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1. Introduction

During the recent years, nuclear reactions induced by heavy ions such as ^{40}Ar, ^{84}Kr and ^{136}Xe have been studied extensively. The new reaction mechanism which manifests itself just on these heavy projectiles is of special interest. This mechanism lies somewhere between a quasielastic process and compound nucleus formation followed by fission on heavy targets. Its main features are as follows: 1) Two final products have masses close to those of initial nuclei. In other words, this process can be called nucleon transfer. In the case of very heavy projectiles, up to several tens of nucleons can be transferred; 2) The kinetic energies of the two products formed are close to the Coulomb energies of the touching nuclei; 3) Similar to simple direct processes, the angular distributions of reaction products are anisotropic

Indications for this reaction mechanism were obtained on comparatively light projectiles, e.g., ^{14}N, ^{16}O and ^{12}C (refs. [1–3]). However, this mechanism showed itself most vividly in investigations of the interaction of ^{22}Ne and ^{40}Ar with ^{232}Th (refs. [4,5]). In these papers the process was termed "deep inelastic process". Later on, similar processes observed in the interaction of ^{84}Kr with ^{209}Bi were called "quasifission" [6]. The authors of ref. [7] termed the deep inelastic processes observed in the interaction of ^{40}Ar, ^{84}Kr, ^{14}N and ^{20}Ne with silver "relaxation phenomena".

The present paper is an extension of our previous paper [5], which dealt mainly with proton stripping reactions in the system ^{40}Ar + ^{232}Th. When protons are picked up by a projectile, multinucleon transfer products cannot be formed because of the dissociation of the initial particle

This fact makes an analysis in terms of the two-body mechanism more reliable.

Until recently proton pick-up reactions on heavy nuclei have been investigated only in quasielastic processes (e.g [8,9]). In this case the pick-up of only one or two protons was observed, the cross sections being 1-2 orders of magnitude lower than those for stripping reactions. It was indicated in ref. [9] that the difference between the proton pick-up and stripping cross sections is determined to a considerable extent by the effects of the Coulomb energy of the interacting nuclei.

In deep inelastic processes a relatively long-lived double nuclear system is formed, which is nearly in statistical equilibrium [10,11]. In this system the relationship between the proton stripping and pick-up cross sections can be different from that observed in quasielastic processes.

Proton pick-up reactions on ^{40}Ar are of particular interest in view of the fact that the mass distribution of the products of reactions involving the pick-up of several protons can overlap to some extent with that of fission fragments from the compound nucleus, the FWHM of the latter distribution being large (ref. [12]). It is difficult to separate fission fragments from the products of direct reactions using radiochemical separation methods, similar to those of ref. [12]. In the present paper, the mechanisms of the formation of nuclear reaction products can be separated on the basis of angular distributions.

2. Experimental Technique

The experiments were carried out using the JINR 310-cm heavy-ion cyclotron. A metallic ^{232}Th target, 3.9 mg/cm^2 thick, was bombarded by 338 MeV ^{40}Ar ions. The products of nuclear reactions were detected by a telescope consisting of two silicon surface-barrier detectors: a ΔE detector 7 μm thick and a E detector ~ 0.5 mm thick. The telescope was placed in the reaction chamber at a distance of 25 cm from the target. It allowed the detection of products at a solid angle of 3×10^{-1} sr. The beam spot on the target was 6 x 6 mm^2, while its angular divergence did not exceed $\pm 0.5^{\circ}$. The entrance window of the telescope was 5 mm in diameter. Under these experimental conditions the angular resolution was not worse than $\pm 1.5^{\circ}$.

A two-dimensional $\Delta E, E_0-\Delta E$ spectrum was recorded in two 4096-channel amplitude analysers operated in the $256(\Delta E)\times 32(E_0-\Delta E)$ channel mode. Products with certain atomic number Z (all the isotopes) were separated according to their hyperbolas in the two-dimensional spectrum. The beam was monitored by elastically scattered ions using a silicon detector located at 30° with respect to the beam direction. The minimum energy registrated by the telescope with the 27 μm ΔE detector was about 3.8 MeV/nucleon for K to Fe. Unfortunately no ΔE detector of smaller thickness was available, so that we could not detect reliably the low-energy parts of the spectra or the formation of products with $Z > 26$. The scale values of the two-dimensional spectra were 9.7 MeV/channel and 0.92 MeV/channel along the E and ΔE axis, respectively.

3. Experimental Results and Discussion

3.1. Energy spectra

The lab. energy spectra of different products from K to Fe are shown in fig. 1. The absolute cross sections were determined by normalization over elastically scattered ions. Nuclear reactions were assumed to occur in the middle plane of the target. Corrections for energy losses in the target for the reaction products recorded were made using the tables of specific energy losses [13]. In the centre of the target the energy of the initial 388 MeV ^{40}Ar ions was 379 MeV. The maximum correction for energy loss in the target was 20 MeV for Fe. The energy loss and subsequent kinematic calculations were done under the assumption that the maximum of the isotopic distribution for a given Z corresponds to the transfer of equal numbers of protons and neutrons. This assumption is in agreement with the data presented in ref. [14], where the isotopic distribution of the products of reactions invol-

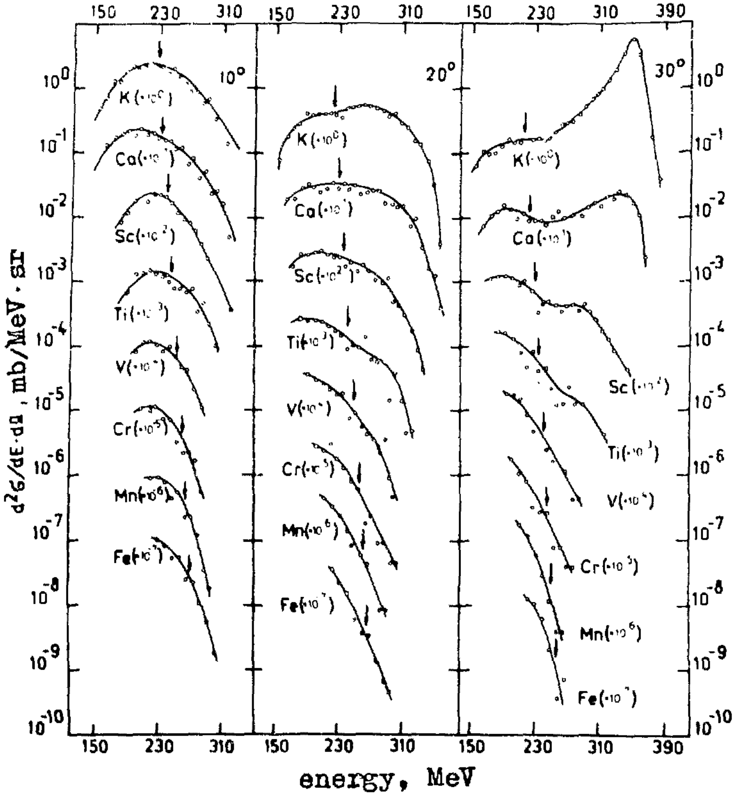


Fig. 1. Energy spectra of proton pick-up products in the $^{40}Ar + ^{232}Th$ system at 10°, 20° and 30° (the lab. system), the ^{40}Ar energy being 379 MeV in the middle of the target. Cross section values for K–Fe are multiplied by 10^{0} - 10^{-7}, respectively.

ving the pick-up of up to four protons in the interaction of ^{40}Ar with ^{232}Th was studied.

Mass variations within ± (2-3) units corresponding to the FWHM of the isotopic distribution do not affect substantially the corrections for either energy losses or transformation of the angles into the c.m. system using the two-body kinematics. The accuracies of calculating these corrections are 1 MeV and 1°, respectively.

At an angle of 30° close to that of the Rutherford scattering at grazing collisions (36°), the energy spectra for K and Ca show pronounced maxima which are close to the energy of elastically scattered ^{40}Ar ions. These maxima correspond to the quasielastic reaction mechanism. The high energy maxima disappear gradually with decreasing angle and only low energy maxima are observable at an angle of 10°, which are due to the deep inelastic mechanism. It is also seen in fig. 1 that for the Sc–Fe nuclei, the deep inelastic mechanism plays the main role at all angles. In this process, only the initial kinetic energy of ^{40}Ar ions leads to the system excitation about 150 MeV in the energy spectrum maximum. The positive difference between the masses of the initial and final nuclei in proton pick-up leads to the release of an additional amount of energy, which reaches about 50 MeV in the case of Fe production. The distribution of excitation energy between light and heavy reaction products is of considerable interest. It can be assumed that due to higher level density the heavy nucleus takes on the main portion of excitation energy and is likely to undergo fission ultimately. In the light nucleus, excitation will result in the emission of neutrons, α-particles, γ-rays and, to a smaller extent, of protons since experimental data suggest that light products are mainly neutron-rich [11,15].

There are no special grounds to assume the c.m. anisotropic emission of secondary particles from the light product. When secondary particles are emitted isotropically, the average velocity and detection angle of the light product change inconsiderably. Correspondingly, a variation in the kinetic energy of the reaction product being detected, with respect to the appropriate Coulomb barrier, will also be small. The arrows in fig. 1 show the Coulomb energies calculated for touching spheres, the distance between their centers being $R = r_0(A_1^{1/3} + A_2^{1/3})$ with $r_0 = 1.46$ fm. It is seen that a considerable part of the energy is below the Coulomb barrier. This indicates that the nuclei undergo considerable deformation at the final stage of the interaction. Unfortunately the thickness of the ΔE detector did not allow us to establish the positions of maxima for elements from Cr to Fe even at 10°. One can notice the general tendency of energy decrease in the energy spectrum with respect to the Coulomb barriers as the number of protons picked-up increases. The energy spectrum maximum for vanadium corresponds to the Coulomb energy calculated with $r_0 = 1.65$ fm, which is close to the effective value of $r_0 = 1.83$ fm obtained for fissile nuclei at the saddle point [16].

Thus, in the deep inelastic interactions of ^{40}Ar with ^{232}Th the products of both proton stripping [5] and proton pick-up have kinetic energies close to the Coulomb energy of touching deformed nuclei.

3.2. Angular Distributions

The c.m angular distributions of proton pick-up products for K to Fe are shown in fig 2. The line lengths correspond to the interval of the c.m angles at a given lab. angle, as a result of the considerable width of the energy spectra over the entire energy range measured.

The values of $d\sigma/d\Omega$ are obtained by integrating the energy spectra $d^2\sigma/dE\,d\Omega$ over energy. In this case at all angles the lower limits of the energy spectra for Sc–Fe are taken at an energy corresponding to the c.m. minimum energy recorded at a maximum angle. This procedure reduces the distortion of the angular distributions by the energy spectra cut-off due to the ΔE detector thickness, since, as seen in fig. 1, the main contribution to the cross section for Sc–Fe is made by the similar portions of the spectra.

The angular distribution for K shows a pronounced maximum in the vicinity of the Rutherford scattering angle ($\theta_{c.m.} \approx 41°$) for grazing collisions. This maximum corresponds to the quasielastic reaction mechanism. In the case of Ca this peak is smoothed. The production cross sections for Sc–Fe increase monotonously with decreasing angle. For comparison, fig.2 shows the angular

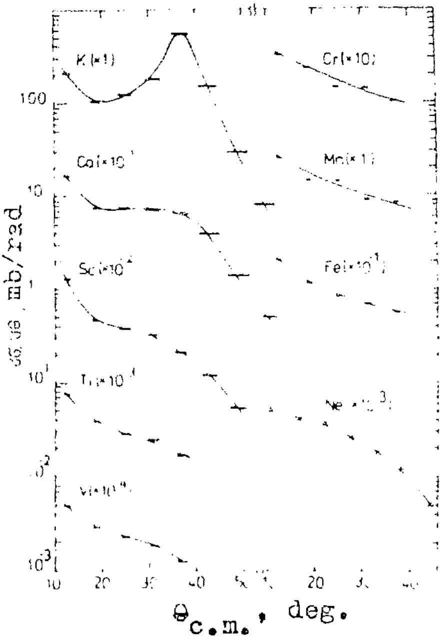
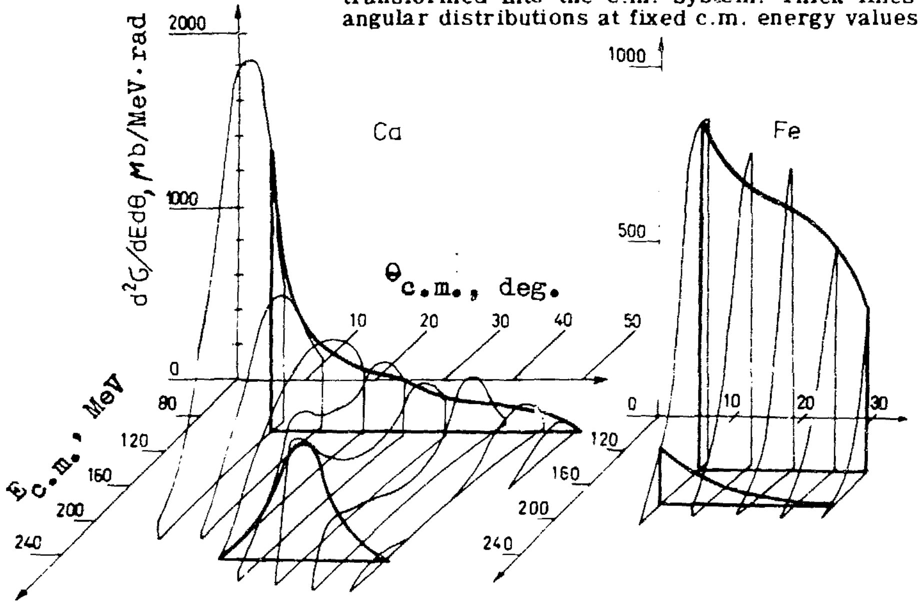


Fig. 2. The c.m. angular distributions of proton pick-up products in the $^{40}Ar + ^{232}Th$ system. The lengths of the straight lines, through which the curves are drawn, correspond to the c.m. angle interval obtained for a given angle in the lab. system as a result of the width of the energy spectra.

distribution for Ne formed as a result of the stripping of 8 protons from Ar. This distribution is similar to that for Fe resulting from the pick-up of 8 protons by Ar. However, for Ne an increase in the cross section at small angles is somewhat smoother while a decrease at large angles is sharper than in the case of Fe.

Anisotropy in the $d\sigma/d\Omega$ ratio in the c.m. system for the Sc–Fe nuclei indicates that transfer reactions are the main contributors to the production cross sections for

Fig. 3. Production cross sections for Ca and Fe as a function of c.m. energy and c.m. angle in the ^{40}Ar + ^{232}Th system. Thin lines show the energy spectra measured at each 5° in the range 10° to 50° (the lab. system), transformed into the c.m. system. Thick lines show the angular distributions at fixed c.m. energy values.



these elements. If one assumes that the whole process of Fe production at $\theta_{c.m.} = 38°$ is associated with the fragments which are formed as a result of fission of the compound nucleus and have an isotropic angular distribution, then not more than 50% of Fe production events can be attributed to fission fragments.

Figure 3 shows the two-dimensional spectra for Ca and Fe (in the c.m. system), which indicate a relationship between the angular distributions and the energy of the products detected. Two maxima are clearly seen for Ca. The peak in the vicinity of the Rutherford scattering angle for grazing collisions at $\theta_{c.m.} = 41°$ and at high energy corresponds to the quasielastic mechanism of Ca production. The peak at low energies and at small angles corresponds to the deep inelastic mechanism of Ca production. In the case of Fe, the production cross section increases with decreasing angle over the entire energy range. Thus, with an increase in the number of nucleons transferred the deep inelastic process becomes the predominant mechanism of the formation of the corresponding products.

3.3 Total Cross Section

The cross sections for the formation of proton pick-up products are presented in table 1. The cross sections $\sigma_{meas.}$ were obtained by integrating the angular distributions over the angle range measured. The same table shows the values of σ obtained by extrapolating the lab. angular distributions from 10° to 0°.

For comparison the cross sections of the formation of proton stripping products, taken from ref. [5], are also presented in table 1. One can see that the difference between the cross sections for the stripping and pick-up of the same number of protons lies within a factor of 4. If one takes into account that for Sc–Fe only the recorded part of the spectrum is included in the extrapolated cross sections, this difference becomes still smaller. We possibly deal with the effects of potential energy, mentioned by W.Swiatecki [17]. The evolution of the system of two interacting nuclei with $(Z_1 + Z_2)^2/(A_1 + A_2) \geq 40$ depends

Table 1.

Element	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Total, mb
σ measured (mb)	110	48	22	13	11	8.3	6.3	4.9	~220
σ extrapol. (mb)	160	140	64	28	23	16	12	10	~450

Element	Cl	S	P	Si	Al	Mg	Na	Ne	
σ measured (mb)	300	210	110	78	46	41	24	18	827
σ extrapol. (mb)	380	300	190	150	86	65	43	33	1247

substantially on the charge-to-charge ratio of the initial nuclei. With $Z_1 \gg Z_2$ the heavy nucleus absorbs the light one. As Z_1 increases, from some critical values of Z_1/Z_2 the configuration of two equal-mass nuclei becomes energetically advantageous. The preferential transfer of nucleons from the heavy nucleus to the light one was observed experimentally in the deep inelastic interaction of 600 MeV ^{84}Kr ions with ^{209}Bi (ref. [18]).

The products of reaction involving the pick-up of a considerable number of protons may have the same atomic numbers as those of the fragments resulting from asymmetrical fission of a compound nucleus. Unfortunately the experimental data on the charge and mass distribution of the fission fragments formed in the system ^{232}Th + ^{238}Ar are unavailable in literature. However, bearing in mind the small mass difference between ^{232}Th and ^{238}U, it is possible to assume that the mass distribution of fragments in the system ^{232}Th + ^{40}Ar coincides by shape with that

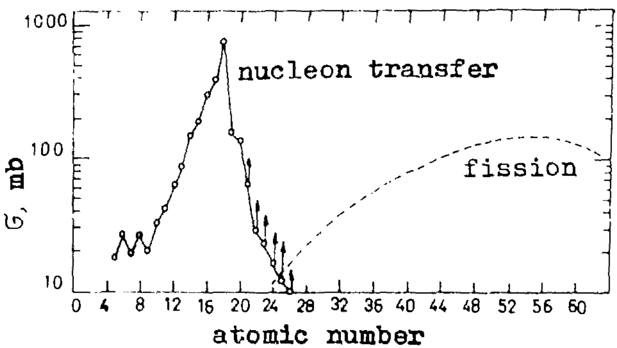


Fig. 4. Cross sections for the formation of transfer reaction products in the ^{40}Ar + ^{232}Th system as a function of atomic number (solid line). The dashed line shows the charge distribution of fission fragments produced in the ^{40}Ar + ^{232}Th system.

for the system $^{238}U + ^{40}Ar$, obtained using radiochemical methods [12]. In this case we neglect some broadening in the mass distribution of fragments in going from the ^{40}Ar energies of 300 MeV (ref. [12]) to 379 MeV used by us. The ratio Z/A in the fission fragments coincides with that for the whole fissioning system /17/ within an accuracy of several per cent. Therefore the mass distribution of the fission fragments, presented in ref. [12], can be transformed into the distribution over atomic numbers assuming Z to be proportional to A. This distribution is shown in fig. 4. Its area is normalized to the total fission cross section of 2.5 b at the ^{40}Ar energy of 379 MeV for the system $^{238}U + ^{40}Ar$, according to the data of ref. [19].

Figure 4 also shows the cross sections for the formation of direct reaction products according to the data of the present work and those of ref. [5]. The arrows for products with Z 21–26 indicate that the cross sections are obtained only for part of the energy spectrum. If the energy spectra shown in fig. 1 are assumed to be high-energy parts of the symmetric curves with maxima, as observed in the stripping of a large number of protons [5], then the production cross sections for Sc–Fe, presented in the figure, should be increased nearly twice.

In spite of a number of rough assumptions made to obtain the shape of the charge distribution of fission fragments formed in the system $^{232}Th + ^{40}Ar$, it is seen in fig. 4 that a considerable portion of the products at the edge of the radiochemically obtained mass distribution of fission fragments can in fact be the products of deep inelastic direct processes.

Figure 4 indicates that with an increase in the number of protons picked-up the relative decrease in cross sections reduces. This can also imply that in the interaction of ^{232}Th with ^{40}Ar the effects of potential energy equalize the masses of the interacting nuclei in the relatively long-lived double nuclear system formed by them.

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