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

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Abstract: In three different heavy ion reactions the energy spectra of the ^{14}O, ^{15}O and ^{12}N nuclei have been measured to obtain some information about their partners in the exit channel - the multineutron systems ^{4}n and ^{3}n. No evidence for the existence of any bound state in the multineutron systems has been obtained at the cross section level of 1 nb/MeV·sr achieved in the experiment. The phase-space analysis has given no positive results concerning the existence of quasistationary states in the ^{4}n and ^{3}n systems either.

E | NUCLEAR REACTIONS ^{7}Li(^{11}B, ^{14}O), E = 48-71 MeV; ^{7}Li(^{11}B, ^{15}O), E = 52-76 MeV; ^{7}Li(^{9}Be, ^{12}N), E = 58-85 MeV; ^{9}Be(^{9}Be, ^{14}O), E = 72-90 MeV; measured σ (E(^{14}O), σ(E(^{15}O), σ(E(^{12}N)); deduced ^{3}n, ^{4}n production σ upper limit. Phase space analysis.

1. Introduction

The study of few-nucleon systems may be an important tool to test different nuclear models as well as the nuclear potentials used. However, the characteristics of the ground states of nuclei consisting of three or four nucleons such as ^{3}H, ^{3}He and ^{4}He do not appear to be very sensitive to the form of the NN potential, as different modelless calculations have proved [1,2]. From this point of view it seems likely that the experimental investigation of both the lightest nuclei and the quasi-stable nuclear systems having an anomalous N/Z ratio and lying near the boundary of the nuclear stability may shed light on the problem since the extreme cases of a nucleon configuration should be more sensitive to the choice of the nuclear potential parameter.

The problem of the stability of light neutron-rich nuclei has been considered by Zeldovich and Goldansky [3]. They have indicated the role of an additional pair of neutrons in the nuclear binding energy and predicted the existence of stable ^{8}He that subsequently was observed experimentally [4]. Their work has stimulated the search for stable neutron-rich nuclei and, in particular, for pure neutron nuclei. 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 and a little dipping of the potential well would make this system stable. The addition of a pair of neutrons might have this effect. According to the microscopic calculations of Baz [5]), 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 a high probability for the existence of heavier stable neutron systems and even big "neutron drops" provided that the tetraneutron (^{4}n) is stable. Moreover, the nonexistence of a stable tetraneutron does not exclude the existence of heavier multineutrons. The calculations done by Komarov *et al.* [6]) indicate the possible existence of the bound tetraneutron as well.

On the other hand, calculations of ^{4}n binding energy using the variational method [7]), the resonating group method [8]) and the method of hyperspheric functions [9]) have shown that this system has no stable states. No positive result was obtained either in the resonant state calculations of the ^{4}n systems using the Hilbert-Schmidt method [10]). As one can see, the theoretical predictions concerning the tetraneutron stability are not univocal.

Many experimental studies were aimed at searching for stable or resonant states of multineutron systems. A review of the situation in this region up to 1973 is given in [11]). As to the methods used, the experiments can be divided into two groups.

The first one includes the experiments in which the multi-neutrons were detected 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 [12–15]). Most experiments have given negative results. However, the authors [14,15]) using the 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.

The second group concerns the measurements in which the multineutron partner in the two-body reaction exit channel is detected. In our opinion, the results of the experiments of the latter type may be considered less ambiguous since the 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 ref. [16]) where the double pion charge exchange reaction ^{4}He $(\pi^-, \pi^+)^4$n 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. Within each pair the final state interaction takes place. This conclusion, differs from the result obtained earlier by Stetz *et al.* [17]) who studied the same reaction under other conditions.

In some cases the two-body heavy ion reactions could become more effective than reactions induced by light ions or pions, as it has been shown in the investigation of quasistationary states of the ^{4}H and ^{6}H systems [18,19]). These reactions have already been used in an attempt to produce the tetraneutron [20,24]). The experiments were performed with a sensitivity of about 30 nb/MeV·sr and this could be the reason why they have not given positive results.

The aim of the present work was to search for stable or quasistationary states in the ^{3}n and ^{4}n systems by exploiting more sensitive experimental apparatus and 12 MeV · A heavy ion beams.

2. Method and experimental set-up

The two-body heavy ion reactions used in our experiment make it possible to determine some characteristics of the nucleus by measuring the energy spectra of its partner in the exit channel. In this way one can establish the stability of the nucleus, measure its mass and, if the nucleus is unstable or still manifesting itself as a resonance, define the resonant parameters of this state. Obviously, along with bound or unbound states (ground or excited) of the nucleus under study states of its partner also appear in the energy spectrum. This might bring serious complications to the data analysis. However, the use of ^{14}O and ^{15}O nuclei as partners makes the situation easier since their first excited states are more than 5 MeV above their ground states and the use of ^{12}N is even more favourable as it does not have nucleon stable excited states at all. Table 1 presents the reactions studied in the present paper and their main characteristics. The Q values were calculated for zero binding energy in the ^{3}n and ^{4}n systems.

TABLE 1
Characteristics of the reactions studied

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

The experiments have been done by using heavy ion beams from the U-300 cyclotron at Dubna. The beam was collimated by carbon slits and its intensity was about 0.5 μA electric on the target. During long runs the bombarding energy was periodically checked by elastic scattering of ions on a thin silver target. Changes in the incident beam energy were smaller than 250 keV and were taken into account in data analysis. The Li targets were prepared by vacuum evaporation of 99.2% enriched ^{7}Li 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}.

Reaction products emitted from the target entered a stepped-pole magnetic spectrograph MSP-144 placed at 5° or 8° with respect to the beam. Its entrance slits were opened to allow an angle of 1° in the reaction plane which corresponds to a 0.6 msr solid angle. A position-sensitive double ionization chamber filled with isobutane at a pressure of 50–400 Torr served as a focal plane detector. It measured three parameters (energy losses ΔE, residual energy E and position x) in order to identify the reaction product and determine its energy. The energy resolution of the spectrograph was $dE/E = 5 \cdot 10^{-4}$ and the resolution achieved in position detection was 0.7 mm. The energy resolution of the ΔE and E sections of the ionization chamber which has to be sufficient to ensure reliable isotope separation is influenced mainly by the dispersion of ion trajectory lengths in the corresponding section. By widening the entrance angle the dispersion is increased and the resolution is getting worse. Thus the definite value of the entrance angle was chosen to have both a reasonable solid angle and reliable isotope separation ensured. A detailed description of the experimental set-up is given in ref. [22]).

The measurement of ΔE, E and x parameters permits a clean isotope separation and energy determination 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 $(\Delta E, E)$ matrix for the ^{9}Be+^{7}Li reaction is shown. One can see that different elements are clearly separated. The data processing program used allows to encircle the events corresponding to a given element on the display and to build then the (x, E) and $(x, \Delta E)$ matrices for these events. As the next step these matrices enable

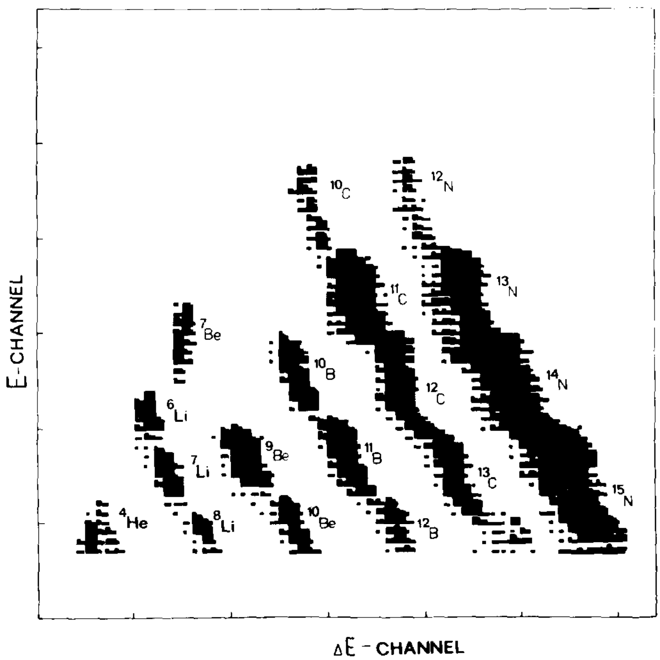

Fig. 1. The $(\Delta E, E)$ matrix for the ^{9}Be+^{7}Li reaction.

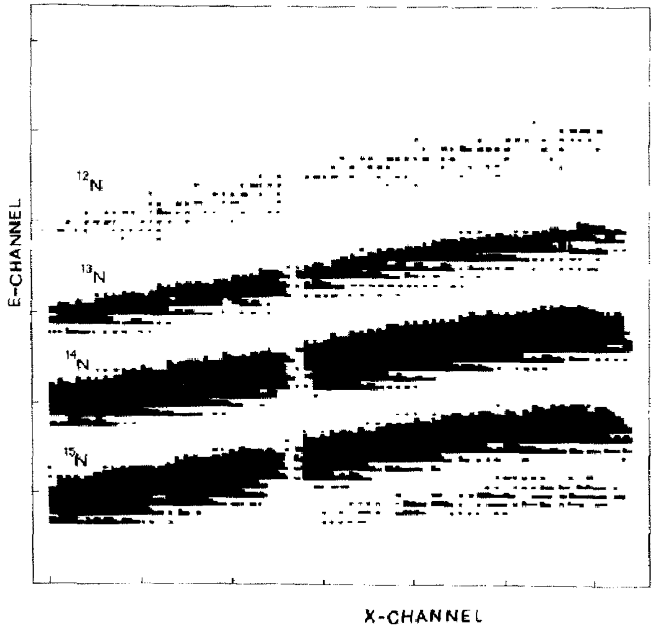

Fig. 2. The (x, E) matrix for nitrogen isotopes obtained from the corresponding events in fig. 1. The gaps in the middle come from the shadowing effect of central part of the detector.

us to separate unambiguously all isotopes of a given element. As an example, fig. 2 shows the (x, E) matrix obtained by transformation of events corresponding to the nitrogen isotopes of the $(\Delta E, E)$ matrix displayed in fig. 1. Finally, the energy spectrum of each isotope is built using the relation $E = k(Bx)^2 Z^2/A$, 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.

3. Experimental results

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 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.

3.1. THE $^7Li(^{11}B, ^{15}O)^3n$ REACTION

The ^{15}O energy spectrum for this reaction is shown in fig. 3. The upper scale indicates the excitation energy of the system consisting of three unbound neutrons. The full curve represents a phase-space calculation that takes into account the following two exit channels: $^{15}O+n+n+n$ and $^{15}O^*_{5.183\,MeV}+n+n+n$. Their relative weights are 0.36 and 0.64 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 on the right of the arrow leads to the upper limit for the formation cross section of a stable ^3n configuration being 10 nb/MeV · sr in this reaction.

3.2. THE $^7Li(^{11}B, ^{14}O)^4n$ REACTION

Fig. 4 shows the ^{14}O energy spectrum measured in this reaction. The full line represents a phase-space calculation for the five-body break-up $^{14}O+n+n+n+n$ in the exit channel that describes the data satisfactorily. The inclusion of contributions from other exit channels has given no significant improvement in describing the energy spectrum. The small bumps over the phase-space curve observed at ^{14}O energies of 58.5 and 61.5 MeV are due to a reaction on impurities in the target.

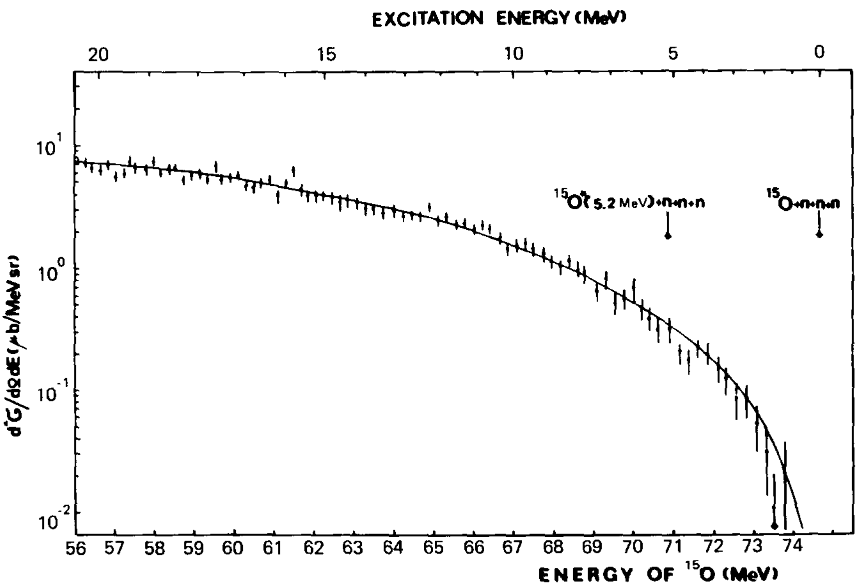

Fig. 3. The ^{15}O energy spectrum for the $^7Li(^{11}B, ^{15}O)^3n$ reaction. The full curve is a phase-space calculation that takes into account the following exit channels: $^{15}O+n+n+n$ and $^{15}O^*$ ($E_x = 5.183$ MeV)$+n+n+n$.

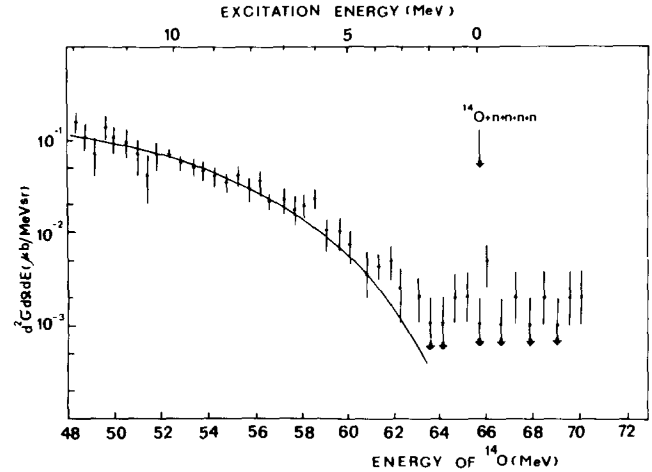

Fig. 4. The ^{14}O energy spectrum for the $^{7}Li(^{11}B, ^{14}O)^{4}n$ reaction. The full line is a phase-space calculation for the $^{14}O+n+n+n+n$ decay in the exit channel.

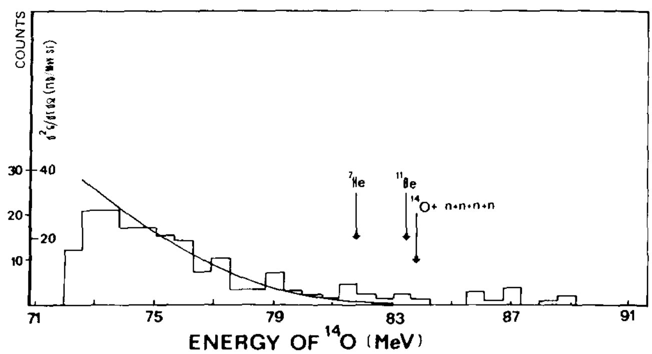

Fig. 5. The ^{14}O energy spectrum for the $^{9}Be(^{9}Be, ^{14}O)^{4}n$ reaction. The full line is a phase-space calculation for the five-body decay in the exit channel. The arrows indicate the position of peaks from reactions on ^{12}C and ^{16}O impurities in the target.

Their positions correspond to the first excited (2.7 MeV) and ground state of ^{9}Li as was confirmed by the measurement of the $(^{11}B, ^{14}O)$ reaction on carbon.

However, in the neighbourhood of zero binding energy in the ^{4}n system which corresponds to the ^{14}O energy being equal to 65.8 MeV 6 events appear in two channels while the mean level of the background observed in nearby channels is about 0.5 events/channel. The background is mainly due to the pulse pile-up in the ionization chamber. Despite the long measuring time as well as the very high sensitivity (1 nb/MeV · sr) achieved in the present experiment the statistical significance of 6 events is rather low to draw any definite conclusion about the production of a stable tetraneutron in the given reaction. Moreover, it should be noted that in the vicinity of 65.8 MeV a peak may appear from the reaction on oxygen impurities in the target at 65 MeV.

3.3. THE ^{7}Li(^{9}Be, ^{12}N)^{4}n REACTION

This reaction was chosen in order to exclude the possibility that contributions from reactions on the target impurities could appear in the region of interest as it has happened in the previous case. 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. Fig. 6 shows the ^{12}N energy spectrum as well as a phase space (full line) calculated for the five-body break-up in the exit channel ^{12}N+n+n+n+n. Other exit channels 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. In this reaction the experimental sensitivity limit achieved is about 1 nb/MeV · sr.

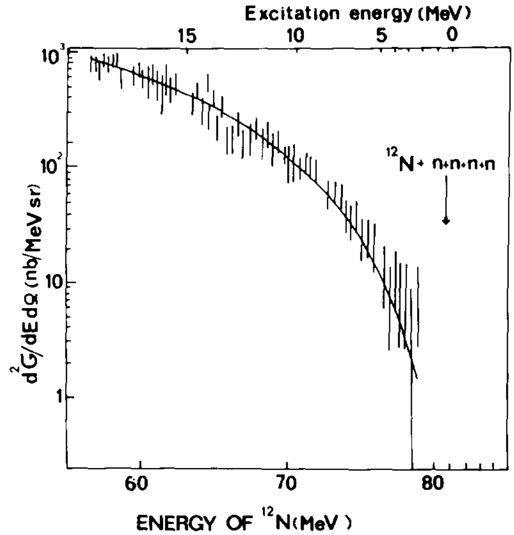

Fig. 6. The ^{12}N energy spectrum for the ^{7}Li(^{9}Be, ^{12}N)^{4}n reaction. The full line is a phase-space calculation for the five-body decay in the exit channel.

3.4. THE ^{9}Be(^{9}Be, ^{14}O)^{4}n REACTION

In the ^{14}O energy spectrum measured in this reaction (fig. 5) few events show up in the 85-89 MeV range, which might correspond to a bound ^{4}n system with cross section of 4 nb/sr. However, the Be targets, due to the preparation technology may contain some traces of copper and it is likely that reactions on these impurities are responsible for the observed events. In addition, poor statistics do not allow any definite conclusion about the production of a stable tetraneutron in the given reaction. The ^{14}O spectrum for energies below that corresponding to zero binding energy in the ^{4}n system (83 MeV) is well described by the phase space calculation for the five-body break-up ^{14}O+n+n+n+n in the exit channel. The positions of some peaks coming from reactions on light impurities in the target are indicated in the figure by arrows.

In all three reactions leading to the formation of the ^{4}n system no grouping of the four neutrons has to be considered in contrast to the result of ref. [16]), where a strong final state interaction was introduced within each of the two pairs of neutrons in order to satisfy the experimental data. In our experiment the range of excitation energies in the ^{4}n system does not reach 18 MeV where, using the analogous relation with the $T=2$ state in ^{4}He, Bevelacqua [23]) predicts a possible quasistationary ^{4}n state. Actually, 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 time-consuming measurements unless the population probability for the given state is at least as high as the phase-space production probability.

4. Discussion

The study of four different reactions which might lead to the formation of the ^{3}n and ^{4}n systems has set only upper limits for their bound states population cross sections. The phase space analysis has given no positive results concerning the existence of quasistationary states in both systems either. The population of such states may depend strongly on the choice of the reaction used, i.e. on its Q-value, the reaction mechanism, bombarding energy, the angle of the measurement as well as on the structural particularities of the partners. The latter even dominates since the experimental method we use needs the formation of both the partner and the system under study. On the other hand, it is evident that for the observation of quasistationary states it is desirable to have a phase space contribution as small as possible. Therefore, it seems worthwhile to look more closely at the phase space production in the reactions studied.

Starting with the ^{7}Li(^{11}B, ^{14}O)^{4}n reaction the 3p transfer from the target to the projectile is likely to take place. Then the unpaired $p_{3/2}$ proton may not change its orbit during the transfer while the two other $s_{1/2}$ protons will be transferred to the $p_{1/2}$ orbit to complete the p-shell in the ^{14}O nucleus. In this reaction the available energy ($E_{c.m.}+Q$) has reached the value of 17.5 MeV and the overall phase-space contribution of the ^{14}O g.s. $d\sigma/d\Omega$ is equal to 13 ± 3 μb/sr. This value has been obtained by integrating the experimental phase space distribution over the region where only the ^{14}O g.s. contributes (0–5 MeV in excitation energy) and by multiplying it by the weight of this portion in the whole phase space of ^{14}O g.s. production.

The ^{7}Li(^{9}Be, ^{12}N)^{4}n reaction having a slightly higher available energy, $(E_{c.m.}+Q) = 23.4$ MeV, can be again a 3p transfer from target to projectile with the following transitions: $(p_{3/2}\rightarrow p_{3/2})$, $(s_{1/2}\rightarrow p_{3/2})$, $(s_{1/2}\rightarrow p_{1/2})$. Since the ^{12}N phase space yield 14 ± 3 μb/sr is almost the same as in the previous reaction, it is likely that the increase in available energy in the present case is compensated by a more complicated transfer.

Meanwhile, the ^{9}Be(^{9}Be, ^{14}O)^{4}n reaction having the highest available energy, $(E_{c.m.}+Q)=35.9$ MeV, represents a rather complicated 4p1n transfer. Despite its complexity, its phase-space yield is significantly higher and reaches a value of 50 ± 10 μb/sr. Thus from the analysis of these three reactions one may conclude that the dominant factor for the phase-space production appears to be the available energy and only to a small extent the reaction complexity. This conclusion has been confirmed by an additional measurement of the ^{7}Li(^{11}B, ^{14}O) reaction at a higher beam energy (190 MeV). The measured phase-space yield was 6 times higher than that obtained with the 88 MeV beam despite the greater incident angle (10°) used in this measurement which should result in a decreasing yield. The phase space yield of 107 ± 10 μb/sr obtained in the (^{11}B, ^{15}O) reaction seems to suit well to this frame as well. The rather high available energy (30.7 MeV) of this reaction dominates over the influence of the complicated four-nucleon transfer. It should be noted that only this reaction needed the inclusion of an excited state of ^{15}O in the phase space fitting. The other three reactions produced phase space distributions that were satisfactorily described by only the ground state contribution of the measured product in this way producing additional evidence that pick-up reactions preferentially populate excited states of the residual nucleus. While having a low phase-space contribution is a necessary condition for observing quasistationary states it is not yet sufficient. Indeed, in order to populate with significant probability stable or quasistationary states in the studied systems some kinematical conditions have to be met also. In order to check how the kinematical matching was fulfilled in the above reactions, the optimum Q-values were calculated according to the Wilczynski model [24]). We can adopt this model because the energies are well above the Coulomb barrier and rather substantial nuclear rearrangements take place as related to the components size so that the effect of the changes in nuclear potential on the reaction kinematics should be taken into account. Results of the calculations indicate that reactions (^{11}B, ^{14}O) and (^{9}Be, ^{12}N) have the highest probability for populating quasistationary states in the interval from 0 to 10 MeV excitation energy while other two have favourable probabilities for population of states at much higher excitation energies. No dissipation energy was introduced in the calculations; considering the fact that measurements were performed at angles in the c.m. system exceeding the grazing angle one may expect a further increase in the obtained Q-values. The mentioned calculations show that the four reactions studied span a wide range of energies in which states in the studied systems could have appeared; however, within the gathered statistics, no such states were observed.

One may summarize the results of the present study as follows:

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/MeV · 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/MeV · 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.

- The phase-space yield corresponding to the formation of the partner nucleus in its ground state depends mainly on the available energy ($E_{c.m.}+Q$) present in the reaction and only to a much smaller extent on the reaction complexity.

However, the obtained results do not allow one to draw any conclusion about the nonexistence of stable or quasistationary ^{3}n and ^{4}n states. Indeed the 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 achieved 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 to be performed in the future at the U-400 cyclotron at Dubna.

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