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STUDY OF He ISOTOPES WITH $A \geqslant 5$ IN HEAVY ION REACTIONS AT $E/A \sim 10$ MeV/NUCLEON

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Introduction

The available He isotopes offer a possibility of studying the properties of this element across the whole valley of stability, from the proton drip line to the particle unstable neutron-rich isotopes. Relatively high intensities ($\sim 10^3$ part/sec) of very neutron-rich He isotopes are presently available at some research centers (e.g., CERN, Berkeley) and this allows one not only to study the decay modes of these isotopes but also to measure their elastic scattering /1/. These beams are mainly produced as a result of spallation or fragmentation reactions at high energies. He isotopes are also obtained as rare events in ternary fission /2/. From a theoretical point of view, for these few-nucleon systems level sequence calculations can be performed and different hypotheses and potentials can be tested with the aim to see what happens at very high N/Z ratios.

In Table 1 some properties of He isotopes with $A > 4$ are given. One can see that while even isotopes (except ^{10}He) are nucleon stable, the odd isotopes are unstable with respect to neutron emission. The addition of a pair of neutrons increases the stability of ^{8}He as compared with ^{6}He and brings the unstable ^{7}He closer to stability than ^{5}He. This does not hold true any more in passing from ^{7}He to ^{9}He and, considering the calculated mass value for ^{10}He, also in moving from ^{8}He to ^{10}He. It seems that going away from the β-stability valley in the region where these isotopes have a binding energy $|E| \lesssim 1$ MeV, the pairing energy makes the even isotopes stable while for the odd isotopes where this energy is absent, quasistationary states (nucleon unstable) still exist. The appearence of such states, as suggested in /3/, is probably determined by the presence of a centrifugal barrier for the last unpaired neutron. Thus, going from an even isotope to the next odd one, the ground state dives into a continuum and becomes a quasistationary one. The width of these states (see Table 1) increases when the system becomes more unbound. As for the known excited states of heavy He isotopes, they are all nucleon unstable and, generally, their widths follow the same trend as those of quasistationary ground states of heavy odd He isotopes.

Another interesting fact is that ^{8}He has N/Z=3, the highest known ratio for a stable isotope across the chart of nuclides. (Higher values are observed only for a quasistationary state in

Table 1

The ground-state properties of He isotopes with A = 4

Isotope	Mass excess (MeV)	Γ (MeV)	Decay	Decay energy (MeV)
^{5}He	11.4	0.6	^{4}He + n	0.89
^{6}He	17.6	-	^{4}He + 2n	-0.97
^{7}He	26.1	0.16	^{6}He + n	0.44
^{8}He	31.6	-	^{6}He + 2n	-2.14
^{9}He	40.8	1	^{8}He + n	1.14
^{10}He	49.4*	?	^{9}He + n	0.52
			^{8}He + 2n	1.66

*Calculated value.

^{6}H /3,4/. In this given case all members of the T=2 isobaric multiplet may be studied /5/. In connection with ^{8}He it should be also mentioned that, due to its high Q value for the β-decay to ^{8}Li (10.65 MeV), new interesting decay modes like β-delayed triton emission /6/ can be studied. The decays of excited states of heavy He isotopes by multineutron emission are also interesting as they offer the possibility of looking for the clustering of few neutrons during this emission. If present, such a clustering will manifest itself in the observed phase space structure.

In the present study, the ground and excited states of He isotopes with $5 \leq A \leq 9$ are populated in the heavy ion reactions: ^{11}B + ^{7}Li, ^{11}B + ^{9}Be, ^{14}C + ^{9}Be, and ^{9}Be + ^{9}Be. ^{5}He, ^{6}He, ^{7}He, and ^{8}He are obtained in different exit channels of the first reaction, ^{7}He in all four reactions and ^{8}He in the first and fourth ones so that some comparison of production cross sections can be made and conclusions can be drawn about the role of the reaction mechanism. A separate study /7/ was devoted to the direct observation of ^{10}He with a high experimental sensitivity. The main characteristics of these reactions are listed in Table 2. Since the studied reactions have very small cross sections, measurements were performed at only one (very forward) angle and at one bombarding energy. Although this fact makes the theoretical interpretation difficult, the concept of kinematical matching (an optimum Q value, Q_{opt}) still can be used. The evaluation of Q_{opt} was done by using the model proposed by Wilczynski /8/, in which the dissipation energy was taken equal to zero.

A brief description of the method of the measurement and of the experimental setup is given in the next section. The obtained data are then discussed in the third section. Some conclusions are formulated at the end. Partially these data have been reported at the International Summer School in Brasov - Romania (Sept. 1-13,1986) and at the All-Union Conference on Nuclear Spectroscopy and Reactions in Yurmala, USSR (April 1987).

Table 2

The main characteristics of the reactions studied in the present work

Reaction	E_{lab} (MeV)	Measurement angle (Lab)	Exit channel	Q-value (MeV)
^{11}B + ^{7}Li	88	8°	^{13}C + ^{5}He	9.56
			^{12}C + ^{6}He	5.98
			^{11}C + ^{7}He	-12.74
	87	8°	^{10}C + ^{8}He	-23.74
^{11}B + ^{9}Be	88	8°	^{13}N + ^{7}He	-11.0
^{9}Be + ^{9}Be	106.7	5°	^{11}C + ^{7}He	-13.62
			^{10}C + ^{8}He	-24.62
^{14}C + ^{9}Be	152.6	8°	^{16}O + ^{7}He	-6.56
	158	8°	^{14}O + ^{9}He	-33.32

2. Experimental

The method adopted in the present study was to use a binary heavy-ion reaction for producing a stable product in the exit channel. The energy spectrum of this product contains information about its partner. Even if this partner is nucleon unstable, its quasistationary states still can be observed and their corresponding widths determined. Indeed, when the partner is nucleon unstable, the observed spectrum will correspond to the available phase space distribution in the given energy interval of the recorded product. Possible deviations from this phase space description can be used to identify the existence of a grouping of particles in the exit channel. In some cases this can be unambiguously connected with the existence of quasistationary states in the nucleon unstable system being studied. The reaction products were analysed using a stepped-pole broad-range magnetic spectrograph (MSP 144 type /9/) that has a straight focal plane, positioned at 5° or 8° with respect to the beam. As a focal plane detector, a position sensitive ($\Delta E, E$) ionisation chamber was used. The resolution capabilities of this detector were: $\delta x \approx 0.7$ mm, $\delta(\Delta E)/\Delta E = 3.2\%$, $\frac{\delta E}{E} = 2\%$. A scheme of the experimental setup and a more detailed description are given in /4,10/. The Li targets were prepared by vacuum evaporation of a 99.2% enriched ^{7}Li isotope on thin ($\sim 10\ \mu g/cm^2$) organic backings and had a thickness of $\sim 350\ \mu g/cm^2$. All subsequent handling was done in a vacuum. The Be targets, also prepared by vacuum evaporation, were deposited on a copper backing that subsequently was etched off with nitric acid. Their thickness was $\sim 230\ \mu g/cm^2$. The beams (including radioactive ^{14}C) were delivered by the U-300 heavy ion cyclotron at Dubna. Typical beam currents on target were $\lesssim 0.5\ \mu A$ (electric); at this beam rate a pulse pileup in the aquisition system is unimportant. The beam energy was periodically controlled by measuring the elastic scattering on a thin silver target and corrections were made in the measured spectra for the observed energy drift. The resolution in mass determination in the test reaction ^{9}Be(^{11}B,^{12}C)^{8}Li was $\sim$300 keV /10/.

3. Experimental data and discussion

3.1. The ^{7}Li(^{11}B,^{13}C)^{5}He reaction

This reaction represents a pn transfer from the target to the projectile. It leads to the closed proton s shell in ^{5}He and closed p3/2 subshell in ^{13}C and has a rather large cross section. The energy spectrum of the recorded ^{13}C is shown in fig. 1. One can clearly see the peak corresponding to the ground state (g.s.) of ^{5}He at an excitation energy of (0.9±0.3) MeV in the ^{4}He + n system. The cross section under the peak is $\frac{d\sigma}{d\Omega} = (12 \pm 3)\ \mu b/sr$ and the width $\Gamma = (0.8 \pm 0.3)$ MeV. The continuous line represents a phase space calculation for the three-body breakup in the exit channel: ^{13}C + ^{4}He + n. This calculation was normalized to the data obtained at E(^{13}C) =89.2 MeV where no other channels can contribute. Downward from E(^{13}C)=89 MeV, a number of excited states of ^{13}C start to contribute. They give a phase space distribution of similar shape superimposed over the g.s. one. This fact makes the determination of the total phase space curve ambiguous and consequently is not shown in the figure. Nevertheless at E(^{13}C)=87.4 MeV, a large peak shows up over the background; its decreasing left edge makes impossible any confusion with the phase space. Besides, no excited levels of ^{13}C lie in the region of the peak (see arrows in fig. 1). Moreover, as

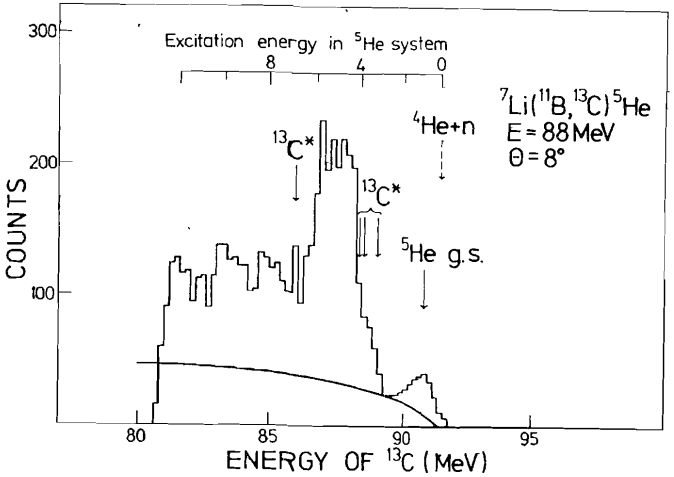


Fig. 1. Energy spectrum of ^{13}C ions for the ^{7}Li(^{11}B,^{13}C)^{5}He reaction. The full line represents the phase space distribution for the (^{13}C+^{4}He+n) exit channel; this calculation was normalized to the data obtained at an energy of 89.2 MeV.

a result of the rather large positive Q value of this reaction as compared with those of the ^{12}C and ^{16}O contaminants (-6.5 and -2.05 MeV respectively), the measured spectrum of ^{13}C is free of contributions from these contaminants in the 84.2-95 MeV region (i.e. they start to contribute at energies below 84.2 MeV). The corresponding excitation energy of ^{5}He is (5.2±0.3) MeV but the cross section under the peak is difficult to estimate as it is flanked by ^{13}C levels. By drawing a smooth background under the peak one may deduce $\frac{d\sigma}{d\Omega} = (60 \pm 10)\ \mu b/sr$. The width of this peak is $\Gamma = (2.0 \pm 0.5)$ MeV, i.e. somewhat smaller than the value ($\sim$ 4 MeV) quoted in the literature /5/.

The higher cross section for the population of this first excited state with $J^\pi = 1/2^-$ as compared with the g.s. ($J^\pi = 3/2^-$) may be explained as follows. For this reaction $Q_{opt} = -17.2$ MeV, i.e. about 27 MeV below the real reaction Q value. This indicates a big momentum mismatch and then one should expect a preferential population of excited states of the reaction products. Therefore, it is possible that at these bombarding energies, the transfer proceeds with a significant probability through a single step (deuteron cluster transfer) after previously exciting one of the p3/2 neutrons in ^{7}Li to the p1/2 orbit (which leaves the proton and the neutron necessary to form the deuteron in the same p3/2 orbit). In this case, after the transfer ^{5}He will remain in its $1/2^{-}$ excited state.

3.2. The $^{7}Li(^{11}B,^{12}C)^{6}He$ reaction

This one-proton pickup reaction leads to the filling of the p3/2 orbit in ^{12}C and has a rather large cross section. Fig. 2 shows the energy spectrum of the recorded ^{12}C. Two peaks, corresponding to the g.s. of ^{6}He and to the first excited state at (1.8±0.3) MeV are observed with cross sections $\frac{d\sigma}{d\Omega} = (320\pm20)$ and (270 ± 30) µb/sr, respectively. The width of the first excited state is almost equal to that of the g.s. (stable) peak. Assuming that the experimental resolution function has a width of ~ 600 keV one may expect for the excited level a width of $\lesssim$ 200 keV. This level lies some 70 keV below the ^{5}He + n threshold and 0.825 MeV above the ^{4}He + 2n threshold. Consequently this last decay is the only one energeticaly possible but the simultaneous emission of two neutrons is an unlikely process (it has a small available phase space) which would lead to an increased lifetime. For this reaction the calculated Q_{opt} is -10 MeV, i.e. 16 MeV below the real Q value. Though this difference is smaller than for the previous reaction it still indicates a momentum mismatch and this is reflected in the cross section values: they are smaller than the typical value of ~ 1 mb/sr for 1p transfer reactions in this energy range /11/. One notes the almost equal cross sections for ground state and first excited state populations. This seems to indicate that the Q window is wide enough to comprise both levels. If not, this feature distinguishes the present reaction from the previous one.

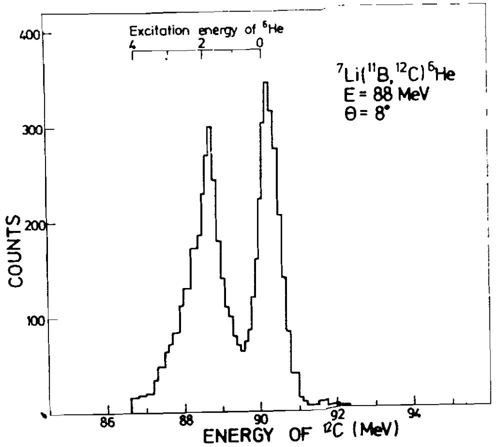


Fig. 2. Energy spectrum of ^{12}C ions for the $^{7}Li(^{11}B,^{12}C)^{6}He$ reaction.

3.3. The $^{7}Li(^{11}B,^{11}C)^{7}He$ reaction

This is a reaction of a charge exchange type. Its negative Q-value leads to small values of cross section (see fig.3). The area under the peak corresponding to the g.s. of ^{7}He at (0.5±0.3) MeV excitation energy in the ^{6}He + n system represents (4.8±0.5) µb/sr. The width of the peak, as in the previous reaction, is close to the experimental resolution. So one may expect that the real width of the level is $\lesssim$ 200 keV. The full line represents a phase space calculation that takes into account the g.s. and the first two excited states of ^{11}C in the three-body breakup (^{11}C + ^{6}He + n) in the exit channel. Other variants also have been considered, for example, the five-body decay: ^{11}C + ^{4}He + n + n + n, and the fit was less successful. The phase space analysis does not allow one to draw any conclusion about the existence of the following decay channels: ^{11}C + ^{5}He + ^{2}n and ^{11}C + ^{4}He + ^{3}n which would start at 1.87 and 0.97 MeV excitation energies, respectively (if the binding energy of the multineutron systems is taken equal to zero). If the reaction is assumed to be a multistep process, then it will proceed through an exchange of nucleons in both directions, breaking the closed p3/2 neutron subshell in ^{11}B and completing the p3/2 proton subshell in ^{11}C and the reaction cross section is expected to be small. At the present energies the one-step charge exchange reaction is probably not yet accomplished. Since the calculated Q_{opt} (-19.5 MeV) is close to the reaction Q value, the g.s. population is kinematically favoured. No other levels are seen in the present experiment with obvious statistical significance.

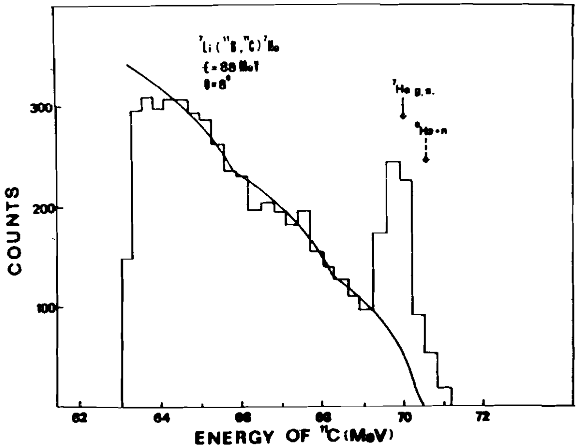


Fig. 3. Energy spectrum of ^{11}C ions for the $^{7}Li(^{11}B,^{11}C)^{7}He$ reaction. The phase space corresponding to the three-body exit channel (^{11}C+^{6}He+n) with ^{11}C ions in the g.s. and in the first two excited states is shown by a full line.

3.4. The $^{9}Be(^{11}B,^{13}N)^{7}He$ reaction

The energy spectrum of ^{13}N measured in this reaction is shown in fig. 4. The peak corresponds to the ^{7}He g.s. at (0.5±0.3) MeV excitation energy and has a width comparable with the experimental resolution (see previous reaction). The cross section under the peak is $\frac{d\sigma}{d\Omega} = (29 \pm 5)\ \mu b/sr$. The full curve is a phase space calculation for the three-body breakup in the exit channel $^{13}N + {}^{6}He + n$, that reproduces the data rather well. There was no need to introduce either the contribution from three-body channels with groupings of neutrons like $^{13}N + {}^{5}He + {}^{2}n$ or $^{13}N + {}^{4}He + {}^{3}n$, or from exit channels with more than three particles which would have a much steeper increase toward smaller energies. Moreover, the excited states of the recorded product (^{13}N) made no contribution (within statistical errors) to the phase space yield measured. In the reaction, two protons are transferred from the target to the projectile. If it proceeds in two steps, then, in the first one, a p3/2 pair in ^{9}Be should be broken to complete the p3/2 orbit in ^{12}C while, in the second, the remaining unpaired p3/2 proton should be transferred to the p1/2 orbit in forming ^{13}N. The g.s. population cross section is about 6 times higher than that in the previous reaction though the kinematic matching conditions are similar ($Q_{opt} \simeq -18$ MeV). The two reactions differ in the way the nucleons are exchanged: in both directions or only in one direction, if they are considered as two-step processes. The last situation in the studied case has a higher probability. One cannot neglect also the structural particularities of the reaction products: e.g. the $1/2^{-}$ g.s. spin of ^{13}N implies transferred angular momentum $l \geqslant 1$ while for the reaction on Li, $l \geqslant 0$. In this reaction, as in the previous one, no significant evidence for other excited states of ^{7}He was observed.

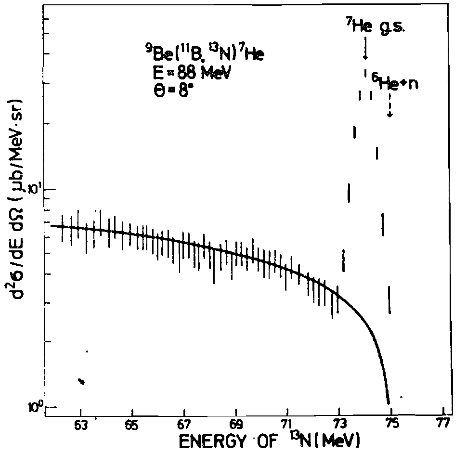
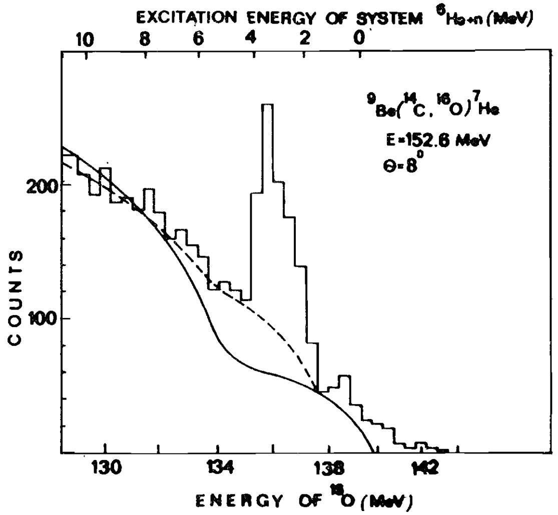


Fig.4. Energy spectrum of ^{13}N ions from the $^{9}Be(^{11}B,^{13}N)^{7}He$ reaction. The three-body phase space contribution of the $(^{13}N+{}^{6}He+n)$ exit channel is shown by a full line.

3.5. The $^{9}Be(^{14}C,^{16}O)^{7}He$ reaction

The energy spectrum of ^{16}O is shown in fig. 5. The full line is a phase space calculation that takes into account the three-body breakup in the exit channel with the ^{16}O in the g.s. and in the first excited state. A better agreement with the data may be obtained if one includes a contribution from the "exotic" three-body channel ^{16}O (g.s.) + ^{5}He + ^{2}n. The latter starts at 1.87 MeV excitation energy (dotted line) if we take zero binding energy for ^{2}n. This better agreement does not prove the existence of the mentioned decay channel but rather suggests the possible existence of a final state interaction in the ^{2}n system and requires a more detailed study by a correlation measurement. A careful analysis of the spectrum shown in fig. 5 reveals the presence of at least two peaks. The first one observed at an excitation energy of (0.5±0.3) MeV in the ^{6}He + n system corresponds to the g.s.of ^{7}He. The cross section under the peak is $\frac{d\sigma}{d\Omega} = (5 \pm 1)\ \mu b/sr$. The second and the most prominent peak lies at an excitation energy of (3.4±0.5) MeV and has a width of (1.5±0.5)MeV. The cross section for the population of this excited unbound level is (84±15) μb/sr. The rather high uncertainty comes from the uncertain assessment of the phase space. One should note that for this level, the decay channel involving the emission of three neutrons ($^{7}He^{*} \longrightarrow {}^{4}He + n + n + n$) is energetically possible and therefore offers the possibility to study this new type of decay. For this purpose, correlation experiments are necessary.

Fig.5. Energy spectrum of ^{16}O ions for the $^{9}Be(^{14}C,^{16}O)^{7}He$ reaction. The phase space corresponding to the three-body exit channel $(^{16}O+{}^{6}He+n)$ with the ^{16}O in the g.s. and in the first excited state is shown by a full line. The dashed line represents the phase space if one includes a contribution from the exit channel (^{16}O (g.s.) + ^{5}He + 2n).



The reaction involves the pickup of two protons onto the p1/2 orbit that leads to the closure of the p proton shell in ^{16}O. The enhanced population of the first excited state in ^{7}He as compared witl the g.s. may be explained by the fact that the reaction proceeds at a rather high energy. The calculated Q_{opt} for this reaction is - 24 MeV, indicating a large momentum mismatch and preferential population of excited states. In order to accommodate this energy excess the system may go to the p1/2 orbit with one of the unpaired neutrons. In this case the excited level would have $J^{\pi} = 1/2^{-}$ and necessarily partial waves with angular momentum $l \geqslant 1$ would be responsible for the transfe

In the region of the observed peak, contributions may appear from levels populated in the reaction on C impurities in the target. Though the $^{12}C(^{14}C,^{16}O)^{10}Be$ reaction was not measured separately, the observed peak is very unlikely to be due to this reaction. Indeed, th reactions on Be and C are of the same type (2p pickup) and have similar kinematic conditions (for the reaction on C Q=-4.85 MeV and the calculated Q_{opt} = -22.37 MeV). Consequently, apart from the structure particularities, the cross sections for the most intensivel populated levels should be comparable. Then, taking into account that the amount of C in the target is about 10 μg/cm² (as the analysis of the Be+Be reaction will show below) the assignment of the observed peak to the reaction on C would lead to cross section values of more than 2 mb/sr, i.e. two orders of magnitude larger than the reference value /11/ for this type of reaction. Therefore we have discarded this possibility.

3.6. The $^{9}Be(^{9}Be,^{11}C)^{7}He$ reaction

The energy spectrum of ^{11}C measured at 5° in the laboratory system is shown in fig. 6. The reaction proceeds with a two proton pickup to fill the p3/2 orbit in ^{11}C. Arrows in fig. 6 indicate the position of the peaks corresponding to the ^{7}He g.s. at (0.5±0.3) MeV and to the excited states of ^{11}C at 2.0, 4.32 and 4.8 MeV respectively. The small peak at the right of the ^{7}He g.s. is due to the reactio on C impurities in the target. The energy spectrum of ^{11}C from the reaction $^{12}C(^{9}Be,^{11}C)^{10}Be$ taken with the same spectrograph setting and with a ^{12}C target of 100 μg/cm² is shown in fig. 7. One can clearly see peaks (marked with arrows) corresponding to the g.s. of the reaction products and to excited states at 2.0 and 3.6 MeV. While the peak at 2.0 MeV may result from the population of $^{10}Be^{*}$ (2.15 MeV and/or $^{11}C^{*}$ (2.0 MeV), the peak at 3.6 MeV is due to the population of an excited state of ^{10}Be and has a smaller cross section than that

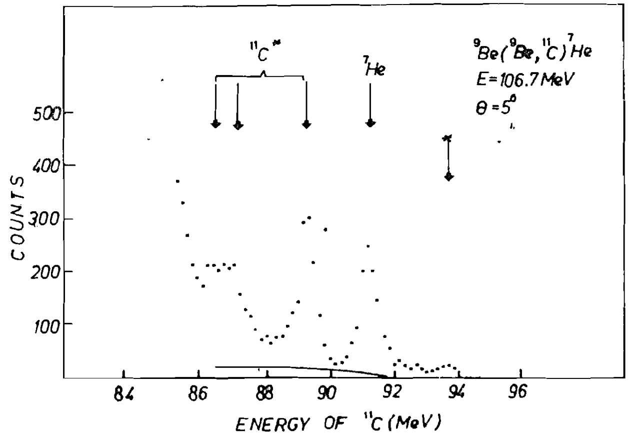


Fig.6. Energy spectrum of ^{11}C ions for the $^{9}Be(^{9}Be,^{11}C)^{7}He$ reaction. The upper arrows indicate the ^{11}C energies corresponding to the g.s. of reaction products (marked ^{7}He) and to different excited states of ^{11}C. The arrow with an asterisk, indicates the energy of ^{11}C for the g.s. production in the reaction on ^{12}C impurities in the target. The full line represents a three-body phase space contribution (see the text).

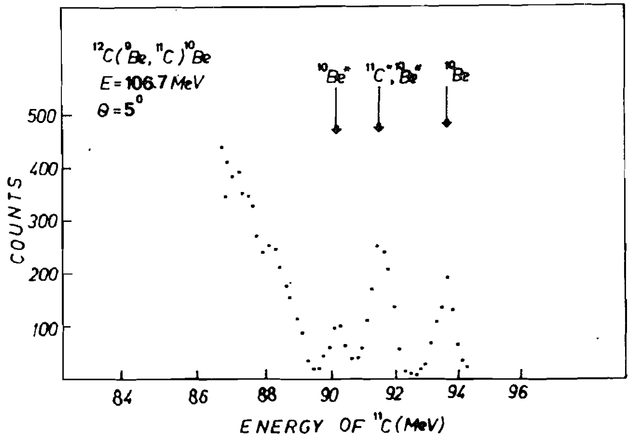


Fig.7. Energy spectrum of ^{11}C ions for the $^{12}C(^{9}Be,^{11}C)^{10}Be$ reaction. The upper arrows indicate the ^{11}C energies corresponding to the g.s. and to different excited states of reaction products.

for the g.s. population. The g.s. peak leads to a cross section value of $\sim 140\ \mu b/sr$. By comparing it with the small peak in fig. 6 after normalization to the corresponding monitors one can obtain an evaluation of C build-up in the Be target that amounts to $\sim 12\ \mu g/cm^2$. The ^{7}He g.s. peak in fig. 6 corresponds to a cross section value of $(39 \pm 3)\ \mu b/sr$. The reaction on Be has a rather small phase space contribution, as demonstrated by the deep valley at E(^{11}C)=90.5 MeV. At ^{11}C energies smaller than this value other peaks appear and make the phase space determination rather ambiguous. Therefore the thin line in the figure shows it only as tentatively normalized to the point at E(^{11}C)=90.5 MeV after subtraction of the background from the reaction on C. In this reaction the above excited state of ^{7}He has not been observed. However one should note that the yield in the region around 3.4 MeV excitation energy(E(^{11}C) around 88 MeV) is rather high even if both the phase space and background contributions are taken into account.

The two reactions (on ^{9}Be and ^{12}C) are of the same type and the kinematic conditions are also similar. The calculated Q_{opt} values are -24.3 and -22.7 MeV, respectively, and the Q value for the reaction on ^{12}C is -11.91 MeV. The difference between the g.s. population cross sections is most likely to be due to the structure particularities.

3.7. The ^{7}Li(^{11}B,^{10}C)^{8}He reaction

This is a complex rearrangement reaction in which nucleons are exchanged in both directions (one proton pickup to fill the p3/2 orbit and two-neutron stripping), and which has a large negative Q-value. At an excitation energy of 2.1 MeV, ^{8}He becomes unstable with respect to the decay into ^{6}He + 2n so that at this energy value a continuum of states described by the phase space distribution starts to contribute. Because of the poor statistics in the excitation energy region between 4 and 7 MeV it is difficult to normalize the phase space curve to the data and therefore, it is not shown in figure 8. With so small cross section values, reactions on impurities may give contributions that can alter the measured spectrum. Therefore, in a separate run of experiments using a thick ($100\ \mu g/cm^2$) carbon target these contributions were measured with the same spectrograph setting and with a current integral on target ten times smaller than in the measurement on the Li target. In this way account was taken of a carbon buildup of about $10\ \mu g/cm^2$. The results of this run are shown in fig. 8 by black blocks. The oxygen contaminants in the target make a very small contribution. Indeed, the g.s. peak for the reaction on ^{16}O lies at the ^{10}C energy of 64.7 MeV while at E(^{10}C) = = 53 MeV a multitude of levels may contribute. However, at this point, a very low background is observed. The spectrum in fig. 8 clearly exhibits the presence of two peaks. The first one, at zero excitation energy, corresponds to the ^{8}He g.s. formation and has a cross section $\frac{d\sigma}{d\Omega} = (57 \pm 7)$ nb/sr. The second one appears at (2.6 ± 0.3) MeV excitation energy in good agreement with /12/ and has a cross section $\frac{d\sigma}{d\Omega} = (93 \pm 25)$ nb/sr and a width $\Gamma = (1.0 \pm 0.5)$ MeV. The large uncertainty in the cross sections here is connected with the uncertainty of the phase space determination of the background under the peak.

The events observed in the excitation energy region from 1 to 2 MeV cannot be explained either by the impurities, or by the phase space contribution and, consequently, we are inclined to believe that an additional level is present, though it is difficult to say something more definite (see 3.8). For this reaction the calculated Q_{opt} = -26.58 MeV, i.e. quite close to the reaction Q value and the ground and the low-lying excited states are populated with almost equal probabilities.

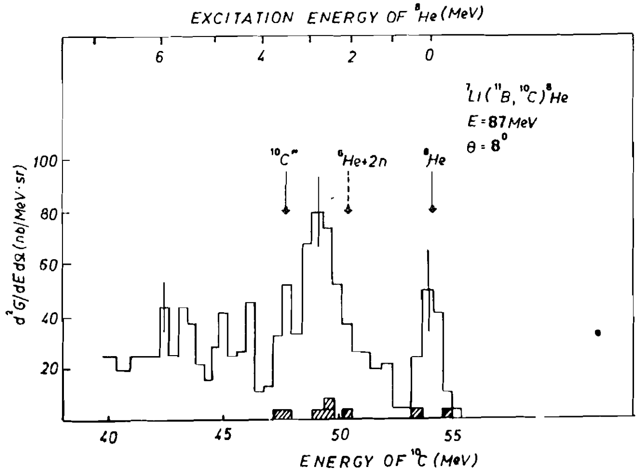


Fig.8. Energy spectrum of ^{10}C ions for the ^{7}Li(^{11}B,^{10}C)^{8}He reaction. The arrows indicate the ^{10}C energies corresponding to the g.s. of reaction products (marked ^{8}He) and to the excited state of ^{10}C. The black blocks are measured events from the ^{12}C(^{11}B,^{10}C)^{13}B reaction.

3.8. The $^{9}Be(^{9}Be,^{10}C)^{8}He$ reaction

In this reaction, which has the same products in the exit channel as the previous one, two protons are picked up from the target and one neutron is stripped from the projectile, i.e. again nucleons are exchanged in both directions. The energy spectum of ^{10}C is shown in fig. 9. Despite the low statistics one can clearly distinguish peaks corresponding to the ground and excited states of the reaction products. The g.s. population cross section is (275 ± 40) nb/sr. The peak at 3.35 MeV excitation energy corresponds to the formation of ^{10}C in its first excited state while the peaks lying at excitation energies of 1.3, 2.6 and 4.0 MeV should be attributed to excited levels in ^{8}He. The cross section under these last peaks are equal to (92 ± 20) nb/sr, (49 ± 15) nb/sr and (160 ± 50) nb/sr respectively. Note that the width can be determined only for the excited state in ^{8}He at 4.0 MeV ($\Gamma = (0.5\pm0.3)$ MeV), for other two states with energies at 1.3 and 2.6 MeV the width cannot be extracted due to the poor statistics. At $E(^{10}C)=74$ MeV another peak appears but its left edge is determined by the registration energy domain of the focal-plane detector and therefore it was not considered in the analysis. The carbon impurities in the target cannot account for the observed peaks, as demonstrated by the spectrum of ^{10}C measured under the same conditions on a thick ^{12}C target (see fig. 10). The events appearing in the ^{10}C energy interval from 80 to 92 MeV correspond to a carbon build-up of less than 10 $\mu g/cm^2$.

The level at 1.3 MeV is nuclear stable while the one at 2.6 MeV may decay by two-neutron emission and the one at 4 MeV even by four-neutron emission. The observation of the peak at 1.3 MeV, though with poor statistics, is also supported by the study of the previous reaction. This level is the first excited state in $A \geqslant 5$ He isotopes which is nucleon stable and it may be helpful in testing different structure calculations.

In a previous work /13/ where ^{8}He has been observed directly in the $(^{4}He,^{8}He)$ reaction on different targets, this level is not reported. It is not clear if the scanned energy did not encompass it or simply it was not observed. In some cases, levels of the complementary product in the exit channel may also mask the observation of the 1.3 MeV level in ^{8}He in the cited work.

The presumable J^{π} for this level is 2^{+} and then, the one at 2.6 MeV will probably have $J^{\pi}=0^{+}$ (from shell occupancy considerations).

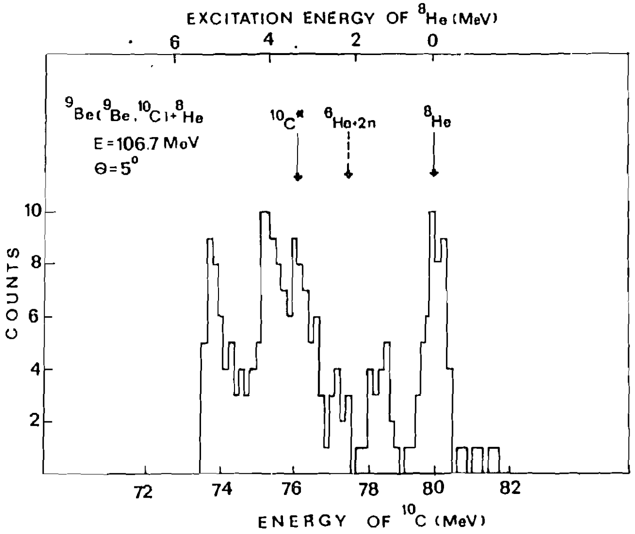


Fig.9. Energy spectrum of ^{10}C ions for the $^{9}Be(^{9}Be,^{10}C)^{8}He$ reaction. The arrows have the same meaning as on fig. 8.

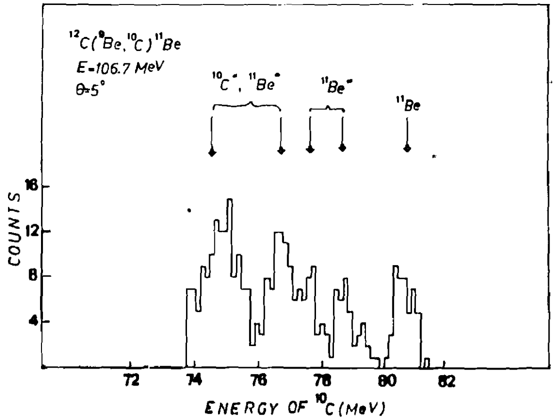


Fig. 10. Energy spectrum of ^{10}C ions for the $^{12}C(^{9}Be,^{10}C)^{11}Be$ reaction. The arrows indicate the energies of ^{10}C corresponding to the g.s. and to different excited states of reaction products.

In an isobar diagram for A=8 /5/ one can see that only in ^{8}Be a level is observed above the first T=2 state; their difference in energy is quite close to 1.3 MeV i.e. the difference between g.s. and first excited state in ^{8}He and this fact may be taken as a hint for the T=2 assignment for that level in ^{8}Be.

The excited state at 4 MeV in ^{8}He offers the possibility of studying the exotic decay by emission of four neutrons. Again, the phase space of this multibody decay may provide evidence for grouping of the neutrons.

3.9. The ^{9}Be(^{14}C,^{14}O)^{9}He reaction

The energy spectrum of ^{14}O is shown in fig. 11. The Q value for this reaction is very low and it is natural to expect low values of cross section. The full line is the phase space calculation for the three-body decay in the exit channel (^{14}O + ^{8}He + n). One can observe an enhancement over the phase space with the corresponding cross section $\frac{d\sigma}{d\Omega} \sim 0.1$ µb/sr. The width of this enhancement is large; one may presume that with improved statistics it may split into more distinct levels /14/. Arrows indicate the zero excitation energy and the 1.8 MeV excitation energy. The obtained cross section is rather uncertain because the normalization of the phase space curve to the data is somewhat arbitrary. The obtained mass for ^{9}He corresponding to the arrow position is (41.5±1.0) MeV.

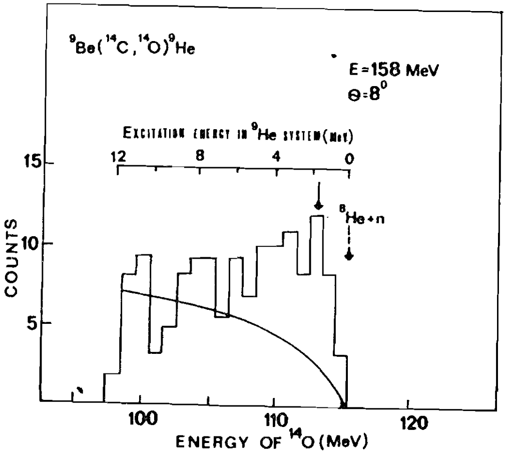


Fig.11. Energy spectrum of ^{14}O ions for the ^{9}Be(^{14}C,^{14}O)^{9}He reaction. The full line represents three-body phase space contribution of the (^{14}O+^{8}He+n) exit channel. The arrow indicates the ^{14}O energy corresponding to the g.s. of reaction products.

4. Conclusion

The main results obtained in the present work are presented in Table 3. They can be summarized as follows:

- The width of the first excited state of ^{5}He obtained in this work is substantially narrower than the value given in the literature, indicating a longer lifetime.
- The excited state of ^{7}He at 3.4 MeV is reported for the first time and a tentative assignment of $J^{\pi}=1/2^{-}$ is made.
- Excited levels at 1.3, 2.6 and 4 MeV in ^{8}He are observed, two of them for the first time and the one at 2.6 MeV in two reactions and with improved statistics as compared with the previously reported works /3,11/.
- A deviation from the phase space distribution in the ^{9}Be(^{14}C,^{14}O) reaction is interpreted as the formation of a nucleon-unstable ^{9}He nucleus.

Table 3

Results of the measurements carried out in this study

Isotope	Reaction	Observed level energy (MeV)	Γ (MeV)	Cross section (µb/sr)
^{5}He	^{7}Li(^{11}B,^{13}C)	0.9±0.3	0.8±0.3	12±3
		5.2±0.3	2.0±0.5	60±10
^{6}He	^{7}Li(^{11}B,^{12}C)	0	-	320±20
		1.8±0.3	$\leq$ 0.2	270±30
^{7}He	^{7}Li(^{11}B,^{11}C)	0.5±0.3	$\leq$ 0.2	4.8±0.5
	^{9}Be(^{11}B,^{13}N)	0.5±0.3	$\leq$ 0.2	29±5
	^{9}Be(^{14}C,^{16}O)	0.5±0.3	$\leq$ 0.2	5±1
		3.4±0.3	1.5±0.5	84±15
	^{9}Be(^{9}Be,^{11}C)	0.5±0.3	$\leq$ 0.2	39±3
^{8}He	^{7}Li(^{11}B,^{10}C)	0	-	(57±7)10^{-3}
		2.6±0.3	1.0±0.5	(93±25)10^{-3}
	^{9}Be(^{9}Be,^{10}C)	0	-	(275±40)10^{-3}
		1.3±0.3	-	(92±20)10^{-3}
		2.6±0.3	-	(49±15)10^{-3}
		4.0±0.3	0.5±0.3	(160±50)10^{-3}
^{9}He	^{9}Be(^{14}C,^{14}O)	~ 1.8	~ 3	~ 0.1

A substantial decrease in the cross section is observed when the Q value decreases. At a comparable Q value, an exchange of nucleons in both directions leads to decreased values of the cross section as compared with the reactions in which the transfer occurs only in one direction. Kinematical matching expressed by the Q_{opt} value plays an important role in the relative population of states. This is illustrated by the fact that only in one of four reactions the excited level of ^{7}He has been observed.

The small cross section values of some of the studied reactions prevented us from making angular distribution measurements and also in such cases the statistics are rather poor. However, in order to correctly assign quantum numbers to the observed states the measurement of angular distributions is imperative.

From some of the observed levels, interesting decay modes are energetically possible like two- and four-neutron decay, the study of which needs special experimental efforts.

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Белозеров А.В. и др. E15-87-733
Исследование изотопов гелия с A ≥ 5
в реакциях с тяжелыми ионами при энергии
E/A ~ 10 МэВ/нуклон

Были исследованы тяжелые изотопы He в следующих двухтельных реакциях: ^{9}Be+^{9}Be, ^{11}B+^{7}Li, ^{11}B+^{9}Be, ^{14}C+^{9}Be. Измерено сечение заселения основного и возбужденного состояний. Впервые обнаружены возбужденные состояния в ^{7}He и ^{8}He.

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Study of He Isotopes with A ≥ 5 in Heavy
Ion Reactions at E/A ~ 10 MeV/Nucleon

Heavy He isotopes are studied by measuring the energy spectra of their stable partners in the exit channel of different two-body direct reactions: ^{9}Be+^{9}Be, ^{11}B+^{7}Li, ^{11}B+^{9}Be and ^{14}C+^{9}Be. The population cross sections for ground and excited states have been measured and the widt of nucleon unstable states have been extracted. New excited states of ^{7}He and ^{8}He have been found.

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

Preprint of the Joint Institute for Nuclear Research. Dubna 1987