ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E7 - 6764

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ЛАБОРАТОРИЯ ЯДЕРНЫХ РЕАКЦИЙ

1972

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Submitted *to Nuclear Physics*

1. Introduction

The multinucleon transfer reactions induced by heavy ions of comparatively high energies have recently been used for the production of many exotic nuclei with large neutron excess (see, e.g., refs. /1,2/). Investigations of some specific aspects of the reaction mechanism, which were performed with the aim to make the search for the new neutron-excessive nuclides more effective, have revealed an exponential dependence of the cross section on the ground state Q-value, Q_{gg} /3,4/. This unexpectedly simple dependence of the cross section on Q_{gg} has been explained by Bondorf et al. /5/ by introducing the concept of partial statistical equilibrium in the system of two colliding nuclei. These authors also studied the kinematics of the multinucleon transfer reactions and invented a model which can be used for predicting the most probable Q-value for the reaction with a given number of the transferred (or exchanged) nucleons /6/.

Also Toeppfer /7/ and Abul-Magd et al. /8/ have proposed models to explain some of the experimentally observed features of the multinucleon transfer reactions.

Multinucleon transfer reactions on heavy nuclei have been studied in refs. /9–14/ using the radiochemical or $\Delta E, E$ methods. However, both of these methods have some serious restrictions. The radiochemical method does not allow us to detect stable isotopes and makes it difficult to measure energy spectra, whereas the $\Delta E, E$ method makes it impossible to separate isotopes of elements with $Z > 8$. The combination of the magnetic analysis and the $\Delta E, E$ method removes these restrictions and permits the reliable detection and identification of light transfer reaction products in the wide range of A and Z /15/.

In this work the energy spectra of about 60 separated reaction products (particles with $3 \leq Z \leq 12$), produced in the bombardment of ^{232}Th with 174 MeV ^{22}Ne ions, were measured at 40° with respect to the beam direction, i.e., near the angle corresponding to the grazing trajectory, where the angular distributions (for predominant reactions) reach their maxima.

2. Experimental Method

The $^{22}Ne(+4)$ beam with intensity $1\text{–}2\,\mu A$ and energy 174 MeV from the 310 cm cyclotron of JINR at Dubna was used to bombard a 2.5 mg/cm^2 target of metallic ^{232}Th.

For detection and identification of light reaction products (with $A < 40$) a system combining magnetic analysis and $\Delta E, E$ techniques was used. Reaction products went through a magnetic spectrometer and were detected in a telescope of two solid-state, surface-barrier detectors: a ΔE detector of thickness 59 μm (or 27 μm) and an E detector. A two-dimensional $\Delta E, E - \Delta E$ spectrum was recorded in a 4096-channel analyser, operating in a 64 x 64 channel mode.

Energy spectra of the reaction products were obtained by measuring the product yields at different magnetic fields in the spectrometer. The yields of products in different charge states for each definite energy have been summarized. The yields were normalized with respect to the elastically scattered ^{22}Ne ions, detected in a monitor solid state counter. Magnetic field in the spectrometer (determining the energies of the particles in each run) was measured by the nuclear resonance method.

In order to obtain absolute data the angular distribution of elastically scattered ^{22}Ne particles was measured. The ratio $\sigma_{el}/\sigma_{Ruth}$ at 40° was found to be 1.17.

3. Results and Discussion

Energy spectra of 58 different reaction products (isotopes of Li, Be, B, C, N, O, F, Ne, Na and Mg) produced in the bombardment of ^{232}Th with 174 MeV ^{22}Ne ions and emitted from the target at 40°, are shown in figs. 1, 2 and 3. With the exception of single nucleon transfer reactions, the energy spectra are of approximately a bell-shaped form with FWHM ranging from 10 MeV to 40 MeV. With decreasing number of transferred nucleons the maxima shift towards higher energies and the spectra become more asymmetric. The mechanism responsible for the low energy ''tails'' in spectra is not clear to us. Test experiments have shown that the possible admixtures of carbon and oxygen in the target do not explain this feature.

The kinematics of the reactions leading to the production of the observed nuclei, can be analysed considering these reactions as two-body processes. The multinucleon transfer reactions investigated in this work are, as a rule, very endoenergetic. The Q-values corresponding to the maxima in the energy spectra reach magnitudes up to $Q{=}-130$ MeV (for lithium isotopes). Nevertheless, such large, negative Q-values do not contradict the assumption of the two-body mechanism because the maxima are still situated above the threshold energies corresponding to the Coulomb barrier for final nuclei.

The Q-values corresponding to the maxima of the energy spectra had been analysed in the framework of the model of Siemens et al./6/. The main assumption of the model is that in the surface collision of two nuclei the transferred nucleons bring their momenta into the resulting nuclei. The transferred momentum is taken as the average value defined by the velocity of the donor nucleus immediately before the transfer takes place (the internal motion of the nucleons is not taken into account because it causes only a certain dispersion of the transferred momentum around this average value). Three parameters are introduced in this model: U_0-effective nuclear potential (the same in the initial and all final reaction channels), r_0 -nuclear radius parameter corresponding to the maximum of Coulomb barrier between the colliding nuclei, and E_{ex} - the loss of kinetic energy of the system, which does not depend on the number of transferred nucleons (the same for all final reaction channels). Such a 3-parameter fit to the measured Q-values is shown in fig. 4. Its parameters are: $-18\ \text{MeV} \geq U_0 \geq -32$ MeV, $r_0 = 1.5$ fm, and $E_{ex} = 14$ MeV. The model does not enable one to determine unambiguously all three parameters if we do not assume arbitrarily the division of E_{ex} between the initial and final reaction channels. Assuming that $E_{ex}^{in} = E_{ex}^{out} = 7$ MeV, the effective potential parameter turns out to be $U_0 = -25$ MeV. The procedure of fitting the experimental data is not sensitive to the variation of r_0 . The *rms* difference decreases with increasing r_0 for low r_0-values and does not practically change for $r_0 > 1.5$ fm. Therefore, we took the value $r_0 = 1.5$ fm, as the most realistic one.

Figure 4 shows that the experimental data appear to contain systematic deviations from the simple model proposed by Siemens et al./6/, especially for the reactions with the transfer of a small number of nucleons. Nevertheless, the model reproduces quite well the overall features of the multinucleon transfer kinematics, and consequently, it can be used for predicting the positions of maxima in the energy spectra (such a problem arose in our previous work, when the ^{10}He nucleus was searched for experimentally /4/).

Besides the kinematics, also the relations among the cross sections for production of different reaction products are essential for understanding the reaction mechanism. In our previous papers/3,4/ it has been shown that for the most endoenergetic reactions involving stripping of many nucleons the logarithm of $d\sigma/d\Omega$ depends almost linearly on the ground state Q-value. Different attempts to explain this regularity have been undertaken based on the molecular wave function method /7/ the statistical theory /8/, and the concept of partial statistical equilibrium /5/. The last one seems to be most realistic. Experimentally observed features (especially angular distributions) show that the system of two colliding nuclei does not lose the memory of its motion in the direction of the relative velocity and, therefore, pure statistical methods cannot be applied in this case.

The data presented in figs. 1, 2 and 3 can be used for the analysis of the cross section relations in many aspects. By integrating the $d^2\sigma/dE \cdot d\Omega$ curves over energy the values of $d\sigma/d\Omega$ were obtained (they are compiled in table 1). In the cases when the energy spectra have, beside the main peak, also a "tail" at low energies (e.g. ^{12}C, ^{14}N, ^{15}O), only the part of the spectrum of characteristic bell-shape form was integrated. The data concerning the nuclides for which the energy spectra are not shown in figs. 1, 2 and 3 (^{11}Li, ^{15}B, ^{21}N, ^{23}O, ^{17}F, ^{24}F, ^{19}Ne, ^{26}Ne, ^{21}Na, ^{28}Na, ^{23}Mg, ^{28}Mg and ^{29}Mg) are also listed in table 1. These energy spectra could not be precisely measured because of extremely small yields. They do not give reliable information concerning the reaction kinematics but may be used for the cross section estimates.

The whole set of cross sections has been analysed with the aim to examine the deviations from the exponential dependence of $d\sigma/d\Omega$ on Q_{gg}. This phenomenological relation can be written in a more general form:

$$\frac{d\sigma}{d\Omega} = const \cdot e^{kQ_{gg}} \cdot f(\Delta z) \cdot F, \qquad (1)$$

where $f(\Delta z)$ is a factor depending on the change of the Coulomb interaction energy due to proton transfer between two ions /3,5/. Considering separately the reactions with $\Delta z =$ const we can write:

$$\ln\left(\frac{d\sigma}{d\Omega}\right) - kQ_{gg} = \ln F + const.$$

The left-hand side of this expression represents the extracted factor responsible for the deviations from the exponential dependence of $d\sigma/d\Omega$ on Q_{gg}. We examined which factors condition the changes of $\ln(d\sigma/d\Omega) - kQ_{gg}$. The value of k ($k = 0.447$ MeV^{-1}) was determined from the data on Li, Be and B isotopes for which the dependence of $d\sigma/d\Omega$ on Q_{gg} shows no deviation from the exponent. To calculate the Q_{gg} values the known masses of nuclides have been taken, including the results of the new mass measurements for ^{12}Be /16/, ^{18}N /17/, $^{21,22}O$ /18/ ^{22}F /17/, ^{26}Na/19/and ^{29}Mg /20/. In the cases where the masses of the nuclides had not yet been measured, the values predicted in the framework of the method of Garvey and Kelson /21–23/ were taken.

Figure 5 shows the values of $\ln(d\sigma/d\Omega) - kQ_{gg}$ as a function of the mass number of the detected particle. For light elements (Li, Be, B) they are nearly the same for all the observed, isotopes, but for heavier elements the experimental points form the curves with distinct maxima. This shows that the factor F in the formula (1) varies systematically with the mass number of resulting isotope. Interpretation of this feature is an open question.

Figure 5 shows that the cross sections for all the multinucleon transfer reactions follow the same general systematics, covering the stripping, pick-up, and exchange reactions as well. This phenomenological systematics can be used for predicting the cross sections for the production of new nuclides.

The authors wish to express their gratitude to Academician G.N.Flerov for his permanent interest in this work. Thanks are also due to B.A.Zager and the cyclotron operation staff for their cooperation.

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Received by Publishing Department
on October 23, 1972.

Table 1

Differential cross sections $(d\sigma/d\Omega)_{40^\circ}$ in (μb/sr) for the production of Li, Be, B, C, N, O, F, Ne, Na and Mg isotopes in the ^{232}Th + ^{22}Ne (174 MeV) system.

Number of transferred protons	Number of transferred neutrons												
	-7	-6	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5
+2							^{23}Mg $\leqslant 0.9$	^{24}Mg 104	^{25}Mg 380	^{26}Mg 850	^{27}Mg 600	^{28}Mg 240	^{29}Mg $\leqslant 18$
+1						^{21}Na $\leqslant 0.7$	^{22}Na 143	^{23}Na 3420	^{24}Na 3400	^{25}Na 2430	^{26}Na 620	^{27}Na 87	^{28}Na $\leqslant 6$
0					^{19}Ne 6 ± 4	^{20}Ne 2880	^{21}Ne 19800	^{22}Ne 3130000	^{23}Ne 54800	^{24}Ne 11100	^{25}Ne 520	^{26}Ne 24 ± 12	
-1				^{17}F 12 ± 6	^{18}F 310	^{19}F 7360	^{20}F 16500	^{21}F 45000	^{22}F 7120	^{23}F 1190	^{24}F 60 ± 30		
-2			^{15}O 10 ± 3	^{16}O 3930	^{17}O 6720	^{18}O 24800	^{19}O 19600	^{20}O 18900	^{21}O 1720	^{22}O 240	^{23}O 2 ± 1		
-3			^{14}N 350	^{15}N 6180	^{16}N 2990	^{17}N 3700	^{18}N 1140	^{19}N 500	^{20}N 42	^{21}N 3 ± 2			
-4		^{12}C 2220	^{13}C 3660	^{14}C 6260	^{15}C 1460	^{16}C 690	^{17}C 90	^{18}C 25					
-5		^{11}B 1840	^{12}B 565	^{13}B 300	^{14}B 18	^{15}B 4 ± 2							
-6	^{9}Be 1180	^{10}Be 1090	^{11}Be 71	^{12}Be 20									
-7	^{8}Li 160	^{9}Li 35		^{11}Li 0.2 ± 0.2									

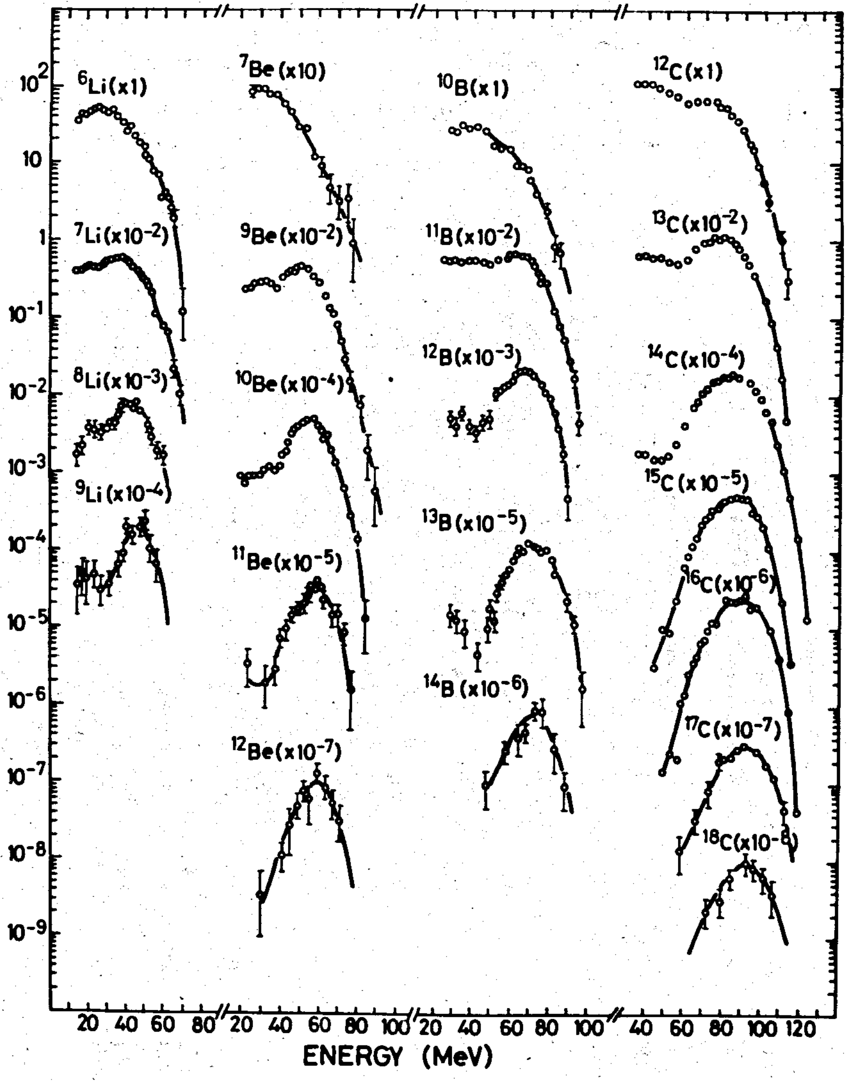

Fig. 1. Energy spectra of isotopes of *Li*, *Be*, *B* and *C* produced in the bombardment of ^{232}Th with 174 MeV ^{22}Ne ions (Θ_{lab} = 40°.).

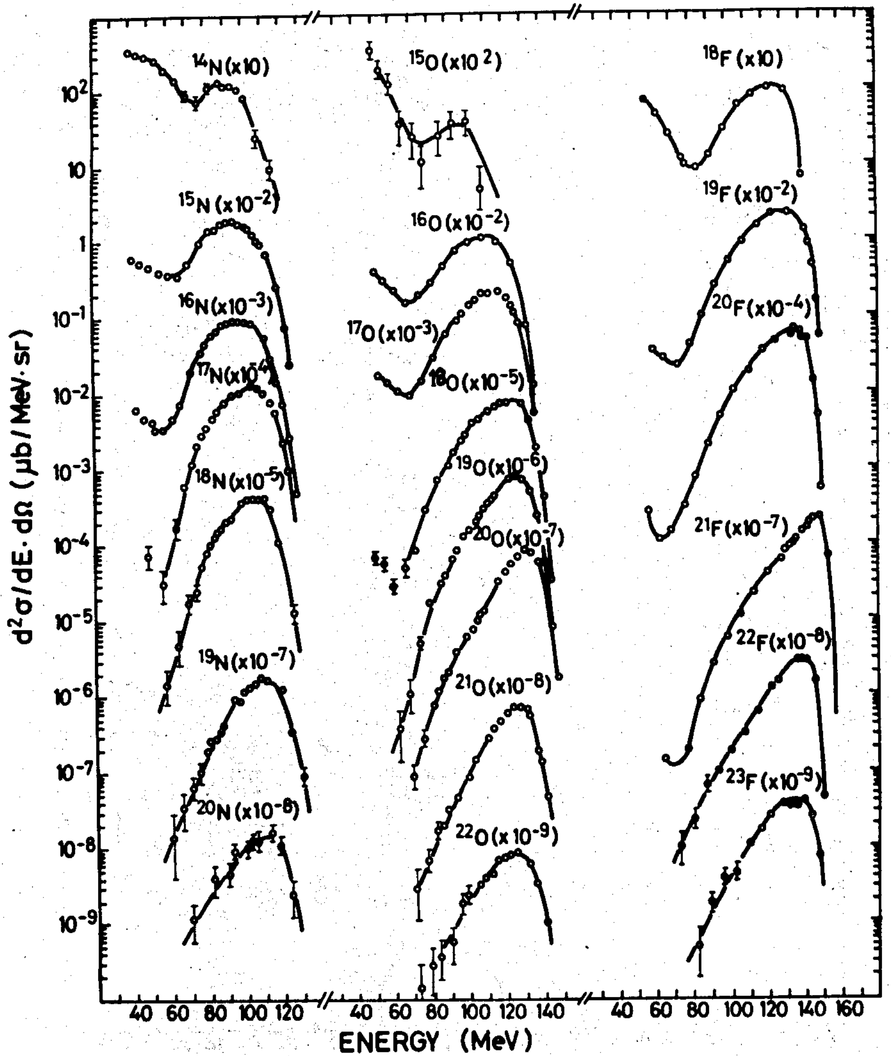

Fig. 2. Energy spectra of isotopes of N, O and F produced in the bombardment of ^{232}Th with 174 MeV ^{22}Ne ions ($\Theta_{lab} = 40°$).

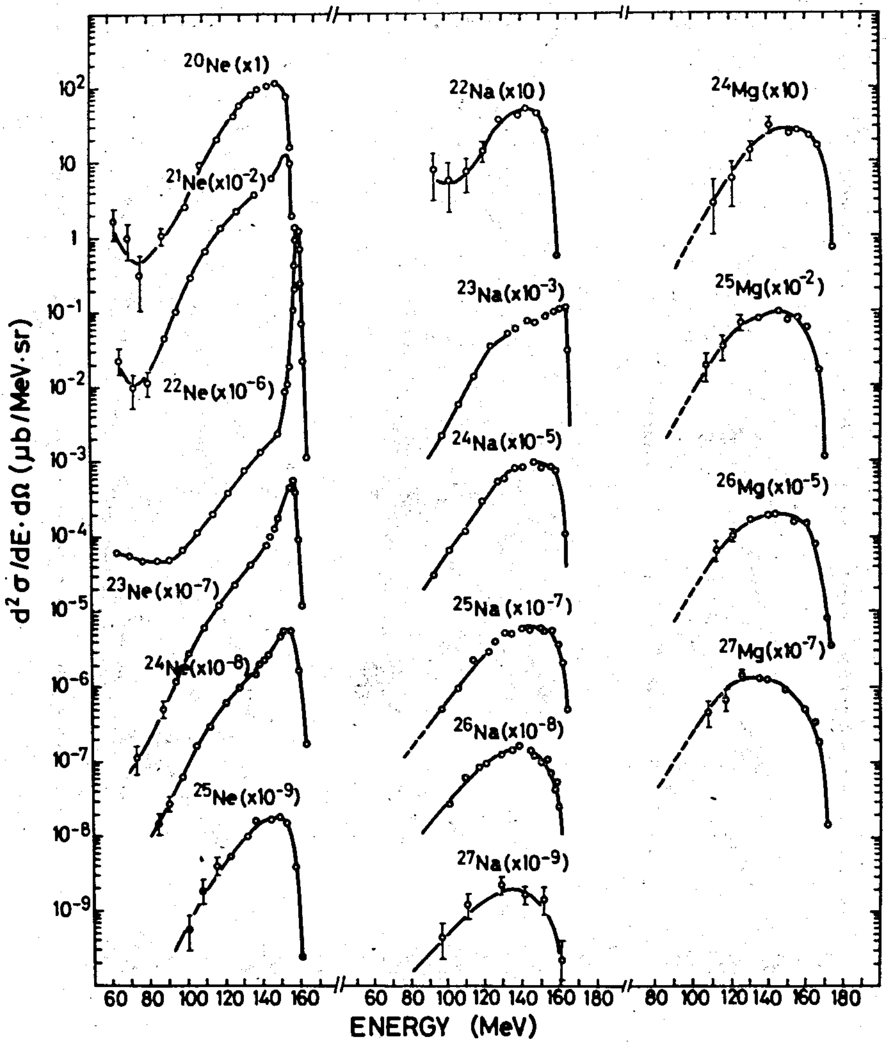

Fig. 3. Energy spectra of isotopes of *Ne* , *Na* and *Mg* produced in the bombardment of ^{232}Th with 174 MeV ^{22}Ne ions($\Theta_{lab} = 40^o$).

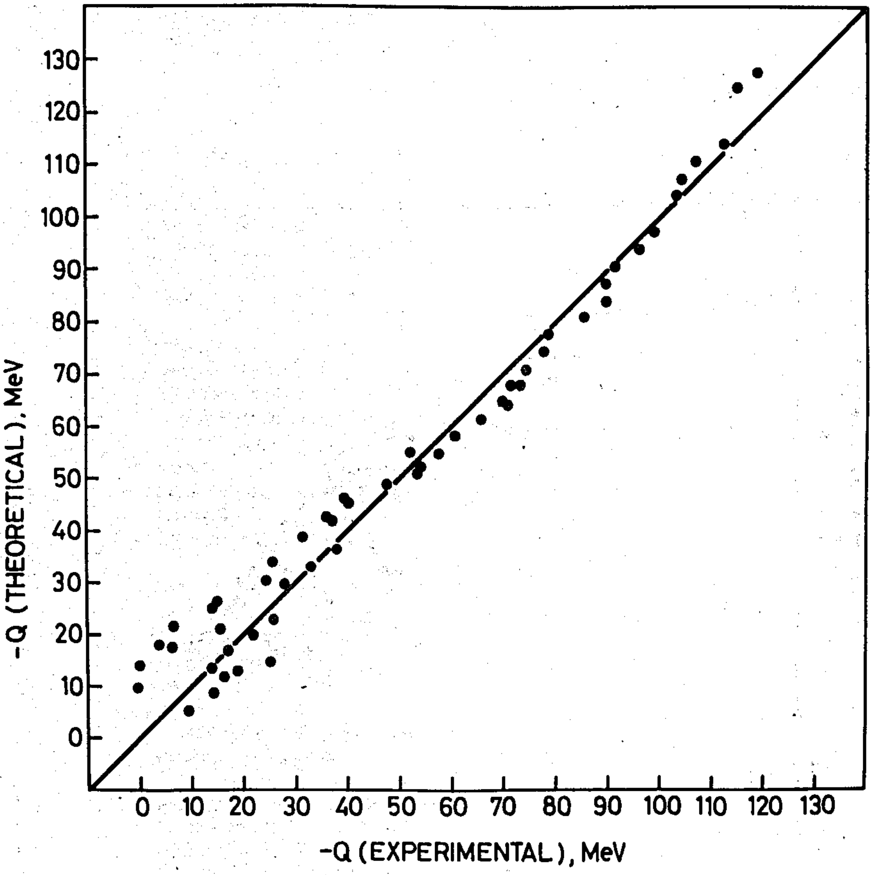

Fig. 4. Comparison of the experimental Q -values corresponding to the maxima of the energy spectra from figs. 1, 2 and 3 with theoretical predictions/6/ (-18 MeV $\geq U_0 \geq$ - 32MeV, $r_0 =$ 1.5 fm, $E_{ex} =$ 14 MeV).

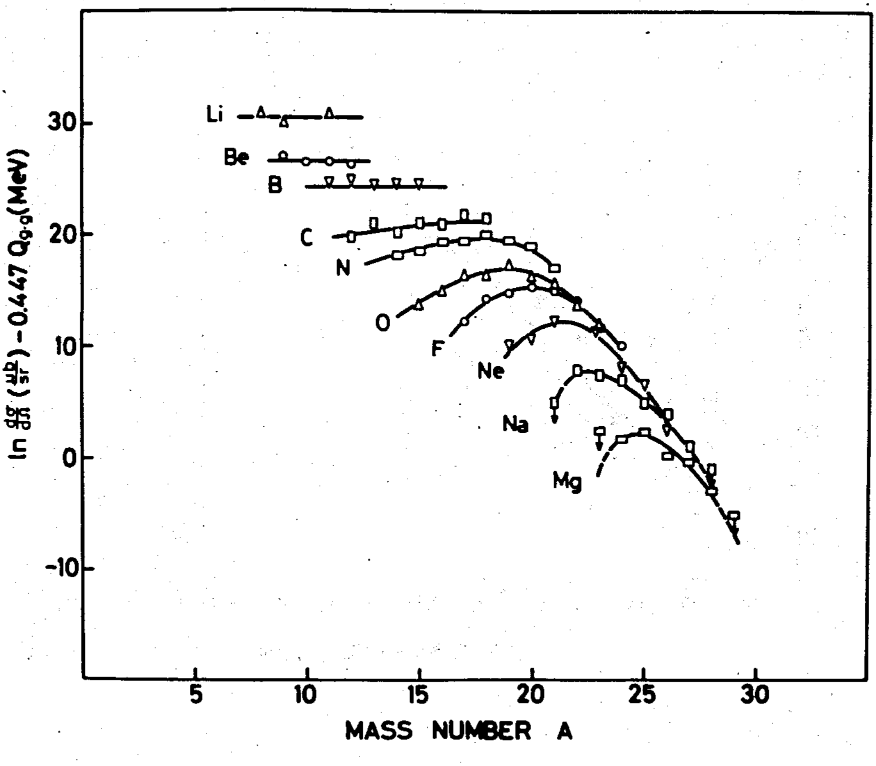

Fig. 5. Deviations from the $d\sigma / d\Omega = const. \exp(k \cdot Q_{gg})$ dependence as a function of mass number of the observed reaction product.