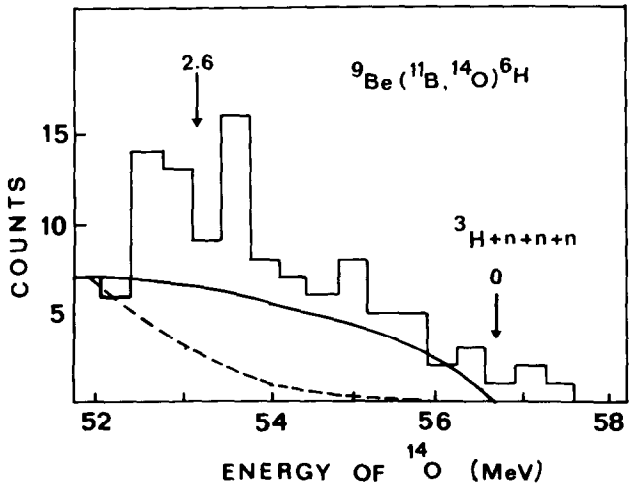

Fig. 5. Energy spectrum of ^{14}O ions from the $^{9}Be(^{11}B, ^{14}O)^{6}H$ reaction. The phase space corresponding to the five-body exit channel ($^{15}O+^{3}H+n+n+n$) is shown by a dashed line. The phase space corresponding to the three-body exit channel ($^{15}O+^{5}H+n$) is shown by the full line.

In order to estimate the contribution from the main contaminants in the target, the reactions $^{12}C(^{11}B, ^{14}O)^{9}Li$ and $^{16}O(^{11}B, ^{14}O)\ ^{13}B$ have been measured. These measurements have shown that the contribution from both of the above-mentioned reactions to the ^{14}O spectrum does not exceed 5% of the peak height. In order to estimate the yield under the observed bump the phase space contribution has been subtracted from the experimental data. The resulting value of the cross section under the peak is $d\sigma/d\Omega = 16$ nb/sr. Such an evaluation is of course affected by some uncertainty. A 50% error of this estimate is quite possible. The peak has been attributed to the level of particle unstable ^{6}H lying 2.6 ± 0.5 MeV above the $^{2}H+n+n+n$ mass and having a width of 1.3 ± 0.5 MeV. This value agrees well with that found in [13]). The difference in cross sections can be explained as due to the use of the 3p transfer reaction in our experiment instead of the 2p-n reaction studied in ref. [13]).

4. Conclusions

In measuring the energy spectra of $^{14,15,16}O$ in one reaction, information has been obtained about the unbound $^{4,5,6}H$ systems. Using the oxygen nuclei whose first excited states lie at least 5 MeV higher than their ground states we were able to explore the relatively wide energy region in which the peaks corresponding to the ground state formation of the unstable products were expected to appear.

In the present experiment unbound levels assigned to the ground states of the ^{4}H and ^{6}H systems have been found at 3.5 ± 0.5 and 2.6 ± 0.5 MeV, respectively. The widths of these levels indicate lifetimes of the order of few units of 10^{-22} s. The cross section for populating the ^{4}H level is higher than that for the ^{6}H level. No sharp states have been observed in the ^{5}H system.

The exit channels leading to the formation of ^{4}H, ^{5}H and ^{6}H (and whose Q-values are 1.7, -13.9 and -27.2 MeV, respectively) are characterized by different transfers, such as 3p2n, 3p1n, 3p as well as $p\alpha$, ^{3}He-p, etc. Presently it is difficult to estimate which of these processes dominate in each case and their further study may give valuable spectroscopic information.

Finally one can draw the following conclusions:

(1) The ^{6}H system is almost 1 MeV more bound than the ^{4}H system. This binding may result from the additional pair of neutrons. A similar situation is observed in the unbound ^{7}He-^{5}He as well as in the bound ^{8}He-^{6}He pairs.

(2) The pairing between the two neutrons in the ^{5}H system plays an important role. Though the spectrum of ^{15}O shows no evidence for a sharp unbound state in the ^{5}H system, there is a phase space contribution from the $^{14}O+^{5}H+n$ exit channel indicating a strong final state interaction with a rather large width ($\Gamma \sim 10$ MeV).

As a result of our investigations we can make up relatively simple systematics of neutron-rich hydrogen isotopes. The final state interaction in the ^{4}H and ^{6}H system between $^{3}H+n$ and $^{5}H+n$ has a narrow width ($\Gamma \leqslant 2$ MeV) and produces relatively

pronounced peaks above the phase-space distribution. At the same time the final state interaction in the ^{5}H system between ^{3}H and a pair of neutrons has a much larger width.

In conclusion the authors would like to express their gratitude to Academician G.N. Flerov for his stimulating support of the present investigations. Thanks are also due to Prof. A.A. Ogloblin and Dr. B.G. Novatskii for fruitful discussions.

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