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# DIRECT REACTIONS INDUCED BY HEAVY IONS

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# DIRECT REACTIONS INDUCED BY HEAVY IONS

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The present paper is a brief review of the experimental results on the direct reactions induced by heavy ions obtained at the Laboratory of Nuclear Reactions, JINR.

These reactions have some peculiar features as compared with those induced by light particles. These features are due to a complex structure of the incident particle, large angular momentum, greater contribution of the Coulomb effect as compared with the nuclear one, strong absorption in the nuclear matter/1-6/. A small length of the heavy ion de Broglie wave ( $\lambda \approx 0.1$ fermi) makes it possible in many cases to use a semiclassical description of the heavy ion motion and more vividly describe the picture of the interaction of two colliding nuclei.

With respect to the angular momentum $\ell$ of the incident particle three regions with peculiar features of the nuclear reactions could be distinguished. The first region includes the reactions with the formation of the compound nucleus. The values of $\ell$ in this region lie between zero and some $\ell_{crit.}$ The values of $\ell$ of the third region correspond to the peripheral surface collisions. This is the region of quasi-elastic processes "classical" single and few-nucleon transfers. The second region lies between these two. The intensity of the nuclear interaction of this region is of a considerable value, however, the compound nucleus is not formed due to a large value of the angular momentum ( $\ell > \ell_{crit.}$). This is the region of inelastic processes. Here one can observe the de-

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x/ See reviews of experimental and theoretical works in/1-6/.

sintegration of the incident particle in the lighter fragment, the knock-out of nucleons or nucleon groups from the target nucleus, the capture of a large number of nucleons from the target-nucleus by an incident particle. The study of the transfer reactions in the surface collision region can give, in principle, a valuable information on the nucleus surface structure, in particular, on the possible formation of alpha particle clusters.

We have experimentally studied single and few nucleon transfers, predominantly with heavy nuclei. Two methods have been used to determine the reaction channel: the radioactive reaction product detection or the measurement of its energy and specific ionization $\frac{dE}{dx} \times E$. In the latter case a two-dimensional analysis on a multi-channel analyzer has been made.

The neutron transfer has been studied in the reaction $(N^{15}, N^{16})$ using $Ta^{181}$, $Au^{197}$, $Th^{232}$, $U^{238}$ target. The differential cross section for the reactions with 102 and 93 MeV $N^{15}$ ions have been obtained. The total cross sections within the incident energy range 70-95 MeV and the $N^{16}$ energy spectra at 99 and 89 MeV have been measured. Besides, the total cross sections have been measured for the isotopes $C^{12}$, $Al^{27}$, $Cu^{63,65}$, $Rh^{103}$.

The principal conclusions are as follows: The angular distributions of $N^{16}$ show characteristic single-nucleon transfer maxima at an angle corresponding to the surface collision of two nuclei. (Fig. 1). A notable rise in the small angle region has not been observed. The half-width of the geometrical area of the neutron transfer is 1.2 fermi and corresponds to ten partial waves with different angular momenta.

The value of $r_0$ often used in calculations by the formula $R = r_0 ( A_1^{1/3} + A_2^{1/3} )$ where $R$ is the distance of the closest approach, $A_1$ and $A_2$ are the colliding nuclei masses, is equal to $1.60 \pm 0.04$ f. If the neutron transfer does not considerable change the particle trajectory, then at the moment of the closest approach of the nuclei the density of the nuclear matter in the overlapping area is 1-2 per cent of the density in the center of the nucleus.

The angular distributions for the strongly deformed $Ta^{181}$ nucleus and the $Au^{197}$ nucleus close to the spherical one, are practically of the same shape. The excitation functions of these nuclei also coincide in shape.

The cross sections for the reactions increase with energies and show at large energies the tendency to saturation. (Fig. 1b). The value of the cross section notably increases with the Q value of the reaction.

It is interesting to note that in contrast to stripping, the pick-up of the neutron by $N^{15}$ does not lead to a considerable excitation of the target-nucleus. That means that the heavy target nuclei transfer their most weakly bound neutrons.

Comparing the transfer reaction area ( $\approx 10^{-24}$ $cm^2$) with the cross section one can estimate the probability of the neutron transfer. In the case of heavy elements and the ion energy of 6-7 MeV per nucleon it is about 1 per cent.

The behaviour of the excitation functions for lighter elements indicates that this value can increase by a factor of 3-4 with increasing energy.

Then by means of the reaction ( $N^{14}$ , $N^{16}$ ) ( $N^{15}$ , $N^{17}$ ) ( $N^{14}$ , $N^{17}$ ) the data on the two- and three neutron pick-up reaction with $Ta^{181}$ and $Au^{197}$ have been obtained (Fig. 2). The angular distributions of all the three reactions show a characteristic maximum corresponding to the surface collisions of the nuclei. The position of the cross section maxima for the transfer of one, two and three neutrons coincide. However, the width of the angular distribution in ( $N^{14}$ , $N^{16}$ ) and ( $N^{14}$ , $N^{17}$ ) reactions is larger than in the case of the one-neutron transfer. This effect may be due to the decrease in the number of partial waves mostly contributing to the reaction and a considerably wider energy spectrum of the reaction products. Note that for the differential cross section $\frac{d\sigma}{d\theta}$ where $\theta$ is the emission angle no increase has been found at small angles, although the measurements of $N^{17}$ have been performed up to the angle $4^{\circ}$.

The excitation functions of the two neutron transfer reactions ( $N^{14}$ , $N^{16}$ ) have been measured for $C^{12}$, $Al^{27}$, $Cu^{63,65}$, $Rh^{103}$, $Th^{232}$, $U^{238}$ . The cross section for two neutron pick-up for the same nuclei has been by an order smaller than the cross section for the single-neutron pick-up.

The proton transfer has been studied in the reactions ( $C^{12}$ , $N^{13}$ ) using $C^{12}$ , $Al^{27}$ , $V^{51}$ , $Nb^{93}$ , $Ag^{105-107}$, $Ta^{181}$, $Bi^{209}$ targets. The data on angular distributions, excitation functions and partly on energy spectra of $N^{13}$ have been obtained. The angular distributions show characteristic single-nucleon transfer maxima corresponding to the surface collision of two nuclei. The most interesting peculiarity of the proton transfer consists in the sharp dependence of the reaction cross section upon $Z$ of the target-nucleus. As is shown in Fig. 3C, in the transition from $Al^{27}$ to $Ta^{181}$ the reaction cross section decreases by two orders (for the equivalent energy $E^* = E_{CM} - E_{CB}$ where $E_{c.m.}$ is the ion energy in the c.m. system and $E_{CB}$ is the height of the Coulomb barrier in the same system). Taking into account the small value of the proton binding energy in $N^{13}$ ( 1.8 MeV) one can believe that the observed peculiarity is due to the "polarization" of the proton wave function in the Coulomb field of the target- nucleus. In Fig. 3d this effect is expressed in terms of the Frahn-Wenter /7/ parameter $r/4\Delta'$ characterizing the nucleon transfer probability. It is shown in this figure that this parameter is dependent not only on $Z$ of the target, but also on the incident energy (numbers at the experimental points). In the case of the neutron transfer this parameter is not actually dependent either on $Z$ or on the ion energy (the hatched area).

Using a good angular resolution one has observed the diffractional structure in the angular distribution in the reactions ( $C^{12}$ , $N^{13}$ ) while bombarding $Al^{27}$ and $C^{12}$ with high-energy $C^{12}$ ions. (Fig. 3a,b). Similarly, the diffraction disappears with decreasing ion energy. The diffraction maxima have not been observed in the case of the reaction ( $C^{12}$ , $C^{11}$ ) where process loses its quasi-elastic character due to large $C^{11}$ energy spread.

In order to determine the effect of the nucleus structure on the transfer reaction parameters the pick-up of two neutrons ( $N^{15}$ , $N^{17}$ ) with the separated zirconium isotopes: $Zr^{90}$ , $Zr^{92}$ , $Zr^{94}$ as targets has been studied. The isotope $Zr^{90}$ has a closed neutron shell ( $N = 50$).

the other isotopes have two and four exceeding neutrons, respectively. The differential cross section and the energy spectra for two values of the $N^{15}$ energy have been measured (the excitation functions for these isotopes were obtained by us earlier /10/ ). The angular distributions in all the cases (Fig. 4) show characteristic maxima whose positions actually coincide for all the isotopes. The widths of the angular distribution curves have also proved to be rather close to each other. Thus, the angular distributions of the transfer reactions represent rather weakly the peculiar features of the nuclear structure. A sharp difference between the isotopes is observed in the values of the cross sections. Thus, with 98 MeV $N^{15}$ ions the cross sections for $Zr^{90}$, $Zr^{92}$, $Zr^{94}$ are related as 1 : 6 : 8 respectively.

In terms of estimating the possible formation of alpha clusters on the surface of heavy nuclei the study of the $He^4$ transfer reaction is of particular interest /11,12/ . The experiments have been performed in which $He^4$ trànsfer was studied in the reactions ( $N^{14}$ , $F^{18}$ ) using $Th^{232}$and $Au^{197}$ targets. The experimental results have been negative. The $He^4$ transfer has not been up to the cross section of $10^{-30}cm^2$. The pick-up of $He^4$ has not been observed by the $dE/dX \times E$ method while bombarding $Th^{232}$ and $Au^{197}$ with $C^{12}$ and $N^{14}$ ions. At the same time when $Al^{27}$ is bombarded with $N^{14}$ ions, $F^{18}$ is formed in significant quantities, though the Q value of the reaction with $Al^{27}$ is much less than for heavy elements. Probably this result is due to a great difference in alpha particle binding energies in heavy and light nuclei. In the case of $Th^{232}$ and $F^{18}$ this difference is 8.7 MeV.

Probably a heavy ion knocks out an alpha particle from the surface of the heavy nucleus rather than captures it.

In the $F^{18}$ energy spectra obtained while bombarding $Al^{27}$ with $N^{14}$ ions, along with a group corresponding to the capture of $He^4$ in the $F^{18}$ bound states, a low-energy part within a wide energy range has been observed. The contribution of this part to the formation of $F^{18}$ rapidly increases with ion energy and emission angle. It is assumed that this group of $F^{18}$ nuclei is formed from the direct reaction occured in the region of inelastic processes. Due to a strong nuclear interaction in this region the $N^{14}$ nucleus "carries away" a considerably light $Al^{27}$ nucleus giving it a large part of its kinetic energy. A bound system of two nuclei is formed for a shart time and then disintegrates with a transfer of four nucleons to the $N^{14}$ nucleus. This reaction is intermediate between a "pure" direct reaction and a reaction with the formation of a compound nucleus.

The "spectra" of the transfer reactions obtained in bombardment of $Ta^{187}$ with $Ne^{20}$ and $Ne^{22}$ ions with energy 8 MeV per nucleon are shown in Fig. 5. The type of the reaction is determined by the radiochemical separation of the product from the irradiated target. The following peculiarities can be seen in the "spectra"; a) the transfer of a large amount of nucleons from nucleus to nucleus; b) the cross section maxima correspond to the equal amount of protons and neutrons transferred. This feature is especially vivid when a small amount of nucleons is transferred.

The following workers of the Laboratory of Nuclear Reactions participated in the experiments reviewed in this paper: A.G.Artyukh, J.Wilzinski, V.V.Volkov, C.F.Gridnev, P.Decowski, G.N.Zorin, T.Kwiecinska, Lan Kuo Chao, E.Lozinski, J.Maly, L.Pomorski, J.Tys, L.K.Tarasov.

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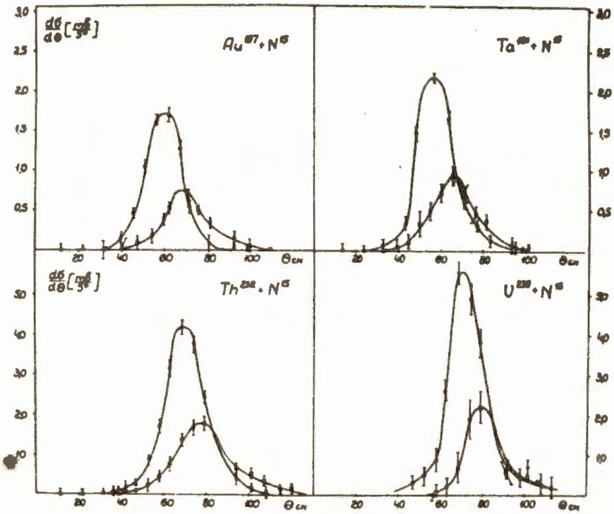
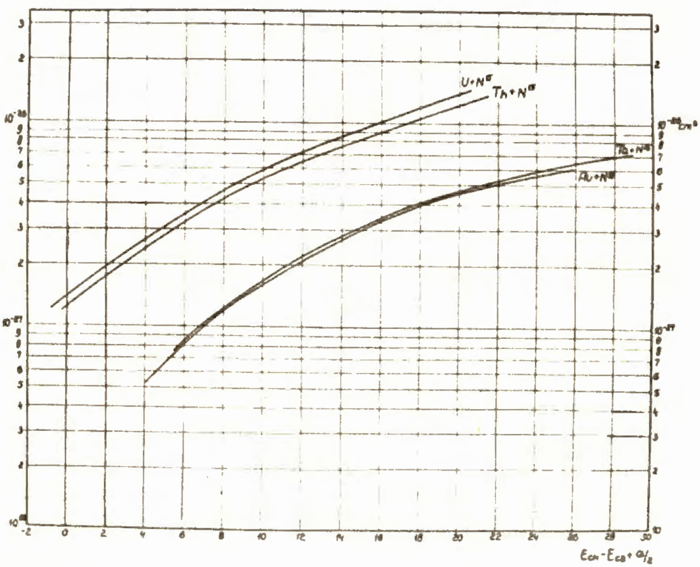



a)




b)

Fig. 1. a) Differential cross sections for the reaction ( $N^{15}$ , $N^{16}$ ) with $Ta^{181}$ , $Au^{197}$ , $Th^{232}$ , $U^{238}$ with 102 and 93 MeV $N^{15}$ ions.
b) The excitation functions for the reaction ( $N^{15}$ , $N^{16}$ ) with $Ta^{181}$ , $Au^{197}$ , $Th^{232}$ , $U^{238}$ .

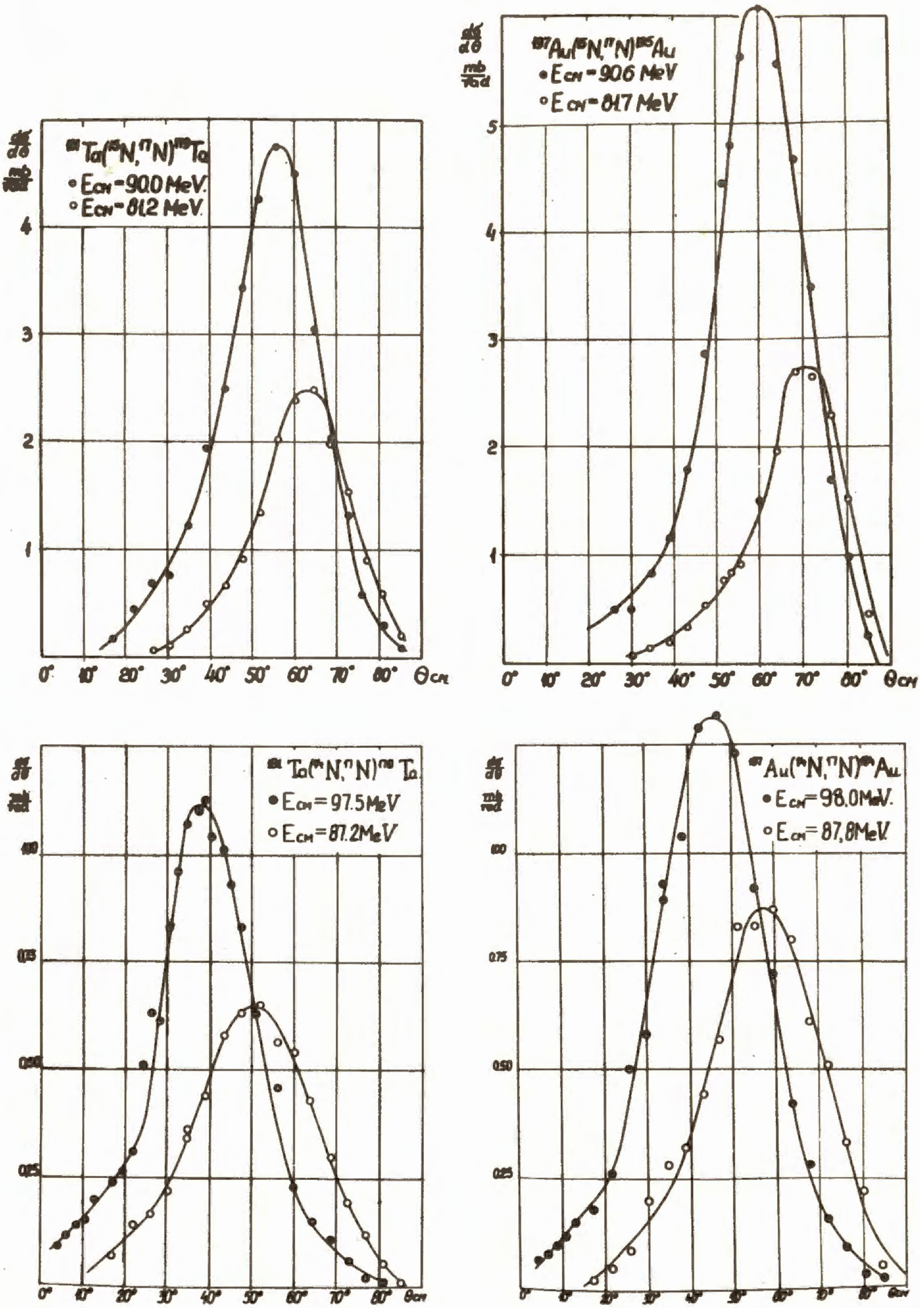



Fig. 2. Differential cross sections for the reaction ( $N^{15}$ , $N^{17}$ ) and ( $N^{14}$ , $N^{17}$ ) with $Ta^{181}$ and $Au^{197}$.

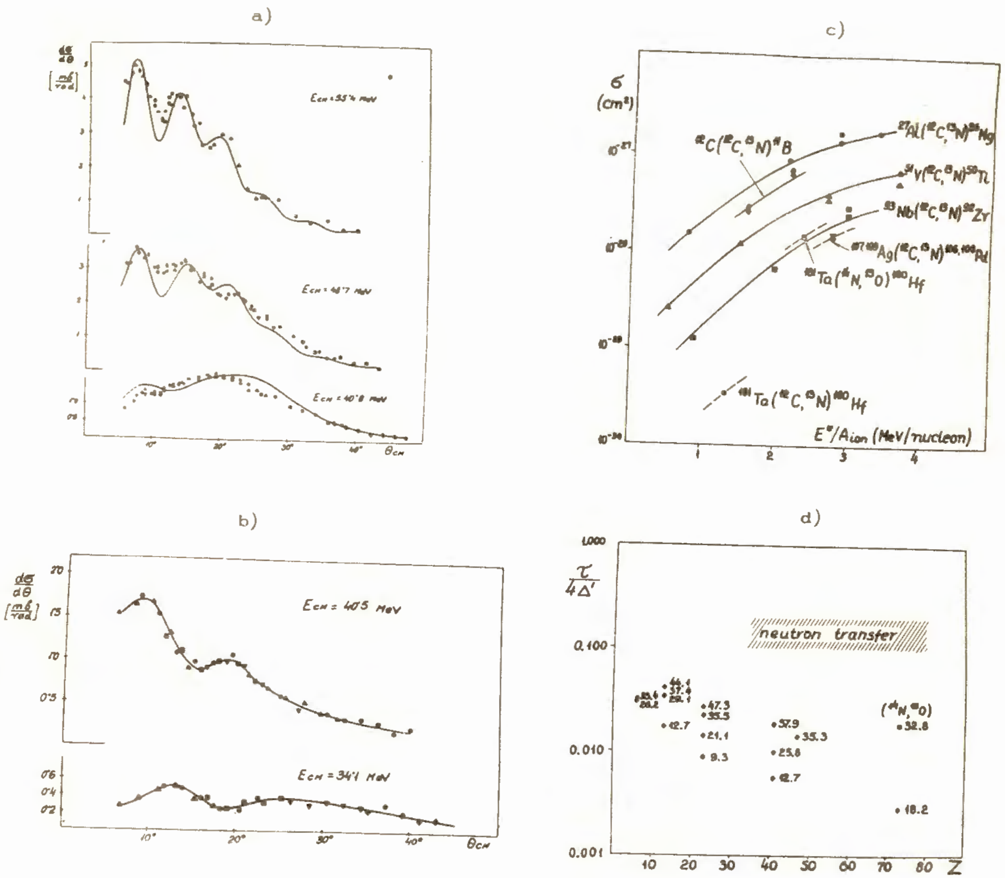



Fig. 3. a) The cross section for the reaction $Al^{27}(C^{12}, N^{13})Mg^{26}$. The continious lines are the results of calculations by the Kalinkin-Grabowski model/8,9/; b) The cross section for the reaction $Al^{27}(C^{12}, N^{13})Mg^{26}$. The continuous lines are experimental. c) The total cross sections for the reactions $(C^{12}, N^{13})$ with different elements. In the case of $Ta^{181}$ the cross sections for the reaction $(N^{14}, O^{15})$ are also given. d) The dependence of the Frahn-Wenter model parameter $\tau/4\Delta'$ charactering the transfer probability on Z of the target-nucleus and on the $C^{12}$ ion energy.



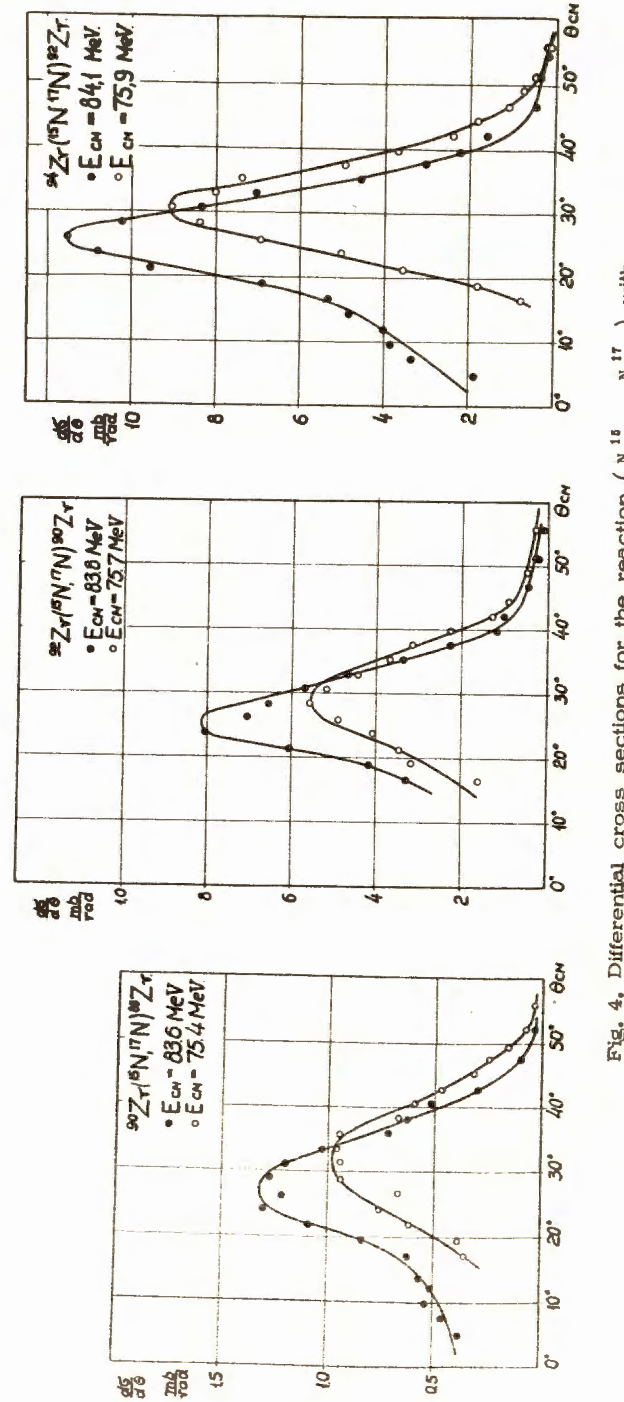
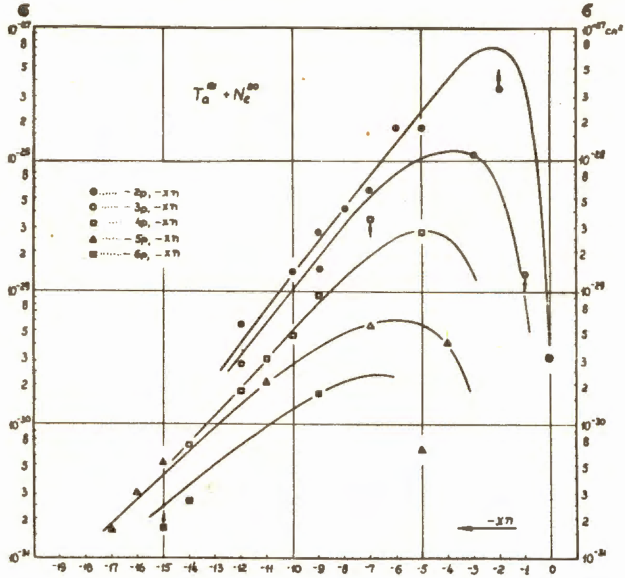


Fig. 4. Differential cross sections for the reaction $(N^{15}, N^{17})$ with $Zr^{90}$, $Zr^{92}$, $Zr^{94}$

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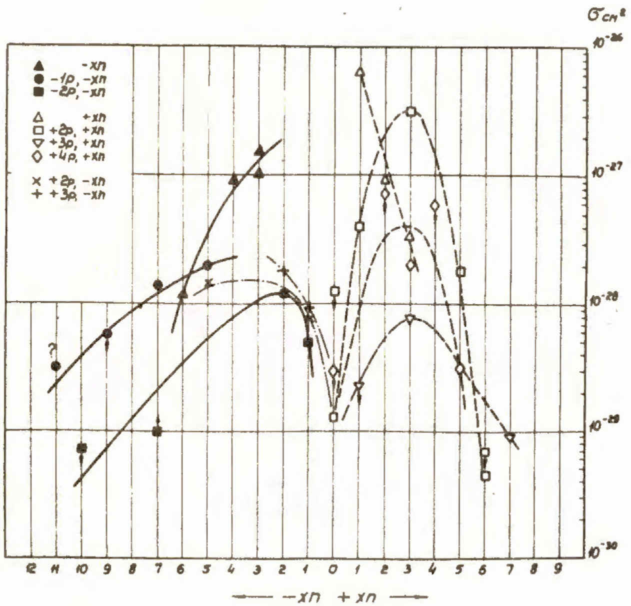


b)

Fig. 5. a) The "spectrum" of the transfer reaction in the bombardent of $Ta^{181}$ with 190 MeV $Ne^{20}$ ions. b) The "spectrum" of the transfer reaction in the bombardment of $Tb^{159}$ with 160 MeV $Ne^{22}$ ions.