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ON SOME REGULARITIES IN MULTI-NUCLEON TRANSFER REACTIONS WITH HEAVY IONS

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1. Introduction

Nuclear reactions with heavy ions represent, as was shown in our previous papers /1-3/, an effective way of producing neutron-rich isotopes of light elements. Large variety of the multi-nucleon transfer reactions of the following three types: (i) protons stripping (projectile $-x$ protons), (ii) neutrons pick-up (projectile$+y$ neutrons), (iii) nucleon exchange reactions (projectile $-x$ protons $+y$ neutrons), leads to the production of these isotopes.

In a search for new neutron-rich isotopes it is very important to have some information about the cross sections for the reactions in which these isotopes are produced. Systematic experimental data on cross sections for multi-nucleon transfer reactions were obtained previously /4,5/ with the radio-chemical method. The cross sections for production of many radioactive nuclei into which the target nucleus may be transformed after the collision have been measured in this way. However, these data give no unambiguous information about the cross sections production of nuclei into which the projectile is transformed.

For the detection of the projectile transformation products in multi-nucleon transfer reactions we used a heavy-ion-identification method which combines a magnetic spectrometer with the dE/dx, E technique. The method allows an unambiguous identification of all the isotopes of light elements (up to neon) emitted from the target with 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.

In the work reported here a systematic data on cross sections for multi-nucleon transfer reactions, especially those leading to the formation of neutron-rich isotopes of light elements were obtained.

The results obtained earlier /6/, 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. The targets of ^{232}Th and ^{197}Au were therefore used in the present experiment. They were bombarded with 137 MeV ^{16}O ions.

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

2. Experimental Procedure

A collimated ^{16}O beam of energy 137 MeV and of intensity 1-2 μA was directed at the target which was placed in the centre of the reaction chamber. The reaction products emitted from the target at 40° with respect to the incident beam passed the magnetic spectrometer and were detected in a counter telescope placed in the focal plane of the spectrometer. The telescope consisted of two semiconductor detectors: a 46.6 μm thick ΔE detector (16 mm in diameter) and a 600 μm thick $E-\Delta E$ detector. The pulses from both detectors, after amplification, were sent to a two-dimensional, 64 x 64 channel pulse-height analyser. Since only the reaction products with discrete energy values $E = const \cdot Z^2_{ion}/M$ could pass the magnetic spectrometer, the magnitudes of ΔE and $E-\Delta E$ pulses were also discrete, and therefore, the unambiguous identification of each isotope in two-dimensional spectrum ΔE, $E-\Delta E$ was possible. For more detailed information concerning the experimental technique we refer to our previous paper[7].

Energy spectra of the reaction products were obtained by measuring the yields at different values of magnetic rigidity BR. The yields were normalized to the counts of the monitor-semiconductor detector placed in the reaction chamber at 30° with respect to the incident beam.

The measurements were performed at the angle $\theta_{lab} = 40^{\circ}$ only. However, the experimental data on the angular distributions in the multi-nucleon transfer reactions (see for example refs.[8,9]) suggest that in the case of the reactions investigated by us the angular distributions should have a wide maximum near the angle $\theta_{lab} = 40^{\circ}$. One can therefore expect that the values of $(d\sigma/d\Omega)_{40^{\circ}}$, reported here, reflect relations between the total cross sections.

The values of the differential cross sections $(d\sigma/d\Omega)_{40^{\circ}}$ were obtained by integrating the energy spectra $(d^2\sigma/d\Omega\, dE)_{40^{\circ}}$ over the whole measured energy range. The energy spectra were well peaked in the energy region corresponding to the excitations of final reaction products of about 10-25 MeV. Absolute values of the differential cross sections were estimated by normalization to the known values of $(d\sigma/d\Omega)_{40^\circ}$ for the elastic scattering in $^{16}O+^{232}Th$ and $^{16}O+^{197}Au$ systems.

The targets used were 2.3 mg/cm^2 of ^{197}Au and 20 mg/cm^2 of ^{232}Th. The use of a so thick thorium target (the ^{16}O ions deposited 34 MeV of their energy in the target) resulted in a significant increase of the reaction product intensity, and consequently, allowed to extend the class of investigated reactions.

3. Experimental Results and Discussion

The differential cross sections $(d\sigma/d\Omega)_{40^\circ}$ for a formation of all observed isotopes of Be, B, C, N, O, F and Ne in $^{16}O+^{232}Th$ interaction are presented in table 1. The number of neutrons and/or protons transferred into the projectile is indicated in the first row and the first column respectively. Since the ^{16}O ions deposited 34 MeV in the target, the values of $(d\sigma/d\Omega)_{40^\circ}$ must be treated as averaged ones, corresponding to the interval of incident beam energy from 137 MeV to 103 MeV.

The analysis of these results show a systematic dependence of the measured yields on the Q-values, calculated for the ground state masses of the reaction products. This dependence, demonstrated in fig. 1, is approximately exponential for all reactions in which the protons are transferred out of the projectile. The Q_{gg}-values for reactions in which the nuclides with the masses yet unknown are formed (^{14}B, ^{15}B, ^{17}C) were calculated using the theoretical estimates of Garvey and Kelson /10/. The relation $\log (d\sigma/d\Omega)_{40^\circ} = \mathrm{const}\, Q_{gg}$ is fulfilled separately for isotopes of given element. As it can be seen from fig. 1 the deviations from this fenomenologically found relation do not exceed a factor of 2, whereas the cross section values vary by a factor of $10^2 - 10^5$.

The same regularity was found for reactions in $^{16}O + ^{197}Au$ system (fig. 2). A comparison of the results obtained on ^{232}Th and ^{197}Au targets show a close relation between the cross sections and the Q_{gg} -values. For example, the relative yields of nitrogen isotopes: ^{13}N , ^{14}N, ^{15}N, ^{16}N , ^{17}N and ^{18}N are completely different in reactions on ^{232}Th and ^{197}Au (1 : 31 : 416 : 114: 61 : 5 and 1 : 14 : 87 : 9 : 2 : 0.06, respectively). However, these differences are closely correlated with the differences in Q_{gg} -values, and in both cases the experimental points lay close to the $\log(d\sigma/d\Omega)_{40^o} = \mathrm{const}\, Q_{gg}$ lines.

Figs. 1 and 2 show that the lines along which the experimental points lay, shift systematically with increasing the number of stripped protons. This suggests that together with Q_{gg} -value also the change of the Coulomb interaction energy $\Delta E_c = (Z_1^i Z_2^i - Z_1^f Z_2^f) e^2/R$ strongly affects the reaction cross section. In case when Z of the target nucleus is larger than Z of the projectile, the Coulomb interaction energy prefers the reactions in which the protons are transferred out of the projectile.

Similar conclusions on the Coulomb energy effects have been drown by Diamond et al./11/, who noticed a systematic dependence of ratio of the yield for the projectiles picking up a single proton to that for the projectiles losing a single proton on the difference in Q -values for the two reactions plus the difference in Coulomb interaction energies.

Experimental results showing the strong Coulomb interaction effects in the proton transfer reactions were also reported in refs./12-14/.

In case of the reactions investigated by us, the inclusion of the changes of the Coulomb interaction energy in the form:

$$\ell og\,(d\sigma / d\Omega)_{40^\circ} = const\,(Q_{gg} + \Delta E_c),$$

does not give a common description for the yields of isotopes of different elements. The ΔE_c values, calculated for two spheres in close proximity, come out too large.

Correct estimation of ΔE_c as well as estimation of all other effects which may influence the cross sections is not simple. One of the obvious questions is the effect of excitation of both interacting nuclei. The largest cross sections correspond to the formation of final nuclei with significant excitation energies. In case of reactions investigated by us the detected nuclei are formed in the ground state or in a bound excited state. Therefore, the number of the bound states, as well as the height of the particle-decay threshold for the observed nuclide may affect the measured cross sections. The data on the energy spectra of the observed reaction products suggest that the nuclides formed in the protons stripping reactions are less excited than the nuclides formed in the protons pick-up reactions. Perhaps, this fact explains the lack of correlation between the cross sections and Q_{gg}-values in case of fluorine and neon isotopes.

The exponential dependence of the cross section on the Q_{gg}-value observed in case of the nucleons exchange reactions (projectile $-x$ protons $+y$ neutrons) is of great practical importance. Extrapolation of these relations may be used to estimate the yields for the reactions in which the nuclides yet unknown (e.g. ^{10}He, ^{14}Be) should be produced. This, in turn, gives possibility of solving experimentally the problem of particle stability of yet unknown nuclides.

Another hopefull conclusion, which seems to follow from the data obtained so far, consists in the possibility of understanding the transfer reactions in terms of simple potential energy considerations. For a better understanding of the problem, further experiments will be necessary, first of all, the experiments in which the energy spectra of final reaction products will be precisely measured.

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TABLE 1

Differential cross sections $(d\sigma/d\Omega)_{40^0}$ (in mb/sr) for production of Be, B, C, N, O, F and Ne isotopes in the ^{232}Th+^{16}O interaction.

number of transferred protons \ number of transferred neutrons	-5	-4	-3	-2	-I	0	+I	+2	+3	+4	+5	+6
+2								^{20}Ne 0.005	^{21}Ne 0.0I6	^{22}Ne 0.026	^{23}Ne 0.008	^{24}Ne 0.002
+I						^{17}F 0.008	^{18}F 0.034	^{19}F 0.23	^{20}F 0.I9	^{21}F 0.II	^{22}F 0.0I0	
0					^{15}O 0.I4	^{16}O 4200	^{17}O I3.4	^{18}O 7.2	^{19}O I.2	^{20}O 0.24	^{21}O 0.006	
-I				^{13}N 0.077	^{14}N 2.4	^{15}N 32.5	^{16}N 8.8	^{17}N 4.7	^{18}N 0.39			
-2		^{10}C 0.00I	^{11}C 0.07	^{12}C 20.0	^{13}C 3I.0	^{14}C 44.5	^{15}C 8.4	^{16}C 2.3	^{17}C 0.06			
-3			^{10}B 0.5	^{11}B II.4	^{12}B 4.8	^{13}B 2.7	^{14}B 0.064	^{15}B 0.0I6				
-4	^{7}Be 0.I5		^{9}Be 3.5	^{10}Be 6.I	^{11}Be 0.54	^{12}Be 0.I0						

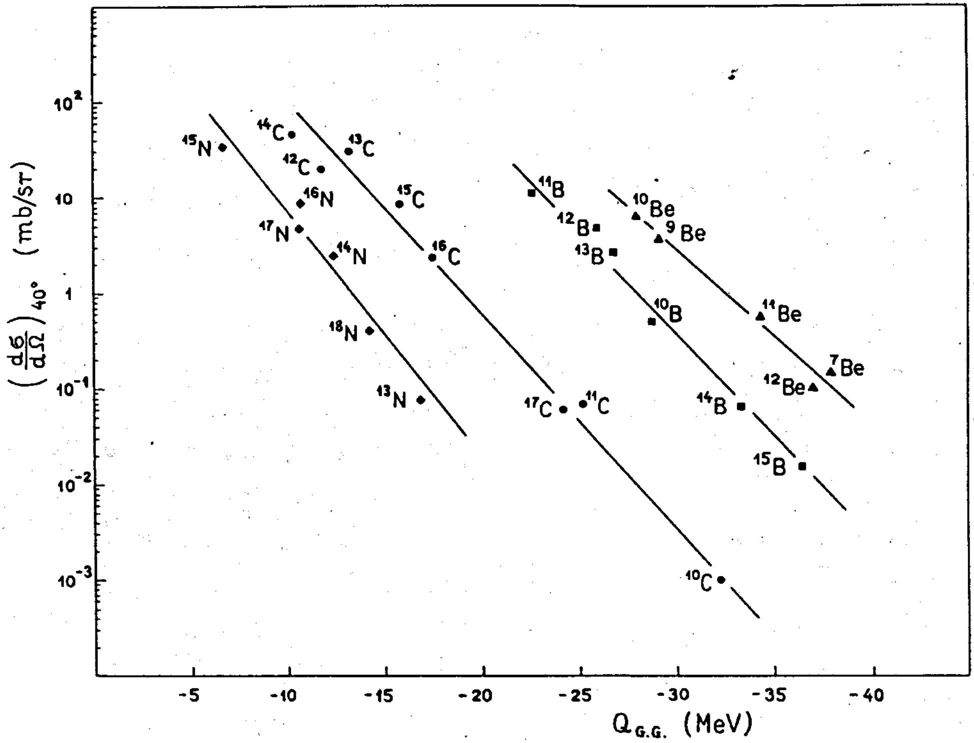

Fig. 1. Differential cross sections $(d\sigma/d\Omega)_{40°}$ for production of Be , B , C and N isotopes in the $^{232}Th + ^{16}O$ interaction as function of Q_{gg} .

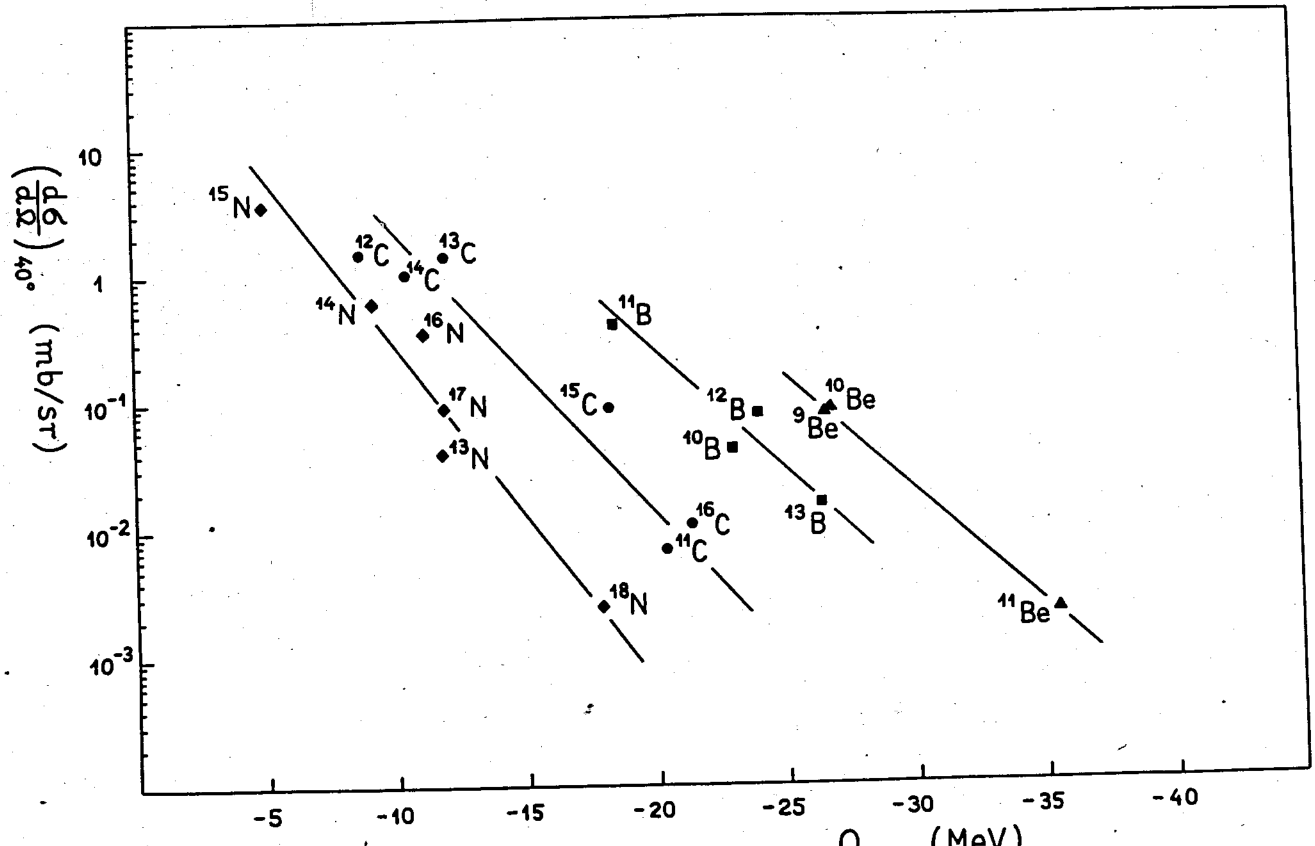

Fig. 2. Differential cross sections $(d\sigma/d\Omega)_{40°}$ for production of Be, B, C and N isotopes in the $^{197}Au + {}^{16}O$ interaction as function of Q_{gg}.