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EVIDENCE FOR PARTICLE INSTABILITY OF ^{10}He

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1. Introduction

The ^{8}He nucleus has the largest relative neutron excess $(N - Z)/Z$ among all the particle stable nuclei known at present. The question of particle stability of ^{10}He is, therefore, especially interesting. According to the theoretical estimates of Garvey and Kelson /1/ and Vinogradov and Nemirovsky /2/ ^{10}He should be unstable with respect to two-neutron emission. There exist, however, experimental data (e.g. the particle stability of ^{11}Li) which suggest that estimates based on the models used by these authors are not satisfactory in case of nucleides far from the β-stability line. It has been shown by Vorobiev et. al. /3/ that the formulas of Garvey and Kelson are not sufficiently reliable in the region of light nucleides with large neutron excess. Vorobiev et. al. /3/ have suggested that the nonlinear extrapolation of the binding energies of a last neutron (for the number of neutron $N = const$) should give more accurate ground state masses in this region of nucleides. The binding energy of the last two neutrons in ^{10}He, obtained in this way, is equal to - 1.2 MeV /3/, whereas Garvey and Kelson /1/ predict that ^{10}He is unstable by 10 MeV with respect to two-neutron emission.

The problem of particle stability of ^{10}He has also been studied theoretically by Baz, Demin and Zhukov /4/ who used the method of K -harmonics. Their calculations of the ^{10}He binding energy were performed with realistic two-body central forces and are convincing enough since tensor forces should not contribute to the binding energy of the doubly closed-shell ground state of ^{10}He .

The conclusion of Baz, Demin and Zhukov /4/ was that even a very weak attractive ^{33}V $(S=1, T=1)$ component in the nucleon-nucleon force (such an attractive ^{33}V potential would not contradict the scattering data) can ensure the particle stability of ^{10}He .

For the reasons mentioned above the problem of testing experimentally the particle stability of ^{10}He has focused the attention of many investigators. In the last few years a number of attempts have been made to detect ^{10}He among the products of the spontaneous fission of ^{252}Cf /5,6/, among the spallation products in reactions with high energy protons /7/ and as a product of the thermal-neutron-induced fission of ^{235}U /3/. All these experiments gave negative results: ^{10}He has not been observed in either of them. This, however, does not prove particle instability of ^{10}He since for all the reactions studied, there has been no reliable way of estimating the value of the cross section for ^{10}He production. Vorobiev et al. /3/ have estimated the expected yield of ^{10}He by an arbitrary extrapolation of the yields of ^{4}He, ^{6}He and ^{8}He . They expected that $Y(^{8}He)/Y(^{10}He) = Y(^{6}He)/Y(^{8}He) = Y(^{4}He)/Y(^{6}He) = 50$ and detecting 2500 events of ^{8}He they observed no single ^{10}He ion. Also in experiments with high energy protons, in which few thousands of ^{8}He events were detected, no effect due to the ^{10}He ions has been observed /7/.

It has been shown recently (see e.g. ref. /8/) that reactions induced by heavy ions are the most effective way of producing light nuclei with large neutron excess. The systematic study of multi-nucleon transfer reactions has also shown that cross sections for these reactions can be predicted from phenomenological systematics with good accuracy /9/. This has opened the way for experimental study of the boundary of particle stability in the region of light nuclei. In the previous paper /10/ the particle instability of ^{13}Be and ^{14}Be has been shown. The results of experiments carried out with the aim of testing ^{10}He particle stability are reported in the present paper.

2. Experimental Procedure

Out of several different multi-nucleon transfer reactions in which ^{10}He can be produced, the stripping of 5 protons from the ^{15}N ions was chosen. It has been shown earlier /11/ that multi-proton stripping reactions occur with the largest cross sections when the projectile is colliding with a heavy nucleus. So the thorium was used as a target in the present experiment. The ^{15}N ion beam of 145 MeV accelerated in the Dubna 310-cm cyclotron bombarded the target of metalic ^{232}Th 25 mg/cm^2 thick. Reaction products were detected at the angle of 40^o with respect to the incident beam, at which the angular distributions of the reaction products should have their maxima (see, e.g. ref. /8/ and references cited there). The reaction products were detected and identified with a system consisting of the magnetic spectrometer and the dE/dx, E telescope placed in its focal plane. The pulses from both detectors were sent to a 4096-channel pulse-height analyser operating in a two-dimensional 64 x 64 channels mode. The dE/dx, E technique combined with the magnetic analysis ensures an unambiguous identification of all the projectile transmutation products (for detailed description of the detection technique see ref.[12]).

Varying the magnetic field in the spectrometer the energy spectra of many reaction products formed in the $^{232}Th + ^{15}N$ collisions were measured. The collection of experimental data so obtained was then used for the estimation of the expected position of the maximum in the ^{10}He energy spectrum and the expected magnitude of the cross section for production of this nucleus. The measurements were performed with dE/dx, E telescope consisting of a 60 μm thick semiconductor ΔE detector and a surface-barrier E detector. The effective area of the telescope was 3.0 cm^2.

In the search for ^{10}He a telescope with larger effective area (5.2 cm^2) was used. The ΔE detector in this telescope was 1 90 μm thick. With the dispersion of the spectrometer equal to 13 mm/1% of momentum, the reaction products in the energy interval $\delta E/E$ = 4% were detected in the telescope.

3. Experimental Results and Discussion

In the collisions of 145 MeV (lab) ^{15}N ions with ^{232}Th target many different reaction products are formed. The energy spectra of the reaction products show distinct regularities. They have the form of broad peaks (with a full width at half-maximum of about 20 MeV), the position of which varies in regular way with the number of transferred nucleons. The energy spectra of the ions produced in the (^{15}N – x protons) and (^{15}N – x protons – 2 neutrons) reactions are shown in fig. 1. For each reaction the excitation energy of the reaction products corresponding to the maximum in the energy spectrum can be estimated: $E^{ex} = Q_{gg} - Q(max)$, where Q_{gg} corresponds to the formation of the reaction products in their ground states. Such estimates are very rough due to the large thickness of the target, but they are good enough for finding the energy region in which the maximum of the ^{10}He energy spectrum should be expected. Excitation energies for different reactions are shown in fig. 2 as a function of the number of transferred protons (the values of E^{ex} were calculated for collisions taking place at half of the target thickness). It follows from the data displayed in fig. 2 that for the fixed number of the transferred neutrons the excitation energy increases with increasing the number of the stripped protons. From these data the excitation energy corresponding to the maximum in the ^{10}He energy spectrum can be predicted with the accuracy of about $\pm$ 5 MeV. Assuming particle stability of ^{10}He (mass excess should then be 47 MeV or smaller) the expected position of the maximum in the energy spectrum of ^{10}He can be determined. The possibility of a sufficiently reliable estimation of the maximum position in the ^{10}He energy spectrum is very important since at a fixed value of the magnetic field in the spectrometer the reaction products can be detected only in a narrow energy interval defined by the dispersion of the spectrometer and by the dimensions of the telescope. When searching for ^{10}He ions the magnetic field should be fixed at the value corresponding to the maximum in their energy spectrum. Due to fact that the width of the peak in the energy spectra is large, the $\pm$ 5 MeV accuracy in the estimation of its expected position is quite sufficient.

The expected yield of ^{10}He ions was estimated from the systematics of the cross sections for the production of different reaction products in the $^{232}Th + {}^{15}N$ collisions. As it has been shown in one of the preceding papers /9/, the cross sections for production of isotopes of a given element in the multi-nucleon transfer reactions depend exponentially on Q_{gg}-values. Fig. 3 shows this dependence for isotopes of carbon, boron, beryllium, lithium and helium produced in the $^{232}Th + {}^{15}N$ system. The extrapolation of the $\log (d\sigma / d\Omega)_{40^\circ} = \mathrm{const}\ Q_{gg}$ line for helium isotopes should not give a significant error, since the neighbouring lines are almost parallel and fit well the experimental points in a wide range of the cross section values.

Following the analysis of the energy spectra (see figs. 1and 2) the search for ^{10}He of about 45 MeV was undertaken. In the 20-h irradiation with the ^{15}N -ion beam current of 1-3 μA, no events corresponding to ^{10}He were detected. The two-dimensional spectrum obtained in this experiment is shown in fig. 4. The region in which ^{10}He ions should be recorded is completely free of any counts, while following the cross section systematics it should contain about 80 counts (this estimation corresponds to $Q_{gg} = -57.8$ MeV, i.e. to the binding energy of the last two-neutrons in ^{10}He $E_{2n} = 0$). The upper limit of the cross section for ^{10}He indicated in fig. 3 ($2.7\ 10^{-33}$ cm^2/sr) corresponds to the case when one ^{10}He count would be recorded in this 20-h irradiation.

It should be noted that a comparatively small number of the ^{8}He events detected in this experiment (fig. 4) cannot be compared with the results of earlier experiments /3,5-7/ in which ^{10}He was searched. In our experiment in which we were searching for ^{10}He of 45 MeV, the energy of the detected ^{8}He ions was 56 MeV, whereas the maximum in the ^{8}He energy spectrum lies at about 36 MeV (see fig. 1). The number (657 events) of the detected ^{8}He ions of 56 MeV is equivalent to about 18000 events of ^{8}He in the maximum of its energy spectrum.

To exclude the possibility of some unexpected anomalies in the energy spectrum of ^{10}He ions, we were looking for, additional measurements were performed at the values of the magnetic field corresponding to the ^{10}He energies equal to 38 and 53 MeV. The respective excitation energies (33 and 18 MeV) are indicated by arrows in fig. 2. The integral flux of the ^{15}N ions bombarding the target in these additional runs was about 3 times smaller than in the experiment at $E(^{10}He) = 45$ MeV. Also in these additional runs no effect due to the ^{10}He ions was observed.

Since even so weakly bound nuclei as ^{14}B ($E_n = 0.4$ MeV/1,3/) and ^{11}Li are produced in multi-nucleon transfer reactions with yields consistent with the cross section systematics, one can conclude that in all probability the ^{10}He nucleus is unstable with respect to nucleon emission.

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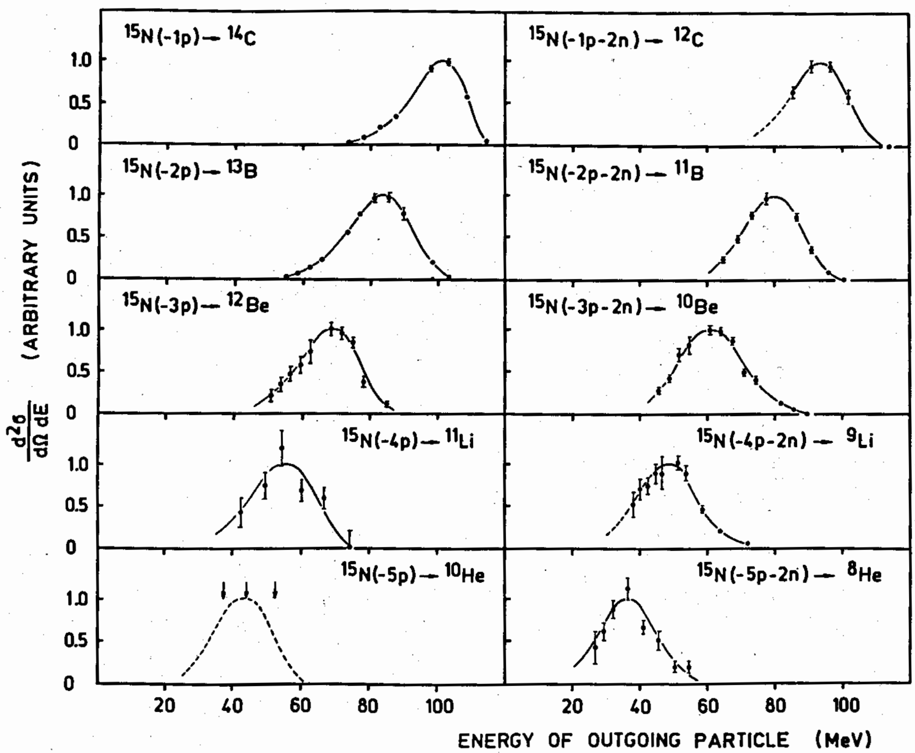

Fig. 1. Energy spectra of the ^{14}C, ^{13}B, ^{12}Be and ^{11}Li ions produced in the multi-proton stripping reactions (^{15}N – x protons) and of the ^{12}C, ^{11}B, ^{10}Be, ^{9}Li and ^{8}He ions produced in the (^{15}N – x protons – 2 neutrons) reactions occured in bombardment of ^{232}Th target with 145 MeV ^{15}N ions. The expected shape of the energy spectrum of ^{10}He ions (assuming particle stability of ^{10}He) is shown. The location of the maximum in the energy spectrum of ^{10}He was determined by the extrapolation of the excitation energies in the multi-proton stripping reactions (see fig. 2). The ^{10}He ions of energies indicated by the arrows were searched for in the experiment.

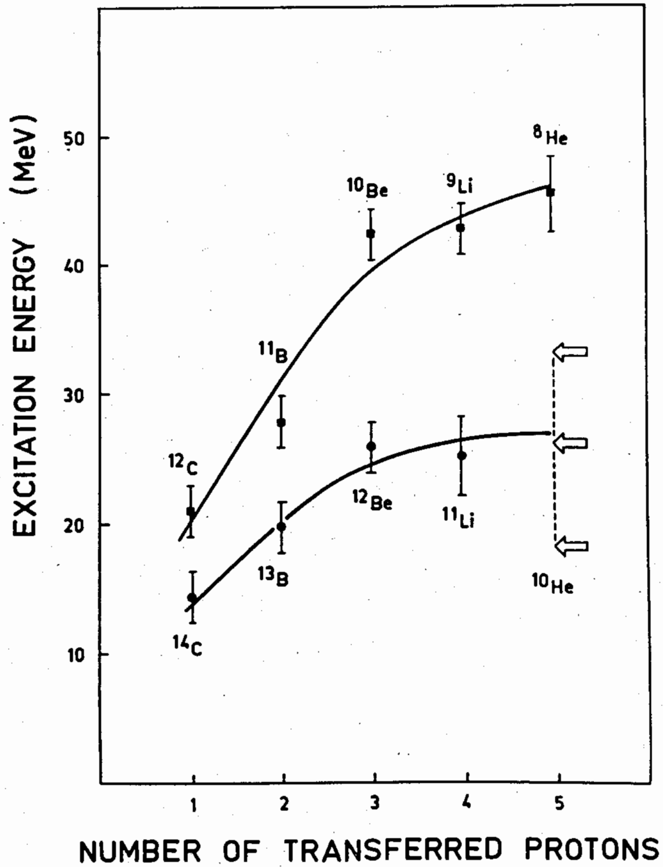

Fig. 2. Excitation energy $E^{ex} = Q_{gg} - Q$ (max) as a function of the number of transferred protons in the (^{15}N - x protons) reactions (lower line) and in the (^{15}N - x protons - 2 neutrons) reactions (upper line). The ^{10}He ions of energy equal to 38 MeV (E^{ex} = 33 MeV), 45 MeV (E^{ex} = 26 MeV) and 53 MeV (E^{ex} = 18 MeV) were searched. These values of E^{ex} are indicated by arrows.

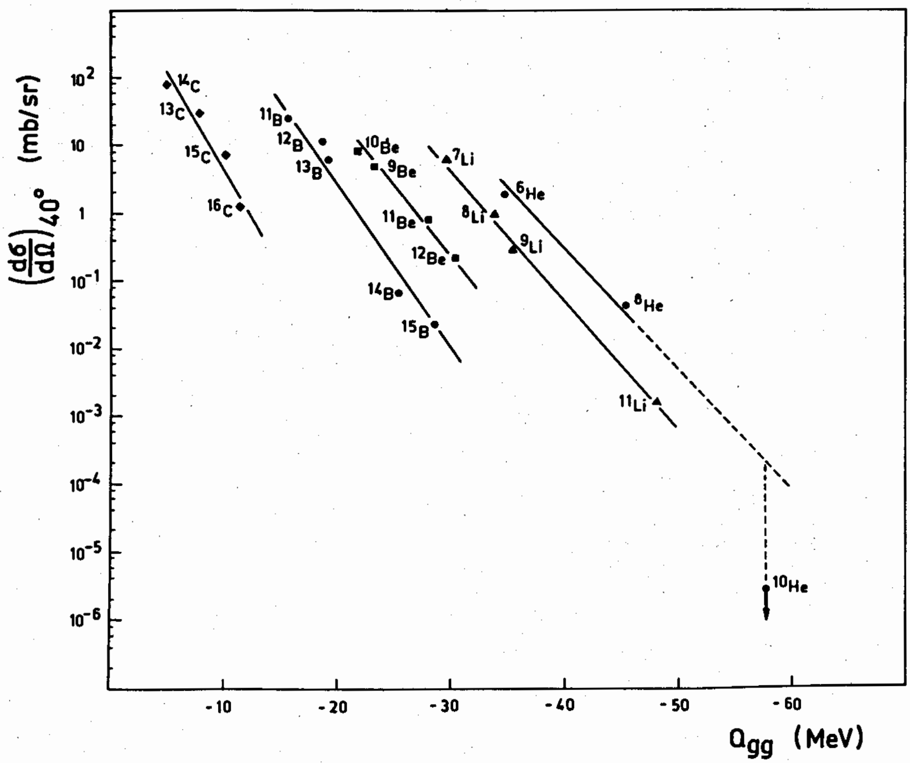

Fig. 3. The differential cross sections $(d\sigma / d\Omega)\ 40^{\circ}$ for production of carbon, boron, beryllium, lithium and helium isotopes in the $^{232}Th + {}^{15}N$ collisions as a function of Q_{gg}. The Q_{gg} – value for ^{10}He corresponds to the particle-stability threshold $E_{2n} = 0$ (for mass exces of ^{10}He equal to 47 MeV).

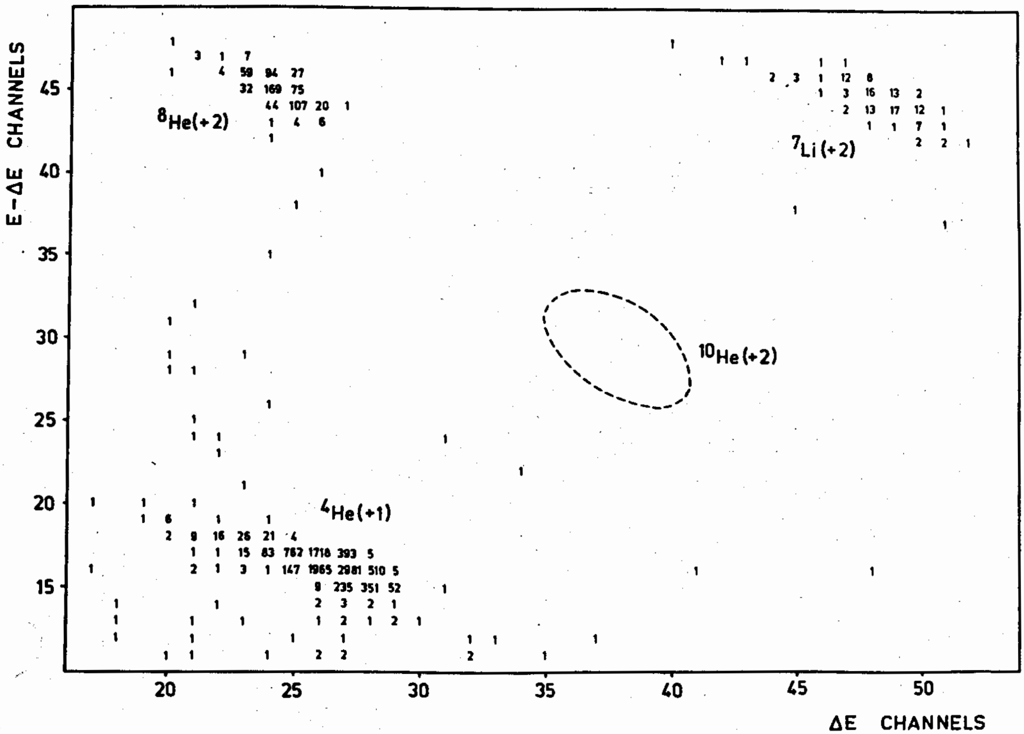

Fig. 4. The two-dimensional identification spectrum. Assuming that ^{10}He is particle stable, about 80 events should be recorded inside the region bordered by the dashed line.