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SEARCH FOR THE TRI- AND TETRANEUTRON IN REACTIONS INDUCED BY ^{11}B AND ^{9}Be IONS ON ^{7}Li AND ^{9}Be

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Introduction

The study of few-nucleon systems may serve as an important tool to test different nuclear models as well as the nuclear potentials they use. From this point of view a special role is played by the nuclei close to the limit of stability for which the choice of the potential parameters becomes critical. It is known that in the light-element region one can find neutron-rich nuclei whose binding energy is close to zero while for medium and heavy elements their neutron-rich isotopes have (neutron) binding energies that are still far from zero. This fact may be explained as follows: most of the mass calculations include the symmetry energy term which is proportional to $(N-Z)^2$; with increasing N/Z ratio this term tends to diminish the neutron binding energy so that at a given N/Z value the neutron becomes unbound. For light elements this condition is met for N/Z= =3.5-4. No such values have been observed yet in the medium and heavy element regions. However, it should be noted that any such calculation is based on extrapolations that start in the region of N/Z corresponding to the β stability valley or close to it. Consequently, they may lead to results that are different from reality. One also cannot exclude beforehand situations in which the neutron stability line does not exist or a second region of stability appears for anomalously large values of N/Z. In this respect the system of two neutrons (the dineutron) may serve as a qualitative example: the resonance in this system appears at an excitation energy of 70 keV; a little dipping of the potential well would make this system stable. The addition of neutrons has this effect. The question of the stability of multineutron nuclei has been considered by Zeldovich and Goldansky /1/. They predicted the existence of stable ^{8}He that subsequently was observed experimentally /2/. Their work has stimulated the search for stable neutron-rich nuclei and, in particular, for pure neutron nuclei. According to the microscopic calculations of Baz /3/, slight changes in the nucleon-nucleon potential that do not affect the phase analysis of nucleon-nucleon scattering may lead to a stabilization of neutronic nuclei. These calculations indicate that if the tetraneutron (^{4}n) is stable, then there is a high probability that other, heavier neutron systems may also be stable and, to limit, big "neutron drops" may exist. Moreover, the non-existence of a stable tetraneutron does not exclude the existence of heavier multineutrons. Calculations of ^{4}n binding energy using the variational method /4/, the resonating group method /5/ and the method of hyperspheric functions /6/ have shown that this system has no stable states. A negative result was obtained in the resonant state calculations of the ^{4}n system using the Hilbert-Schmidt method /7/.

On the other hand, the calculations done by Komarov et al /8/ indicate the possible existence of the bound tetraneutron. As one can see, the theoretical predictions concerning the tetraneutron stability are not univocal. Many experimental studies were aimed at recording stable or resonant states of multineutron systems. All these experiments can be divided into two types: direct registration or registration of the multineutron partners in the exit channel. In the first case the multineutrons were detected either using the time-of-flight technique or applying an activation method with the subsequent radiochemical separation of decay products coming from nuclei that absorbed the multineutron. Most experiments have given negative results. However, the authors of /9,10/ using an activation method claim to have observed a stable multineutron. It is noteworthy that such experiments need extremely high purities of target material and a detailed analysis of all possible background sources. Therefore, in our opinion, the results of the experiments of the second type may be considered less ambiguous. Moreover, registration of the partner energy spectrum permits also the observation of unbound (resonant) states of the multineutron system as well as their mass measurements. One experiment of this kind is described in /11/ where the double pion charge exchange reaction $\pi^- + {}^4\text{He} \rightarrow \pi^+ + 4n$ was studied. By analyzing the π^+ energy spectrum the authors come to the conclusion that in the given case the 4n system may be considered as consisting of two pairs of neutrons, in each pair the two neutrons interacting in the final state. Their result differs from that obtained earlier by Stetz et al./12/ who studied the same reaction under other conditions.

Heavy ion reactions have also been used in an attempt to produce the tetraneutron /13,14/ but with negative results. On the other hand, the use of intense heavy ion beams proved to be efficient in studying the ^{4}H, ^{5}H and ^{6}H systems /15,16/ and this encouraged us to perform the present work.

Experimental

The aim of the present work was to search for the stable or quasistationary states of the ^3n and ^4n systems. For this purpose, binary heavy ion reactions were used. These reactions give the possibility of establishing some characteristics of one product by measuring the energy spectra of its partner in the exit channel. This way one can establish its stability, measure its mass and, if the product is unstable but still manifesting itself as a resonant state, define the parameters of this resonance. For this inclusive type of measurements we were able to attain a level of sensitivity of 1 nb/sr. Obviously, along with bound/unbound (ground or excited) states of the searched product states of its partner also show up in the energy spectrum of this partner. This is a complicating factor in the data analysis. From this point of view, nuclei like ^{14}O, ^{15}O, and ^{12}N are very convenient since for the first two nuclei excited levels are more than 5 MeV above the g.s. while the third one does not have nucleon stable excited states at all. Table 1 presents the reactions studied in the present paper and their main characteristics.

Table 1

Reaction	Beam energy (E_{lab}/E_{CM})MeV	Exit channel products	Q values, MeV	Measured energy interval, MeV	Lab.angle of measurement
$^{11}B + {}^7Li$	88/34.22	$^{11}O+{}^4n$	-16.716	48-71	8° ± 0.5°
		$^{15}O+{}^3n$	-3.492	52-76	
$^9Be + {}^7Li$	107/46.81	$^{12}N+{}^4n$	-23.366	58-85	5° ± 0.5°
$^9Be + {}^9Be$	107/53.5	$^{14}O+{}^4n$	-17.596	72-90	5° ± 0.5°

The Q values were calculated for zero binding energy in the ^3n and ^4n systems. The experiments have been done by using heavy ion beams from the U-300 cyclotron at Dubna. The bombarding energy was periodically controlled by measuring the elastic scattering on a thin silver target. During long runs changes in the beam energy were by less than 250 keV and these shifts were taken into account in data reduction. The Li targets were prepared by vacuum evaporation of 99.2% enriched ^7Li on a thin (20 μg/cm^2) organic backing. Their thickness was 350 μg/cm^2. The Be targets were also made by vacuum evaporation but on a copper backing that subsequently was etched off with nitric acid. Their thicknesses were 230 μg/cm^2. The typical beam intensity on target was 0.5 μA electric and was limited mainly by the appearance of pulse pile up in the detector. Reaction products, after passing through a stepped pole magnetic spectrograph MSP-144, were recorded by a position sensitive (ΔE,E) ionization chamber placed in the focal plane. The spectrograph was placed at 5° and 8° with respect to the beam; its energy resolution was $\Delta E/E=5.10^{-4}$ and the entrance slits were opened to determine an entrance angle of 1° in the reaction plane which corresponds to a 0.6 msr solid angle. This value was chosen in order to reach an optimum between the luminosity and resolution of the ΔE and E sections of the ionization chamber. Indeed, the ΔE and E parts of this chamber are placed, respectively, before and after the focal plane and trajectories that cross at the focal plane have different lengths in these sections though they correspond to the same energy. Thus, the observed resolutions of the ΔE and E sections of the ionization chamber are somewhat spoiled so that the mentioned optimum has to be attained in order to have both a reasonable solid angle and good isotope separation ensured. The resolution in position detection was 0.7 mm. A detailed description of the experimental set-up is given in /17/. The measurement of ΔE, E and x parameters permits a clean isotope separation and determination of energy with an accuracy of ~300 keV. For each event these three parameters were recorded on tape and subsequently processed off-line. In fig. 1, the ΔE-E matrix for the ^{9}Be + ^{7}Li reaction is shown. One can see that different elements are clearly separated. A special program allows then to encircle on the display the events corresponding to a given element and then build the (x,E) or (x,ΔE) matrices for these events. As an example, fig. 2 shows the (x,E) matrix for the nitrogen isotopes obtained from the corresponding events in fig. 1. These matrices served to identify and then build the energy spectrum of the given product by making use of the relation $E = k(Bx)^2Z^2/A$, where B is the spectrograph rigidity, Z and A are the atomic charge and mass of the product, x is the point of its incidence on the focal plane and k is the spectrograph constant.

Experimental results and discussion

The energy spectra of ^{14}O, ^{15}O and ^{12}N from the reactions induced by ^{11}B and ^{9}Be ions on ^{7}Li targets are shown in figs. 3-6. The full lines represent phase space calculations. In the general case, the phase space curve is obtained as the weighted sum of contributions

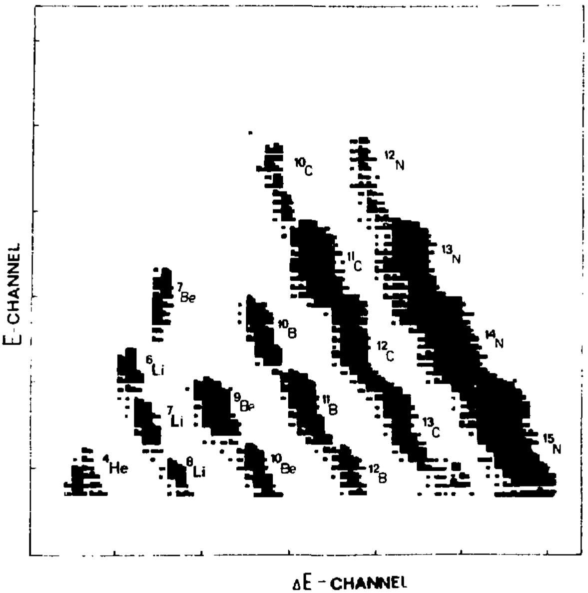

Fig.1. The (ΔE-E) matrix for the ^{9}Be + ^{7}Li reaction.

coming from different exit channels that contain the observed product. These channels differ in the number of constituents and their excitation energies. The weights of their contributions remain as fit parameters. Any deviation of the data from the phase space curve indicates that a group of particles is emitted together in the exit channel and this fact is not accounted for in the given calculation. These deviations show up like Breit-Wigner resonances and their widths are connected with the lifetime of the particle group.

A. The ^{7}Li(^{11}B,^{15}O)^{3}n reaction

The ^{15}O energy spectrum for this reaction is shown in fig. 3. The upper scale indicates the excitation energy of the system of three neutrons and starts at zero binding energy (see the arrow). The full curve represents a phase space calculation that takes into account the following two exit channels: ^{15}O + n + n + n and ^{15}O* (E_x=5.183 MeV) + n + n + n. Their relative weights are 0.34 and 0.64

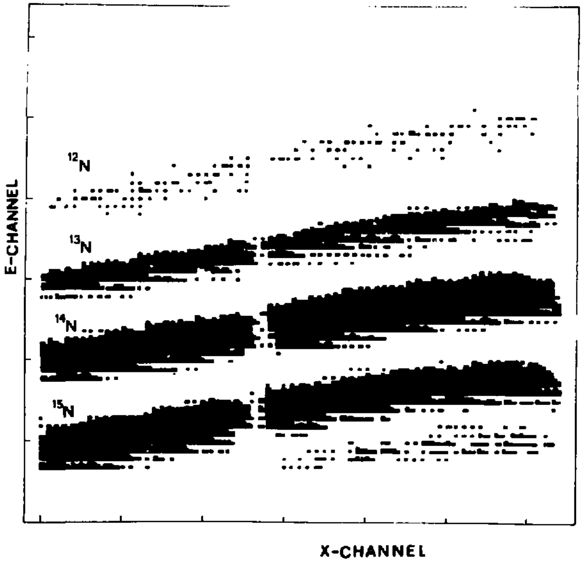

Fig.2. The (x-E) matrix for nitrogen isotopes obtained from the corresponding events in fig.1. The gaps in the middle come from the shadowing effect of some detector part.

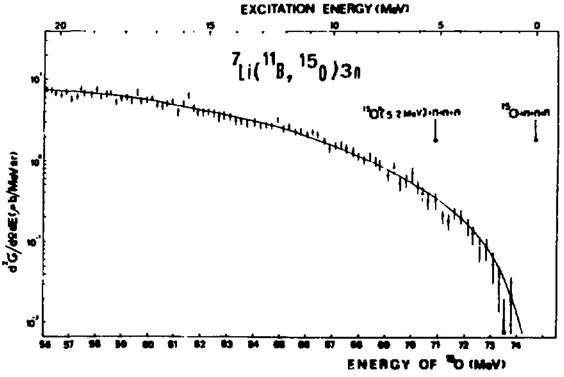

Fig.3. The ^{15}O energy spectrum for the $^{7}Li(^{11}B,^{15}O)^{3}n$ reaction. The full curve is a phase space calculation that takes into account the following exit channels: $^{15}O+n+n+n$ and $^{15}O*$ (E_x = 5.183 MeV) +n+n+n.

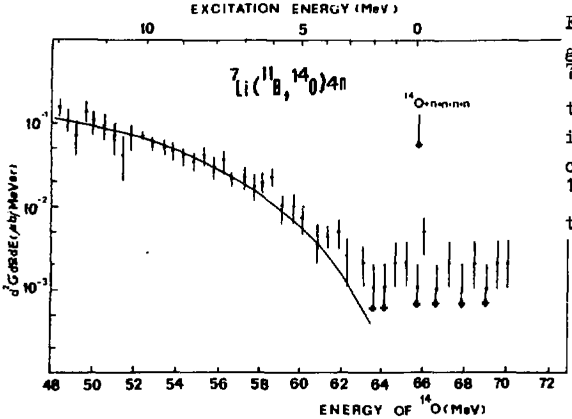

Fig.4. The ^{14}O energy spectrum for the $^7Li(^{11}B,^{14}O)^4n$ reaction. The full line is a phase space calculation for the $^{14}O+n+n+n+n$ decay in the exit channel.

respectively, as determined by fitting. Inclusion of contributions from other exit channels, in particular the one in which two of the three neutrons are grouped with zero binding energy, does not bring any improvement to the fit. As one can see, the data are rather well reproduced and no significant deviations can be observed. This fact indicates the absence of any quasistationary state in the ^3n system populated in the present reaction. The lack of events at the right of the arrow leads to the upper limit for the formation cross section of a stable ^3n configuration set at 10 nb/sr in the above reaction.

B. The $^7Li(^{11}B,^{14}O)^4n$ reaction

Fig. 4 shows the ^{14}O energy spectrum measured in this reaction. The full line is a phase space calculation for the five-body break up in the exit channel: $^{14}O + n + n + n + n$ that describes the data satisfactorily. The inclusion of contributions from other exit channels does not improve the fit so that they were not considered. The small bumps over the phase space curve at ^{14}O energies of 58.5 and 61.5 MeV may be explained as being due to reactions on carbon impurities in the target: $^{12}C(^{11}B,^{14}O)^9Li^*$ (E_x=2.7 MeV and 0 respectively). These reactions were measured for a thick carbon target during a short run; comparing the yields in the two cases one comes to the conclusion that a level of 3-5 $\mu g/cm^2$ carbon impurities in the Li target may explain the observed bumps. In the neighborhood of zero binding energy in the ^4n system ($E_{^{14}O}$ = 65.8 MeV) 6 events appear in two channels while the background observed in the adjacent channels is at a 0.5 events/channel level. To the right of the arrow that indicates zero binding energy a number of events due to pulse pile-up in the ionization chamber appear; they give a uniform background that limits the sensitivity of the present experiment to a 1 nb/MeV.sr level. It should be noted that at a close energy of ^{14}O(65 MeV) a peak may appear from the ^{16}O(^{11}B,^{14}O)^{13}B reaction on oxygen impurities in the target though the energy resolution allows one to separate two peaks at a distance of 0.8 MeV.

C. The ^{9}Be(^{9}Be,^{14}O)^{4}n reaction

In the ^{14}O energy spectrum measured for this reaction few events show up in the 85-89 MeV range (see fig. 5), which would correspond to a bound ^{4}n system and their cross section is 4 nb/sr. However, the feeble statistics does not allow any definite conclusion about the production of a stable tetraneutron in the given reaction. What is more, a detailed analysis of possible contributions from reactions on impurities has not yet been performed. In this respect it should be mentioned that Be targets, because of the technology of their preparation may contain some heavy impurities such as Cu. The ^{14}O spectrum for E$<$83 MeV (that corresponds to zero binding energy in the ^{4}n system) is well described by the phase space calculation for the five-body breakup in the exit channel (^{14}O + n + n + n + n). Positions of some peaks coming from reactions on light impurities in target are indicated in the figure by arrows.

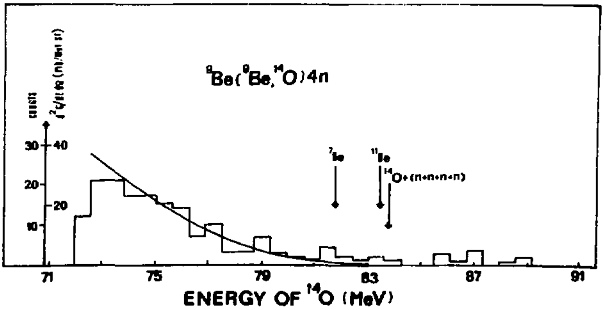

Fig.5. The ^{14}O energy spectrum for the ^{9}Be(^{9}Be,^{14}O)^{4}n reaction. The full line is a phase space calculation for the five-body decay in the exit channel. The arrows indicate the position of peaks from reactions on ^{12}C and ^{16}O impurities in the target.

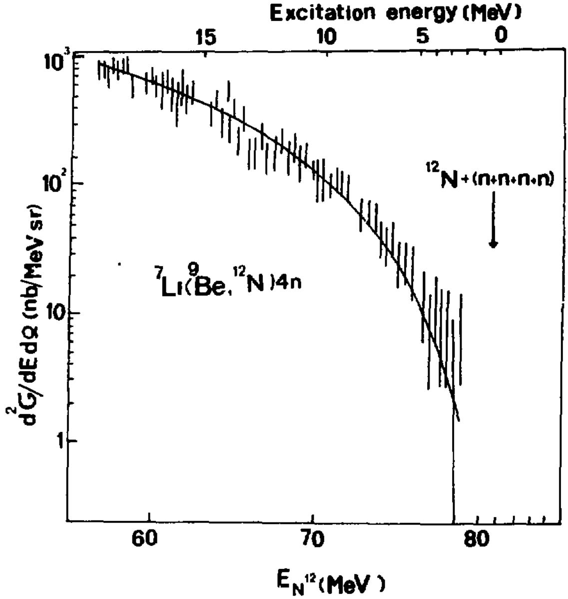

Fig.6. The ^{12}N energy spectrum for the ^{7}Li(^{9}Be,^{12}N)^{4}n reaction. The full line is a phase space calculation for the five-body decay in the exit channel.

D. The ^{7}Li(^{9}Be,^{12}N)^{4}n reaction

This reaction was chosen in order to exclude contributions from reactions on the target impurities which prevented us from drawing a positive conclusion in the case B. Indeed, peaks from the ^{12}C(^{9}Be,^{12}N)^{9}Li and ^{16}O(^{9}Be,^{12}N)^{13}B reactions lie 6.6 and 2.6 MeV to the left of the ^{12}N energy corresponding to zero binding energy in the ^{4}n system. Moreover, the reaction Q values (-30.95 and -27.3 MeV respectively) are unfavourable as compared with the studied reaction (-23.37 MeV) and this fact may lead to a smaller production cross section. Fig. 6 shows the ^{12}N energy spectrum. The full line is a phase space calculation for the five-body breakup in the exit channel: ^{12}N + n + n + n + n. Other exit channels need not be included as they do not improve the fit to the data. No significant deviations from the phase space curve can be observed and this fact may indicate the nonexistence of a bound or quasistationary state in the ^{4}n system. The limit of experimental sensitivity attained in the present measurement is 1 nb/MeV.sr.

The first reaction studied that leads to the formation of the 3n system is the 3p1n transfer from the target to the projectile. This reaction is characterized by rather favorable (-3.5 MeV) Q value (as compared with the rest of the reactions studied) and by an available energy (E_{CM}+Q) of 30.7 MeV. Taking for orientation the cross section values at forward angles for different transfer reactions compiled in /18/ it seams that the reaction proceeds in two steps: the first one is a 1p1n transfer to form ^{13}C with a closed proton subshell and the second is a 2p transfer resulting in ^{15}O with a closed proton shell. In the first phase the proton transferred does not change the subshell while the neutron does. In the second one, the two paired protons rise to the p 1/2 subshell.

No deviations from the phase space curve were observed in the range of excitation energies of the ^3n system from 1 to 4 MeV where some papers /19.20/ mention possible quasistationary ^3n states. The second reaction studied, $^7Li(^{11}B,^{14}O)^4n$, represents a 3p transfer with Q=-16.7 MeV and E_{CM}+Q=17.5 MeV. It probably proceeds in two stages: first, the transfer of a p3/2 proton from ^7Li to fill this subshell forming ^{12}C and, second, the transfer of two paired s protons to fill the p 1/2 subshell and complete the p proton shell in ^{14}O. It should be noted that an additional short run at the U-400 cyclotron with 17 MeV/A ions and with a spectrograph placed at 10° has given a yield in the phase space region of 9 to 12 MeV excitation energy (in the ^4n system), which is 6 times higher than the corresponding yield in the same excitation energy region, as shown in fig. 4. Though this increased phase space yield does not permit any conclusion about the population of states in the ^4n system it nevertheless claims a more detailed study. We intend to pursue such a study in the near future. As for the problem of target impurities, some considerations are in order. The reaction of C impurities has an unfavourable Q value of -24.3 MeV but a higher available energy, E_{CM}+Q=21.6 MeV. This can be viewed upon as a 3p transfer from the target to the projectile but also as a kick-off of the target nucleus after a 2p capture from the projectile; in the latter case it will have a much higher cross section as the reaction proceeds to the filling of the p shell in ^{14}O. Then, even small amounts of C impurities will give peaks and the problem of background subtraction becomes very important. For safety, the peak regions should be excluded, as in the above analysis. The $^7Li(^9Be,^{12}N)^4n$ reaction, as compared with the previous one, has an unfavourable Q=-23.4 MeV but a higher available energy, E_{CM}+Q=23.4 MeV. This is again a 3p transfer from target to projectile, but it does not proceed through closed subshells or, if it does, then it should break pairs and change orbits. Nevertheless, the phase space yield is almost the same as in the previous reaction. An explanation may be the increased available energy in the present case as well as the smaller measurement angle.

The $^{9}Be(^{9}Be,{}^{14}O)^{4}n$ reaction with Q=-17.6 MeV has the highest available energy $E_{CM}+Q=35.9$ MeV. On the other hand it represents a complicated 4p1n transfer. A possible path is the following: first a 1p transfer to form ^{10}B, then a 1p1n transfer to produce ^{12}C with closed proton and neutron subshells and eventually a 2p transfer to close the p proton shell in ^{14}O. Despite its complexity, the phase space yields of the previous two reactions do not differ significantly. From the analysis of the last three reactions one may conclude that, as far as the phase space yield is concerned, the dominant factor appears to be the available energy and to a less extent the reaction complexity and the Q value. The phase space calculations from all three reactions correspond to a five-body decay in the exit channel. No grouping of the four neutrons has to be considered in contrast to the result of /11/, where a strong final state interaction was introduced within each of the two pairs of neutrons in order to satisfy the experimental data. **The range of excitation energies in the ^{4}n system measured in these three reactions does not extend as far as 18 MeV where, using the analogous relation with the T=2** state in ^{4}He, Bevelacqua /19/ predicts a possible quasistationary ^{4}n state. In fact, with the present experimental technique the observation of an anomaly at an excitation energy at which the phase space yield is rather high would imply very long measurements unless the population probability for the given state is at least as high as the phase space production probability.

The main results of the present study may be summarized as follows:

- Using the technique of recording the energy spectra of the stable partner of the searched (stable or unstable) product, an experimental sensitivity of 1 nb/MeV.sr was obtained.
- No evidence for stable ^{3}n production in the reaction $^{11}B(^{7}Li,{}^{16}O)^{3}n$ down to a level a 10 nb/sr has been found. From the phase space analysis, no evidence for quasistationary states has been obtained either.
- The study of three different reactions for producing a bound ^{4}n system has set only the upper limits for the cross sections of its formation. In two cases this limit equals the experimental sensitivity of 1 nb/sr. The phase space analysis has given no positive results concerning the existence of quasistationary (unbound) states in the ^{4}n system.
- No evidence for grouping of neutrons in the exit channel has been obtained in the reactions studied. However, the obtained results

do not allow one to draw any conclusion about the non-existence of stable or quasistationary ^3n and ^4n states. Indeed population of such states may depend strongly on the reaction mechanism, i.e. on the choice of the reaction, its Q value, bombarding energy and angle of measurement. It is also possible that the attained level of sensitivity may be insufficient. In order to shed more light onto this problem, experiments with somewhat improved sensitivity and at various beam energies are planned in the future at the U-400 cyclotron at Dubna.

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Поиск ^{3}n и ^{4}n в реакциях ускоренных ионов
^{11}B и ^{9}Be с ядрами ^{7}Li и ^{9}Be

В двухчастичных реакциях с тяжелыми ионами ^{11}B(88 МэВ) + ^{7}Li, ^{9}Be (107 МэВ) + ^{9}Be, ^{9}Be + ^{7}Li измерялись энергетические спектры ^{15}O, ^{14}O, ^{12}N для получения информации о партнерах в выходном канале реакции - системах ^{3}n, ^{4}n. Для проведения исследований создана установка на базе магнитного спектрографа МСП-144, позволяющая измерять энергетические спектры с точностью 280 кэВ и пределом по сечению 1 нб/ср. Энергетические спектры хорошо описываются кривыми фазового пространства многочастичного развала в выходном канале реакции. Не обнаружено ядерностабильных или квазистационарных состояний в системах ^{3}n, ^{4}n, только в спектре ^{14}O из реакции $^{7}Li(^{11}B,^{14}O)$ содержится указание на возможное образование квазистационарного ^{4}n, однако малая статистика не позволяет сделать однозначных заключений. Предел по сечению образования ^{4}n составил величину 1 нб/ср.

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Search for the Tri- and Tetraneutron in Reactions
Induced by ^{11}B and ^{9}Be Ions on ^{7}Li and ^{9}Be

The energy spectra of ^{15}O, ^{14}O and ^{12}N nuclei have been measured in ^{11}B(88 MeV) + ^{7}Li, ^{9}Be(107) + ^{9}Be, ^{9}Be + ^{7}Li reactions to obtain information about their partners in reaction exit channel ^{3}n and ^{4}n systems. The energy spectra are well described by many-body phase space curves. No indication about the existence of nuclear stable or quasibound states has been obtained. The small enhancement found in the spectra of ^{14}O from $^{7}Li(^{11}B,^{14}O)$ reaction is due to the poor statistics insufficient to make any definite conclusion about the existence of bound or unbound state ^{4}n at the cross section level of 1 nb/sr.

The investigation has been performed at the Laboratory of Nuclear Reaction, JINR.

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