NEUTRON-RICH ISOTOPES OF LIGHT ELEMENTS PRODUCED IN TRANSFER REACTIONS WITH HEAVY IONS

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I. INTRODUCTION

In the last few years the study of the neutron-rich isotopes of light elements has grown in importance. The discovery of such nuclei as ^{8}He and ^{11}Li has shown that neutron excess in light nuclei may reach a considerable value. This in turn arose the question of the boundary for the particle stability of nucelides with large neutron excess.

The boundary for the proton-rich nuclei can be estimated quite accurately, since the Coulomb repulsion between protons gives strong limitation for the proton excess. In the case of neutron-rich nuclei the problem is not so clear. Different theoretical approaches give quite different results.

The liminations for the neutron excess follow mainly from the Pauli's exclusion principle. For a nucleus with large neutron excess more single particle levels of high energy must be occupied than for the nucleus with the same A but with $N - Z = 0$. Some of these high lying levels may turn out to be unbound.

However, the application of the shell model to light nuclei with large neutron excess arises serious doubts. Recently, the K-harmonic method/1,2/ was used for binding energy calculations in a region of light nuclei. In the framework of this method the ground state solution of the Schroedinger equation for the

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system of nucleons can be obtained with good accuracy. To do that, the nucleon-nucleon force must, of course, be known sufficiently well. For the neutron-rich nuclides the knowledge of the $V^{(33)}$ potential (it is the potential for nucleon-nucleon interaction in the $S = 1$, $T = 1$ state) is especially important. However, the magnitude of $V^{(33)}$ cannot be reliably determined from the experiments on nucleon-nucleon scattering.

As has been pointed out in ref./2/, a small contribution of attractive $V^{(33)}$ potential leads to the possibility of the existence of ^{10}He and even ^{22}He. This statement may, of course, be inverted: studying the properties of light nuclides with large neutron excess one can obtain information on nuclear forces acting between the neutrons. Thus, experiments in this field have a fundamental character.

2. PRODUCTION AND IDENTIFICATION OF NEUTRON-RICH ISOTOPES OF LIGHT ELEMENTS

Several methods have been used until now for production of light neutron-rich nuclides: spontaneous fission of ^{252}Cf, fission of ^{235}U and ^{239}Pu induced by thermal neutrons,reactions with high-energy protons, and finally, reactions of negative pion recharging. In our experiments the neutron-rich isotopes of a number of light elements were produced in transfer reactions with heavy ions. Large variety of the multi-nucleon transfer reactions leads to the production of these isotopes: the proton stripping (projectile-x protons), the neutron pick-up (projectile + y neutrons) and the nucleon exchange reactions (projectile - x protons + y neutrons). Several types of reactions resulting in the production of the neutron-rich nuclides observed in our experiments are listed in Table 1.

Table 1

Types of reactions resulting in the production of neutron-rich isotopes of light elements

1) neutron pick-up

$^{18}O\ (+1n) \rightarrow {}^{19}O$

$^{18}O\ (+2n) \rightarrow {}^{20}O$

$^{18}O\ (+3n) \rightarrow {}^{21}O$

$^{18}O\ (+4n) \rightarrow {}^{22}O$

$^{22}Ne\ (+1n) \rightarrow {}^{23}Ne$

$^{22}Ne\ (+2n) \rightarrow {}^{24}Ne$

$^{22}Ne\ (+3n) \rightarrow {}^{25}Ne$

$^{22}Ne\ (+4n) \rightarrow {}^{26}Ne$

2) proton stripping

$^{11}B\ (-3p) \rightarrow {}^{8}He$

$^{15}N(-4p) \rightarrow {}^{11}Li$

$^{15}N\ (-3p) \rightarrow {}^{12}Be$

$^{16}O\ (-4p) \rightarrow {}^{12}Be$

3) nucleon exchange

$^{15}N\ (-2p,\ +2n) \rightarrow {}^{15}B$

$^{16}O\ (-3p,\ +2n) \rightarrow {}^{15}B$

$^{18}O\ (-2p,\ +2n) \rightarrow {}^{18}C$

$^{18}O\ (-1p,\ +3n) \rightarrow {}^{20}N$

$^{22}Ne\ (-3p,\ +2n) \rightarrow {}^{21}N$

$^{22}Ne\ (-2p,\ +3n) \rightarrow {}^{23}O$

$^{22}Ne\ (-2p,\ +4n) \rightarrow {}^{24}O$

$^{22}Ne\ (-1p,\ +4n) \rightarrow {}^{25}F$

The main experimental difficulty in the study of the direct reactions with heavy ions is the problem of identification of the reaction products. The rediochemical method is not suitable for the detection of nuclides with large neutron excess since they decay in a fraction of a second. Also, the $dE/dx, E$ technique alone is not good enough because of an insufficient isotope resolution.

For an unambiguous identification of the projectile transformation products in transfer reactions we use a heavy-ion identification method which combines a magnetic spectrometer with the $dE/dx, E$ technique/3/ (See, Fig. 1). The reaction products pass the magnetic spectrometer and are detected in a counter telescope placed in the focal plane of the spectrometer. The telescope consists of two semiconductor detectors: a thin ΔE detector and a thick $E - \Delta E$ detector.

The pulses from both detectors, after amplification, are sent to a two-dimensional, 64x64 channel pulse-height analyser. Since only the reaction products with discrete energy values $E = \text{const}\, Z^2_{ion}/M$ can pass the magnetic spectrometer, the values of ΔE and $E - \Delta E$ pulses are also discrete, and therefore, the unambiguous identification of each isotope in two-dimensional spectrum $\Delta E, E - \Delta E$ is possible (an example of such a two-dimensional spectrum is shown in fig. 2).

The method allows an unambiguous identification of all isotopes of light elements emitted from the target of energies higher than 2-3 MeV per nucleon. In comparison with the standard dE/dx,E technique our method gives much better separation of neighbouring isotopes. Moreover, the method allows to remove the elastically scattered particles from the reaction product beam before it gets into the telescope. This gives the possibility to detect the reaction products formed with very small cross sections.

3. NEW ISOTOPES OF CARBON, NITROGEN, OXYGEN, FLUORINE AND NEON PRODUCED IN TRANSFER REACTIONS WITH HEAVY IONS

The results obtained earlier/4/ as well as the data from some additional experiments show that the cross sections for the reactions: (projectile - x protons), (projectile + y neutrons) and (projectile - x protons + y neutrons), leading to the production of neutron-rich isotopes of light elements are large when heavy elements are used as targets. Therefore, the target of ^{232}Th was used in our experiments. It was bombarded with ^{18}O, ^{22}Ne, ^{15}N and ^{11}B ions.

Experiments were performed with the 310-cm heavy ion cyclotron of Nuclear Reaction Laboratory, JINR, at Dubna.

The reaction products were detected at an angle corresponding to the surface collision trajectory. The angular distiributions in these reactions should have the wide maxima near this angle (see, for example, refs./5,6/).

At a given magnetic rigidity BR all the reaction products could be detected only within narrow energy intervals. Measuring the yields of nuclides at different values of BR the energy spectra of the reaction products could be obtained.

As an example, the dependence of the yields of oxygen isotopes on the magnetic rigidity BR is shown in Fig. 3 for the case in which a thorium target was bombarded with 122 MeV ^{18}O ions.

In bombardment of ^{232}Th with ^{18}O ions we expected to produce the ^{22}O isotope in the pick-up reaction of 4 neutrons. The experiment was performed for magnetic rigidity at which the heaviest isotopes of oxygen were observed with maximum yields. The results of the 6-hour irradiation are shown in Fig. 4. Apart from a number of already known nuclides, three new nuclides: ^{22}O, ^{20}N and ^{18}C have been obtained. It should be noted that ^{20}N and ^{18}C nuclides were produced in the nucleon exchange reactions: (projectile - 1 proton + 3 neutrons) and (projectile - 2 protons + 2 neutrons), respectively. Thus, the nucleon exchange reactions turned out to be a very effective way of producing the nuclides with large neutron excess.

In the next series of experiments the thorium target was bombarded with 174 MeV ^{22}Ne ions. In these experiments four new nuclides: ^{23}F, ^{24}F, ^{25}Ne and ^{26}Ne were obtained (Fig. 5). Finally, after increasing the efficiency of the detecting system and increasing the time of irradiation we succeded to obtain subsequent four new nuclides: ^{21}N, ^{23}O, ^{24}O and ^{25}F (Fig. 6).

In bombarding the thorium target with 145 MeV ^{15}N ions all the heaviest known isotopes of helium, lithium, beryllium and boron (^{8}He, ^{11}Li, ^{12}Be, ^{15}B) were produced.

A list of eleven new nuclides produced in transfer reactions with heavy ions, together with the heaviest isotopes of light elements known earlier is presented in Table 2.

Table 2

Isotopes of light elements with large neutron excess produced in transfer reactions with heavy ions

a) known isotopes

^{8}He, ^{11}Li, ^{12}Be, ^{15}B, ^{17}C, ^{19}N, ^{21}O, ^{22}F, ^{24}Ne

b) new isotopes

^{18}C, ^{20}N, ^{22}O, ^{23}F, ^{25}Ne
^{21}N, ^{23}O, ^{24}F, ^{26}Ne
^{24}O, ^{25}F

It should be noted that the yields of neutron-rich isotopes in reactions with heavy ions are much higher than in reactions with high-energy protons. This gives possibility of spectroscopic study of nuclei with large neutron excess. In the Laboratory of Nuclear Reactions, JINR, the experiments in this field were initiated with the use of the magnetic mass-separator operating on-line with the heavy ion cyclotron.

4. THE BOUNDARY OF PARTICLE-STABILITY FOR LIGHT NUCLIDES WITH LARGE NEUTRON EXCESS, EVIDENCE FOR PARTICLE-NONSTABILITY OF ^{14}Be

It is interesting to compare the present list of known nuclides with the theoretical predictions concerning the boundary of particle stability (Fig. 7). It can be seen from Fig. 7 that according to Garvey and Kelson /7/ and Vinogradov and Nemirovsky/8/ the isotopes of H, He, Li, Be and B which are heavier than already known nuclides (^{3}H, ^{8}He, ^{11}Li, ^{12}Be and ^{15}B), should be particle-unstable.

However, the question of the existence of ^{10}He and ^{14}Be has still been unsettled. The calculations of Baz, Demin and Zhukov/2/, performed in the framework of the K-harmonic method, did not exclude the possibility of particle stability of ^{10}He. As for ^{14}Be, only Garvey and Kelson /7/ gave a definite answer. They predict that the neutron binding energy in ^{12}Be is equal to

-2.7 MeV and the binding energy of two neutrons in ^{14}Be is equal to -2.4 MeV. According to Vorobiev et al./9/ these quantities are -0.1 MeV and +1.9 MeV, respectively. The analysis in the framework of the shell model/8/ did not provide an unambiguous answer. Some years ago Poskanzer et al./10/ reported their experimental results which suggested that ^{13}Be is probably particle-unstable.

We undertook experiments with the aim to give an answer to the question of the existence of ^{10}He and ^{14}Be. The experiments on ^{10}He are under way. Here we report only the results of the experiment on ^{14}Be.

The experiment can give a definite answer to the above question because one can estimate the expected yield of a given nuclide from the cross section systematics for multi-nuclon transfer reactions, as reported by us elsewhere/10/. The cross sections for the nucleon stripping - and nucleon exchange reactions (projectile - x protons ± y neutrons) depend exponentially on the Q-values, calculated for the ground state masses of the reaction products. As an example of this dependence the data on cross sections for production of a large number of nuclides in the bombardment of a thorium with 137 MeV ^{16}O ions is shown in Fig. 8.

The search for ^{14}Be was performed in the ^{15}N + ^{232}Th reaction at the energy of ^{15}N ions equal to 145 MeV. The values of differential cross sections $(d\sigma/d\Omega)_{40^\circ}$ for the production of carbon, boron, beryllium and lithium isotopes in this reaction are shown in fig. 9. The extrapolated line for beryllium isotopes (shown in fig.9) should not contain any significant error, since the neighbouring lines are almost parallel and fit well the experimental points in a wide range of the cross section values.

In our experiment we detected about 20000 events of ^{12}Be, whereas no effect due to the ^{13}Be and ^{14}Be ions was observed. The background, defining the upper limit of the ^{13}Be and ^{14}Be yields was about 3 events. Assuming that ^{13}Be and ^{14}Be are extremely weakly bound the expected yields of ^{13}Be and ^{14}Be should be about 550 events and 30 events, respectively. In the case of the binding energy of two neutrons in ^{14}Be equal to 1.9 MeV, as suggested by Vorobiev et al./9/, the expected yield of ^{14}Be should be even larger (about 70 events).

Fig. 9 shows that even so weakly bound nuclei as ^{14}B and ^{11}Li are produced with yields consistent with our systematics. Therefore, we can conclude that in all probability the ^{13}Be and ^{14}Be nuclei are particle-unstable.

The problem of the particle-stability of ^{10}He is now under study in a similar experiment.

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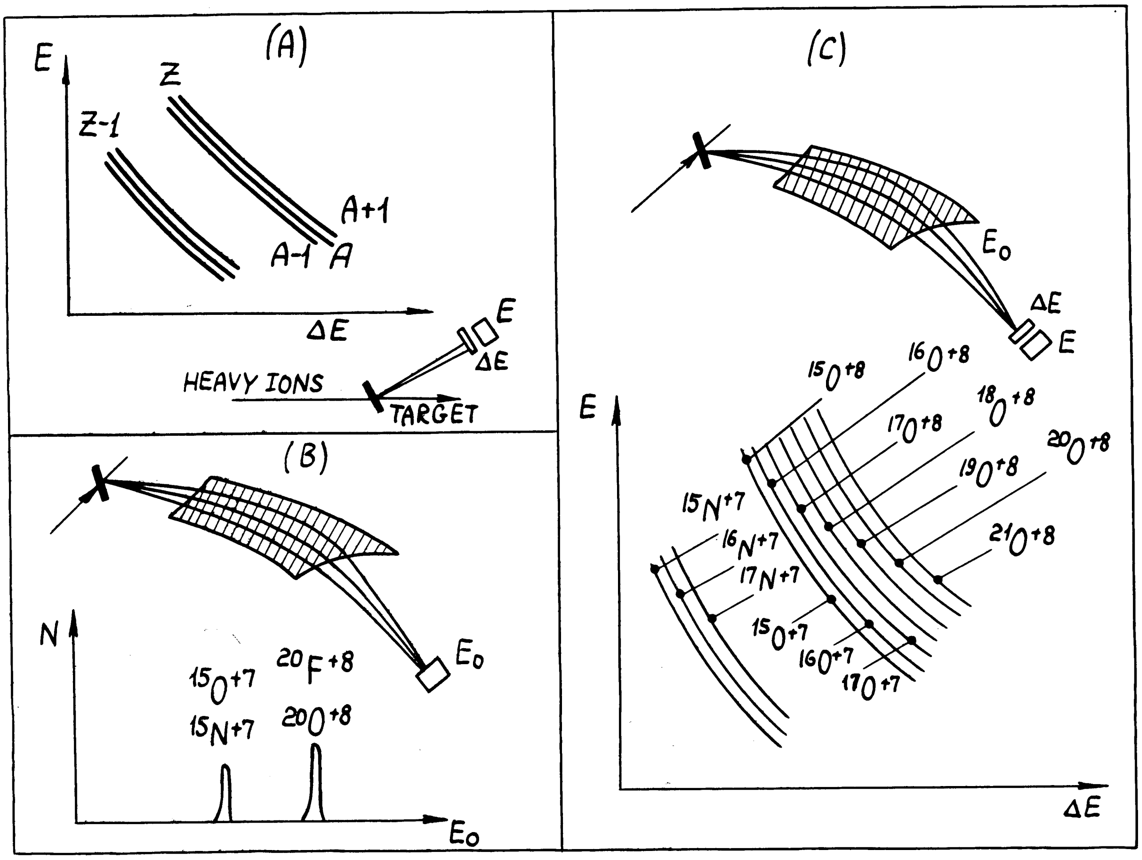

Fig. 1. Comparison of the methods of particle identification: (A) the standard $dE/dx, E$ method; (B) the magnetic analysis with the measurements of energy; (C) the combination of the magnetic analysis with the $dE/dx, E$ method.

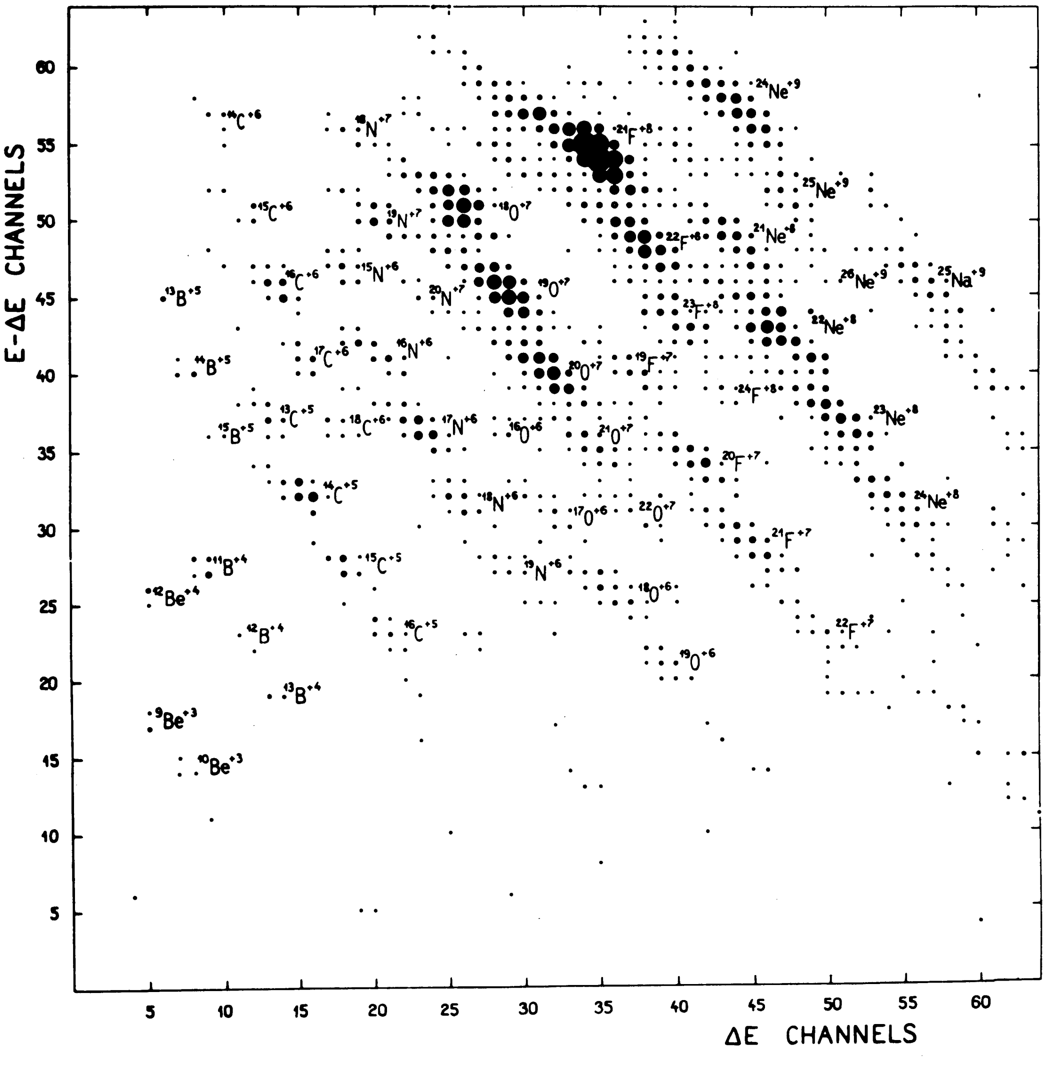

Fig. 2. Two-dimensional (ΔE, E-ΔE) spectrum obtained in bombardment of the ^{232}Th target with 174 MeV ^{22}Ne ions. The area of each circle is proportional to the square root of the number of counts.

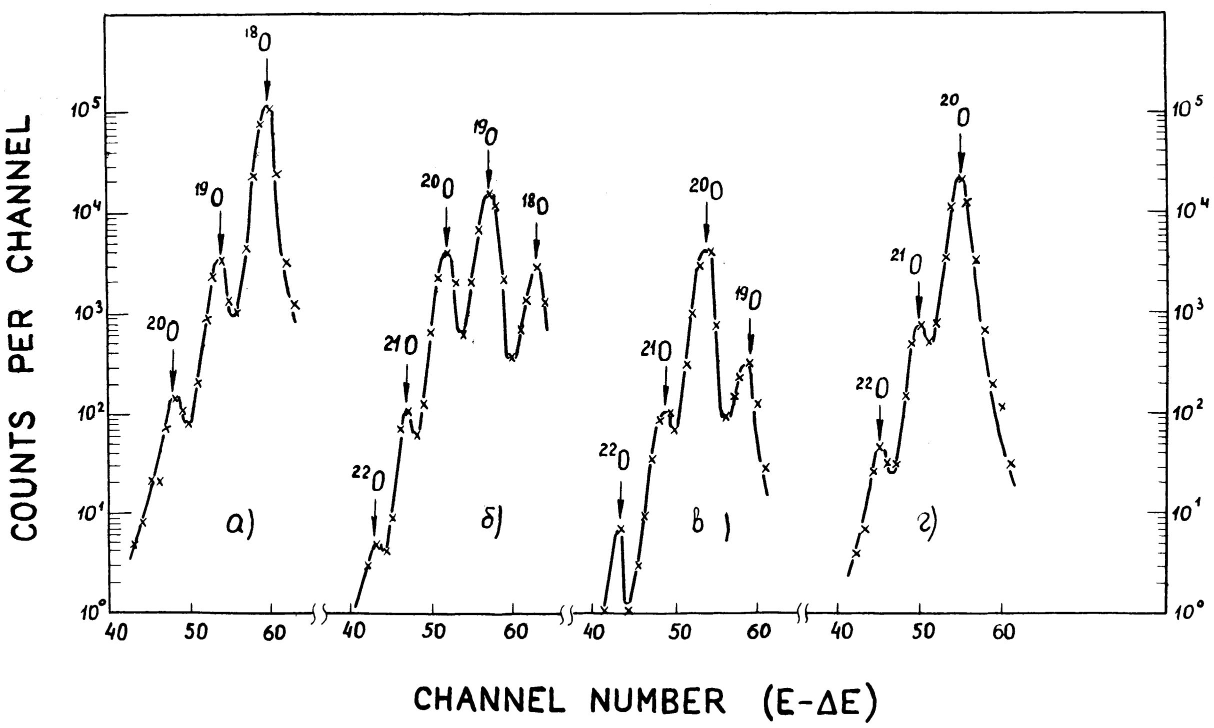

Fig. 3. Yields of oxygen isotopes from the ^{232}Th + ^{18}O reaction (E(^{18}O) = = 122 MeV) at four different values of the magnetic rigidity BR. a) BR = = 7.87 kGs.m, the ion flux through the target J = 2.3.10^{14} particles; b) BR = 8.03 kGs.m, J = 1.9.10^{15} particles; c) BR = 8.10 kGs.m, J = = 1.9.10^{15} particles; d) BR = 8.17 kGs.m, J = 1.4.10^{16} particles.

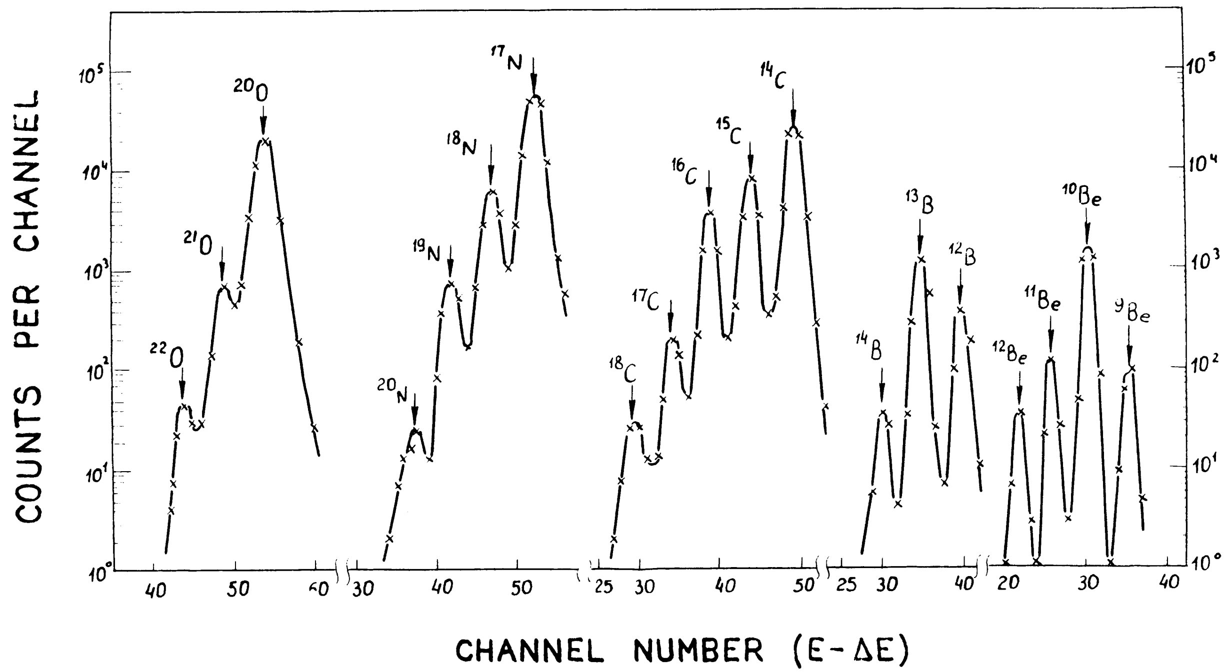

Fig. 4. Yields of oxygen, nitrogen, carbon, boron and beryllium isotopes from the $^{232}Th + {}^{18}O$ reaction. $E(^{18}O) = 122$ MeV; BR = 8.17 kGs.m; the ^{18}O flux through the target $J = 1.4.10^{16}$ particles.

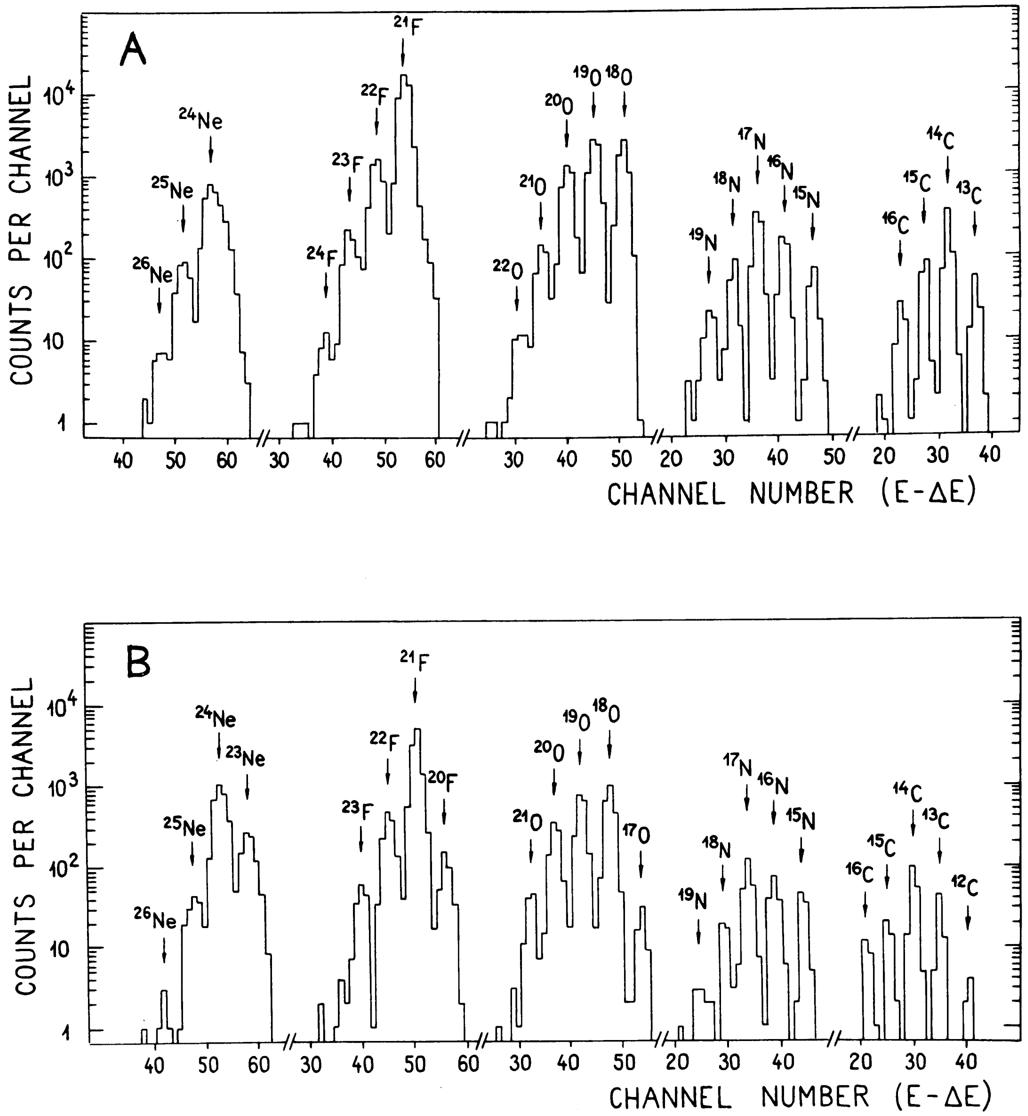

Fig. 5. Yields of neon, fluorine, oxygen, nitrogen and carbon isotopes from the ^{22}Ne + ^{232}Th reaction. E (^{22}Ne) = 174 MeV. (A) BR = = 9.92 kGs.m, the ^{22}Ne flux through the target J = $9.2.10^{15}$ particles; (B) BR = 9.74 kGs.m, J = $2.3.10^{15}$ particles.

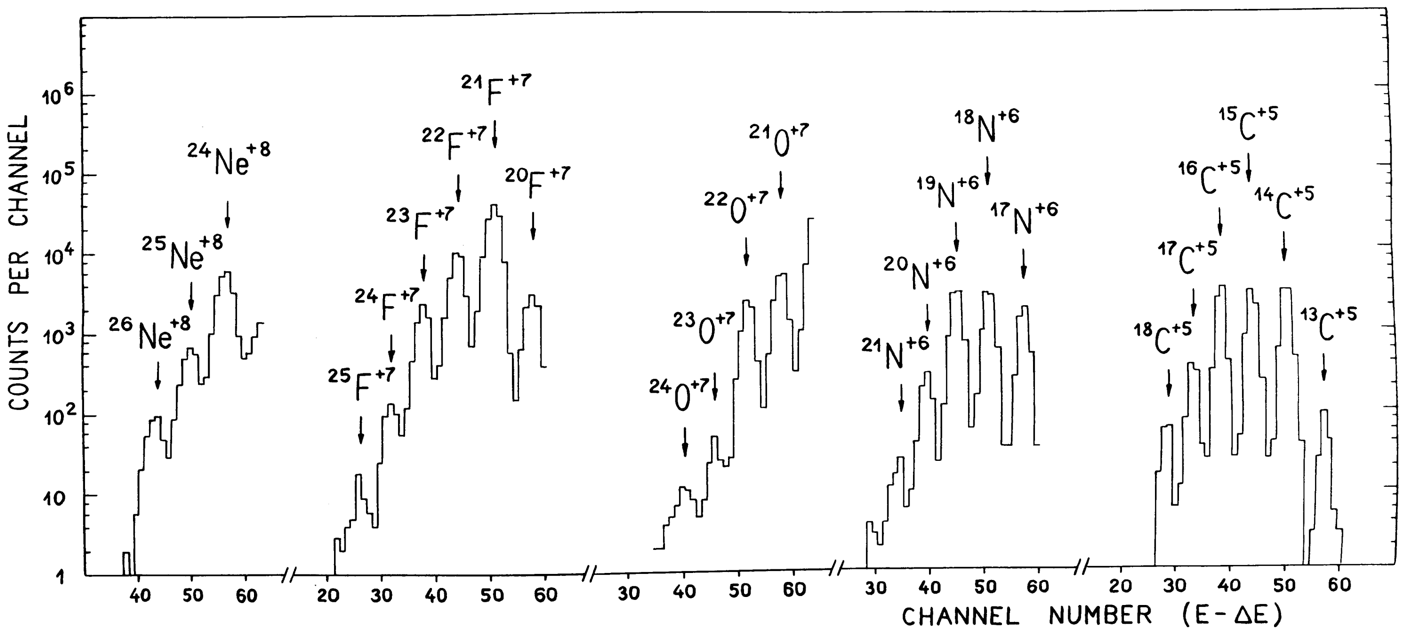

Fig. 6. Yields of neon, fluorine, oxygen, nitrogen and carbon isotopes from the ^{22}Ne + ^{232}Th reaction. $E(^{22}Ne)$ = 174 MeV; BR = 10.4 kGs.m; the ^{22}Ne flux through the target $J = 5.1.10^{16}$ particles.

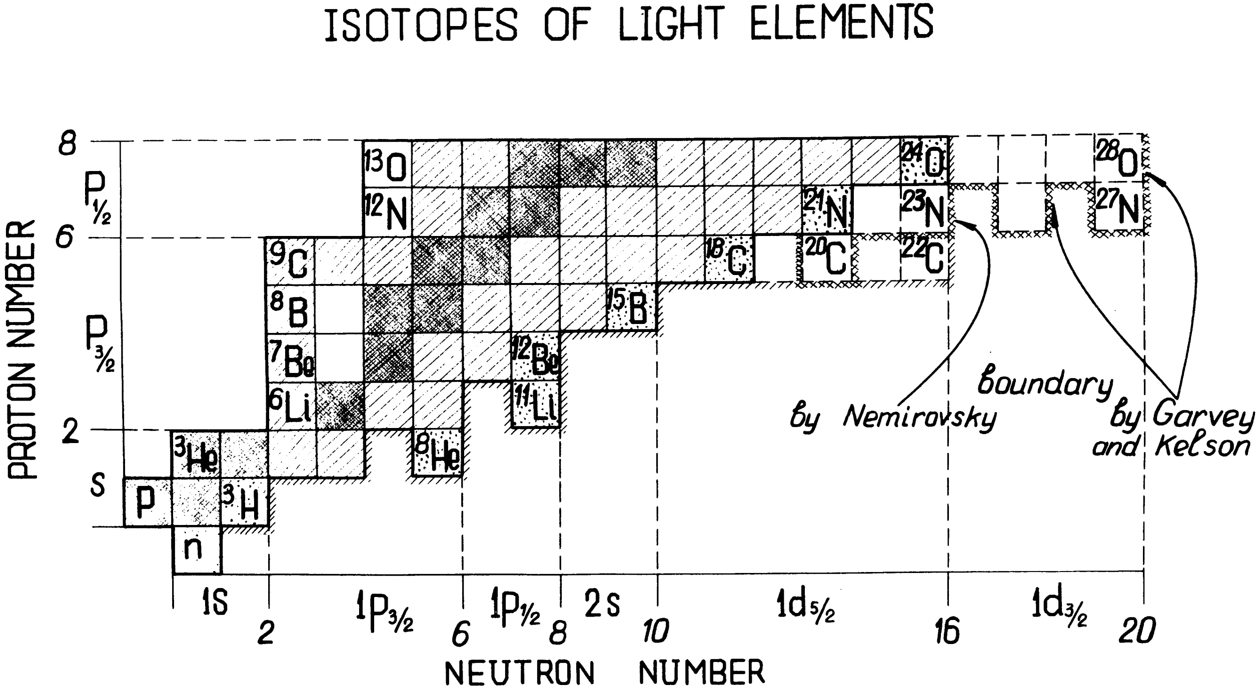

Fig. 7. Theoretical predictions concerning the boundary of particle stability for light nuclides with large neutron excess.

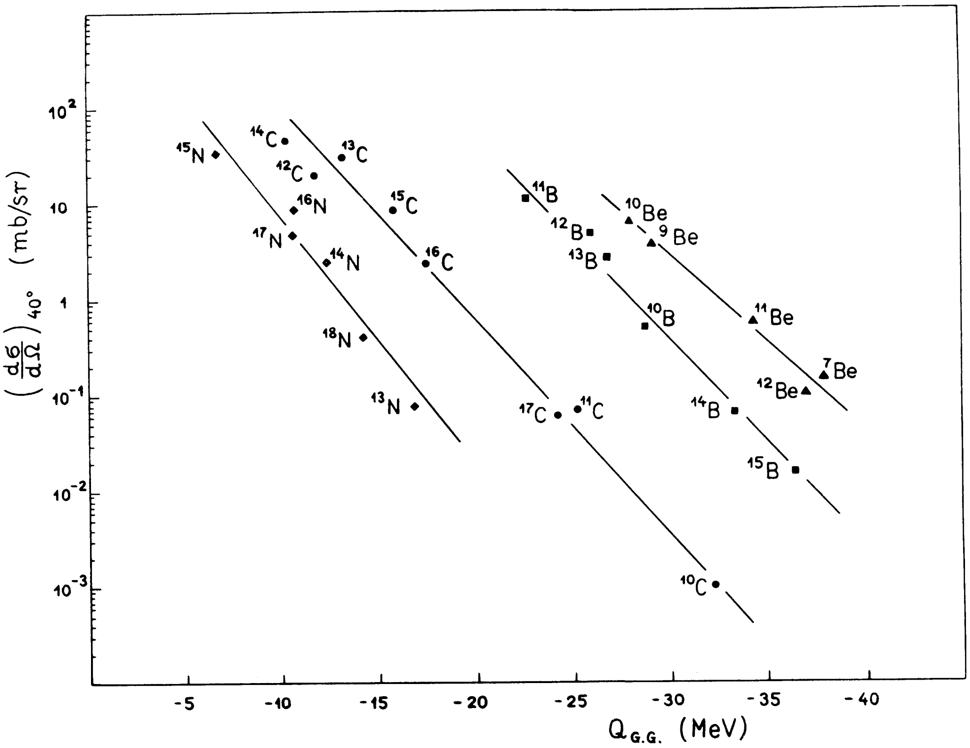

Fig. 8. Differential cross sections $(d\sigma/d\Omega)_{40°}$ for production of Be, B, C and N isotopes in the ^{232}Th+^{16}O reaction as function of Q_{gg}.

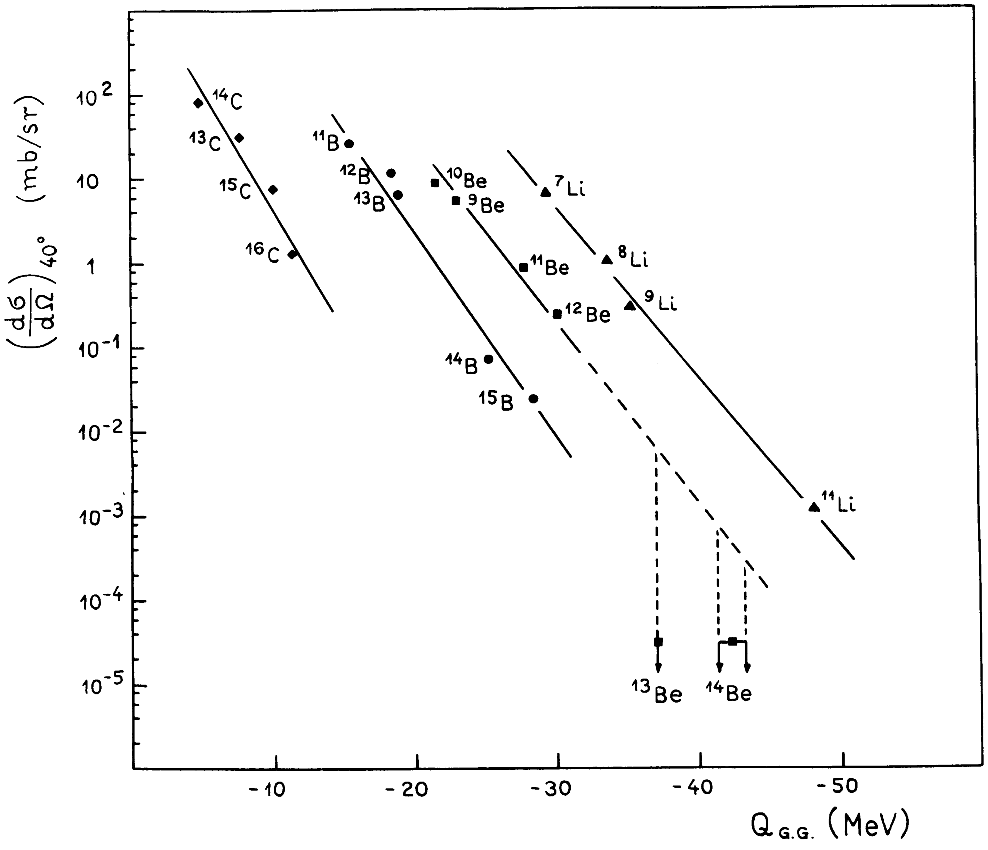

Fig. 9. Differential cross sections $(d\sigma/d\Omega)_{40°}$ for production of Li, Be, B and C isotopes in the ^{232}Th + ^{15}N reaction as function of Q_{gg}. The Q_{gg}-value for ^{13}Be correspond to the particle-stability threshold ($E_n = 0$). For ^{14}Be the left and right arrows indicate the Q_{gg}-values for $E_{2n} = +1.9$ MeV and $E_{2n} = 0$, respectively.