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NUCLEON TRANSFER REACTIONS IN THE BOMBARDMENT OF ^{197}Au WITH 220 MEV ^{40}Ar IONS

Submitted to ЯФ

Артюх А.Г. и др. **E7 - 10464**

Реакции передачи нуклонов при взаимодействии ^{40}Ar (220 МэВ) с ^{197}Au

Проведено облучение ^{197}Au ионами ^{40}Ar с энергией 220 МэВ, соответствующей превышению над барьером взаимодействия в 1,15 раза. С помощью методики $\Delta E, E$ зарегистрировано образование продуктов с атомными номерами $11 \leq Z \leq 35$.

Показано, что для реакций многонуклонных передач, реализующихся в глубоконеупругих столкновениях ядер, угловые распределения направлены вперед. В реакциях малонуклонных передач вид угловых распределений зависит от степени диссипации исходной кинетической энергии.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ.

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Nucleon Transfer Reactions in the Bombardment of ^{197}Au with 220 MeV ^{40}Ar Ions

A ^{197}Au target was bombarded with ^{40}Ar ions with an energy of 220 MeV which exceeds the interaction barrier by a factor of 1.15. By using the $\Delta E, E$ technique the formation of reaction products with atomic numbers $11 \leq Z \leq 35$ has been recorded. The angular distributions of the products of multinucleon transfer reactions involved in deep inelastic nuclear collisions are found to be forward peaked. In reactions involving the transfer of few nucleons the shape of the angular distributions depends on the extent of the dissipation of the initial kinetic energy.

The investigation has been performed at the Laboratory of Nuclear Reactions, JINR.

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1. INTRODUCTION

At present the study of deep inelastic transfer reactions (DIT) is a rapidly developing trend of heavy ion physics [1-6]. These reactions have been observed with a great variety of targets bombarded with different projectiles ranging from carbon to uranium.

Deep inelastic transfers are characterized by a high extent of the dissipation of the initial kinetic energy, and this leads to the formation of products with energies close to their exit Coulomb barriers. The angular distributions of the DIT products are, as a rule, asymmetric with respect to 90° in the c.m. system. Maximum yields are observed for atomic numbers Z and mass numbers A close to those of the initial nuclei.

In the first investigations [7,8] carried out with relatively light bombarding particles such as ^{22}Ne and ^{40}Ar the products of nuclear reactions were identified according to their Z-values. It was established that the products of multinucleon transfer reactions are formed in deep inelastic processes and have forward peaked angular distributions. The angular distributions of the products of few-nucleon transfer reactions, averaged over the entire energy, range exhibited maxima in the vicinity of the Rutherford grazing angle, Θ_{Ruth} . However the analysis performed in ref. [8] showed that with an increasing dissipation of the initial kinetic energy the angular distributions of few-nucleon transfer products become forward peaked.

Initial studies [9-11] using very heavy ions, ^{84}Kr, did not involve the Z-identification of the products. Due to the coincident measurements of the correlated fragment energies the reaction products were classified as "Kr-like" and "Bi-like" ones [9]. The angular distributions of the "Kr-like" products of energies close to the exit Coulomb barrier showed maxima near Θ_{Ruth}. This factor was the reason why deep inelastic reactions on Kr and heavier ions were considered as a special type of reaction - "quasifission".

Subsequent work [4,12] using Kr and Xe ions, in which reaction products were identified, showed that the shapes of the angular distributions change with an increasing number of transferred protons in the same manner as observed in deep inelastic transfers on Ar [8]. Thus it has been established that deep inelastic transfers and "quasifission" imply the same phenomenon.

An interesting problem involved in the studies of the DIT is the dependence of the angular distributions on the initial kinetic energy. A number of investigators [4,13,14] believe that the DIT occuring at kinetic energy E_i slightly higher than the interaction barrier B_i, i.e., at $E_i/B_i<(1.2\text{-}1.5)$, have angular distributions with maxima in the region of Θ_{Ruth}, which disappear only at $E_i/B_i \gtrsim 1.5$ thus leading to forward peaked or nearly isotropic angular distributions.

In ref. [3] it was suggested to use as a parameter defining the shape of the angular distributions the parameter

$$\eta' = \frac{Z_p \cdot Z_t \cdot \sqrt{\mu} \cdot e^2}{\hbar \cdot \sqrt{2(E_i - B_i)}},$$

where Z_p and Z_t are the atomic numbers of the projectile and target nucleus, respectively; μ is the reduced mass and e is the electron charge. According to its physical significance the parameter η' is proportional to the ratio between the Coulomb repulsion and nuclear friction forces. From ref. [3] one may expect a forward peaking in the angular distributions for $\eta' < 150\text{–}200$, whereas for $\eta' > 250\text{–}300$ a large part of the angular distribution should be concentrated in the vicinity of Θ_{Ruth}.

The purpose of the present work is to study the shape of the angular distributions of the DIT products as a function of the number of transferred nucleons in the system $^{197}Au + {}^{40}Ar$ (220 MeV) with the Z-identification of the products. For this system the η' value equals to 264, and $E_i/B_i = 1.15$. The B_i value was calculated within the framework of the energy density formalism [15].

In ref. [16] the DIT occuring in the system $^{197}Au + {}^{40}Ar$ have been investigated at 288 and 340 MeV with the Z-identification of reaction products. The angular distributions turned out to be peaked forward tending to isotropy in the case of many-nucleon transfers. In ref. [14] the DIT were studied in the system $^{197}Au + {}^{40}Ar$ at 220 MeV without the Z-identification of the reaction products, but with mass measurements at different angles using the time-of-flight technique. Evidence was provided that light reaction products were concentrated near Θ_{Ruth}.

The Z-identification of the DIT products performed in the present work makes it possible to consider the dependence of the shape of the angular distributions of the DIT products on the extent of the reconstruction of the initial nuclei with a small value of E_i/B_i in more detail than in ref. /14/.

2. EXPERIMENTAL TECHNIQUE

The experiments were carried out at the U-300 Heavy Ion Cyclotron of the JINR Laboratory of Nuclear Reactions. The reaction products were detected using a $\Delta E, E$ telescope. To measure the specific energy losses ΔE, an ionization chamber with a Frisch grid was used, whereas the residual energy E of the particles was measured by a semiconductor detector.

The measuring equipment is shown schematically in fig. 1. A ^{197}Au target 0.3 mg/cm^2 thick was placed in the centre of the scattering chamber 70 cm in diam. Before hitting the target the 220 MeV ^{40}Ar ion beam passed through a collimator with a 6x6 mm^2 slit. The beam intensity was measured by a Faraday cup and a monitor detector that recorded elastically scattered ions. Some part of the chamber side wall was made of a beryllium bronze belt which could glide on a vacuum-tight rubber gasket without disturbing the vacuum. The slit available in the belt

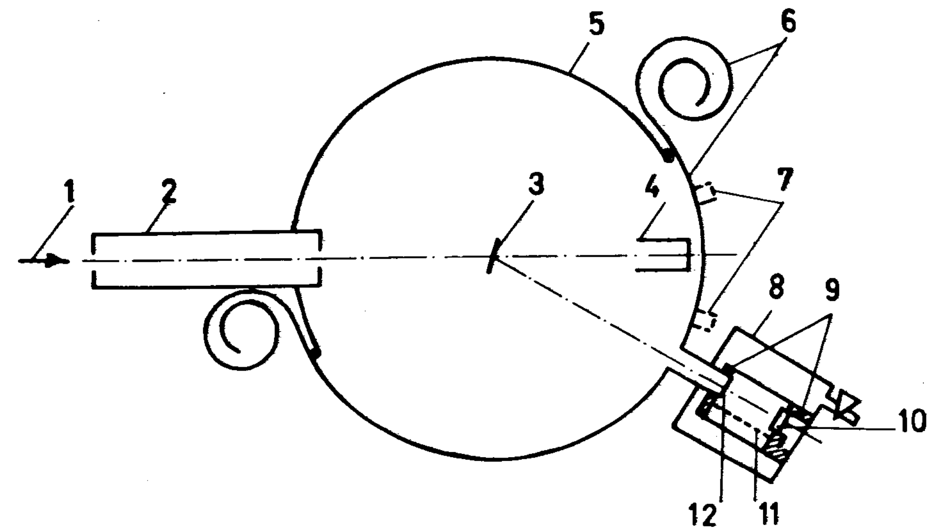

Fig. 1. A schematic view of the experimental arrangement: (1) beam, (2) collimator, (3) target, (4) Faraday cup, (5) the body of the scattering chamber, (6) the sliding bronze belt, (7) monitor detectors, (8) the body of the ionization chamber, (9) insulators, (10) semiconductor detector, (11) Frisch grid, (12) mylar entrance window.

was connected with the body of the telescope of the ionization chamber ΔE and semiconductor detector designed for measuring the residual energy E. Owing to the drawing of the belt it was possible to change the angular position of the telescope within 10-150° without disturbing the vacuum. The angular resolution of the telescope was $\pm 0.3^{\circ}$ at a solid angle of 2×10^{-4} sr. The particle trajectories in the ionization chamber were parallel to the Frisch grid. The composition of the gas used was 95% Ar and 5% CH_4. The pressure was 100 torr which corresponded to the gas effective layer equivalent to about 8 μm Si, provided that the particle path in the chamber was about 10 cm. The energy resolution of the ionization chamber for the elastically scattered ^{40}Ar ions was about 3% thus permitting the Z-identification of nuclear reaction products with Z up to ~35.

After amplification and amplitude digital conversion, pulses from the ΔE and E detectors were recorded on a Minsk-32 computer. Each coincident event was recorded as a 24-digit binary code (12 digits per detector) on magnetic tape.

After terminating an exposure a two-dimensional control spectrum with dimensions of $256(\Delta E)\times 32(E)$ channels was printed. The plotting of the energy spectra of individual elements was made using a computer code based on that for treating γ-ray spectra /17/. After the conversion of the two-dimensional spectra $\Delta E, E$ to the spectra $\Delta E, E+\Delta E$ each cross section of the two-dimensional spectrum was treated as a one-dimensional spectrum along the axis ΔE. As a result, we obtained the numbers of events for each element for a certain energy. The energy calibration of the ΔE and E detectors was made by means of the ^{40}Ar ions scattered at 40°. The total energy of the elastically scattered ions was measured by a magnetic analyzer. Then the measurements of pulse heights of the E detector were performed, first, in the case of a straightforward incidence of the scattered ion beam on the detector, with a mylar window in the ionization chamber without and, finally, with the gas.

The effective thickness of the mylar entrance window was 0.62 mg/cm^2. It was found from the energy losses of the elastically scattered ^{40}Ar ions by using Nortcliffe and Schilling's Tables /18/. Corrections for the energy absorption in the mylar window and the target were also made using the same tables /18/. The table values of the particle range in the energy interval of interest, 1-10 MeV/nucleon, were approximated by polynomials of the third power with four factors determined by the method of least squares. The mass numbers of reaction products were assumed to correspond to the average values of A/Z of the initial system ^{197}Au + ^{40}Ar (ref. /3/).

The cross sections were calibrated by the elastically scattered ions in the angle interval of 30° to 50°, in which the scattering cross section is the same as the Rutherford one /19/.

3. RESULTS AND DISCUSSION

3.1. Energy Spectra

The energy spectra of elements of $11<Z<35$ were measured in the angle range of 50° to 110° in the lab. system. No measurements could be performed at larger angles because of considerable energy losses in the entrance window and in the gas of the ioniza-

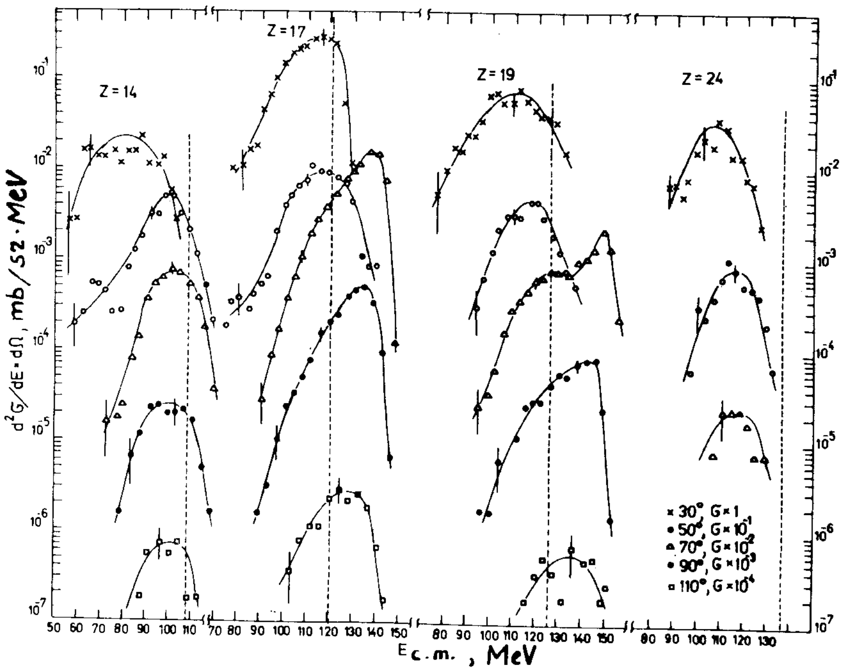

Fig. 2. The c.m. energy spectra of products with Z = 14, 17, 19 and 24 obtained by bombarding a ^{197}Au target with ^{40}Ar ions with a lab. energy of 220 MeV. The energies corresponding to the exit Coulomb barriers are shown by dashed lines. The lab. angles of observation and multiplying factors of cross sections for different angles are shown in the lower right-hand part of the figure.

tion chamber. Typical energy spectra of the products having Z = 14, 17, 19 and 24, obtained at different measuring angles are shown in fig. 2. The Θ_{Ruth} value for the system

$^{197}Au + {}^{40}Ar$ at 220 MeV is 78° in the lab. system (86° in the c.m. system) for $r_0 = 1.46$ fm. One can see from fig. 2 that at angles of 70° and 90° that are close to Θ_{Ruth} a substantial portion of the energy spectra of the products having Z = 17 and 19 lie above the exit Coulomb barriers E_{Coul} shown by dashed lines. The Coulomb barriers were calculated for spherical nuclei with $r_0 = 1.46$ fm. The high-energy part of these spectra corresponds to quasielastic reactions. However at 70° and 90°, some of the Z = 17 and 19 products have energies close to and even lower than the exit Coulomb barriers by tens of MeV. These parts of the spectra are connected with deep inelastic nuclear interactions. The superposition of the two mechanisms is especially vivid for Z = 19 at an angle of 70°.

For products having Z = 14 and 24 differing considerably from the initial particle in the Z value, most of the energy spectra lies in the vicinity of the Coulomb barriers and below them. Thus deep inelastic reactions are the main mechanism of their production.

The average energies of different reaction products observed at different angles are given in fig. 3. The averaging was made over the entire energy range with a weight proportional to the corresponding differential cross section.

The energies corresponding to the exit Coulomb barriers, calculated for spherical nuclei with $r_0 = 1.46$ fm are shown by thin lines in fig. 3. One can see that at all angles the average energies of the reaction products differing in Z from the initial

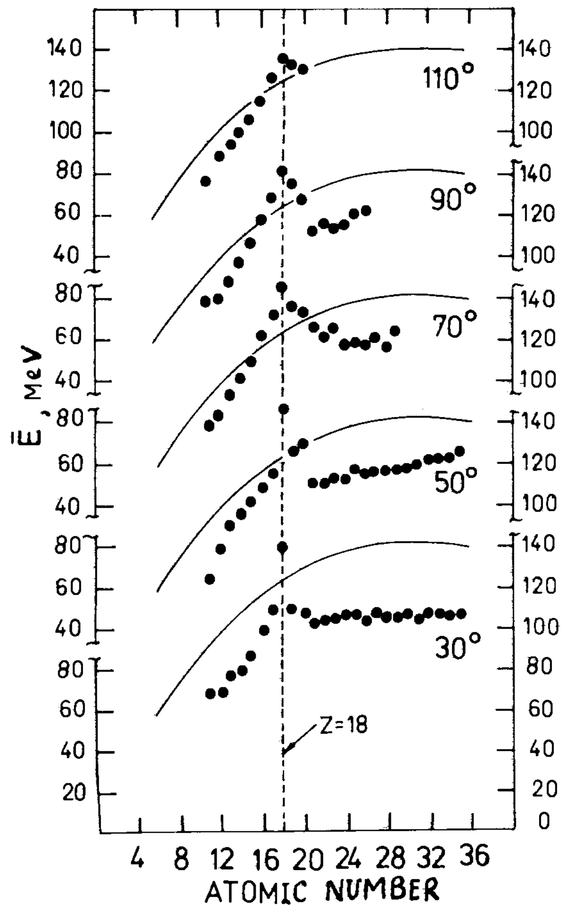

Fig. 3. The average energies of reaction products in the c.m. system observed at different lab. angles are presented by points. The energies corresponding to the exit Coulomb barriers for spherical nuclei are shown by thin lines.

particle by more than two units ($|\Delta Z| > 2$) are lower than the exit Coulomb barriers.

At 30°, the average energies of these products are about a factor of 1.3 lower than the Coulomb barriers for spherical nuclei. This can be regarded as evidence for a substantial deformation of the final nuclei before scission.

Reaction products of $|\Delta Z| \leq 2$ observed at 30° and 50° are characterized by energies close to and even smaller than the Coulomb barriers. At the same time, their average energies are noticeably nearer to the Coulomb barriers as compared with the products formed as a result of the transfer of a considerable number of protons. Thus, due to the contribution from quasielastic processes the dissipation of the initial kinetic energy in the case of the formation of the $|\Delta Z| \leq 2$ reaction products turns out to be, on the average, smaller than that for larger $|\Delta Z|$ products.

3.2. Angular Distributions

The c.m. angular distributions of reaction products with $11 \leq Z \leq 33$ are presented in fig. 4. Dots on the curves correspond to the angle values averaged over the energy range with a weight proportional to the corresponding differential cross section. On the whole, they are similar to the angular distributions of the same products, obtained in the bombardment of ^{232}Th with ^{40}Ar ions at 388 and 295 MeV (refs./8,20/).

Reaction products having relatively small Z values exhibit maxima near Θ_{Ruth}. Reac-

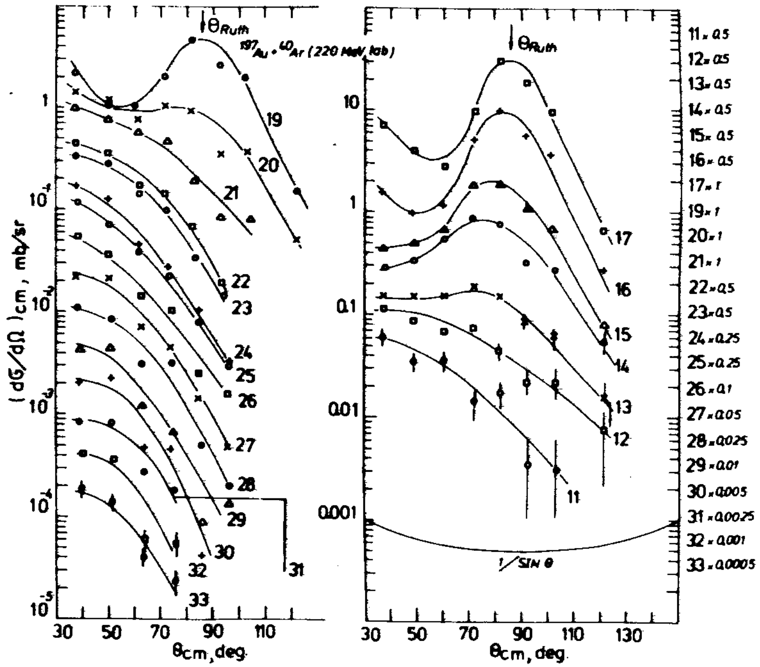

Fig. 4. The angular distributions of the products formed in the bombardment of ^{197}Au with 220 MeV ^{40}Ar ions. Numbers near the curves indicate the Z values of the products, whereas the numbers to the right give the multiplying factors for the cross sections.

tion products formed as a result of a strong reconstruction of the nuclei have a forward peaking in their angular distributions. The maxima in the angular distributions of the products pick-up reactions disappear with increasing ΔZ more easily than in those for the products of stripping reactions.

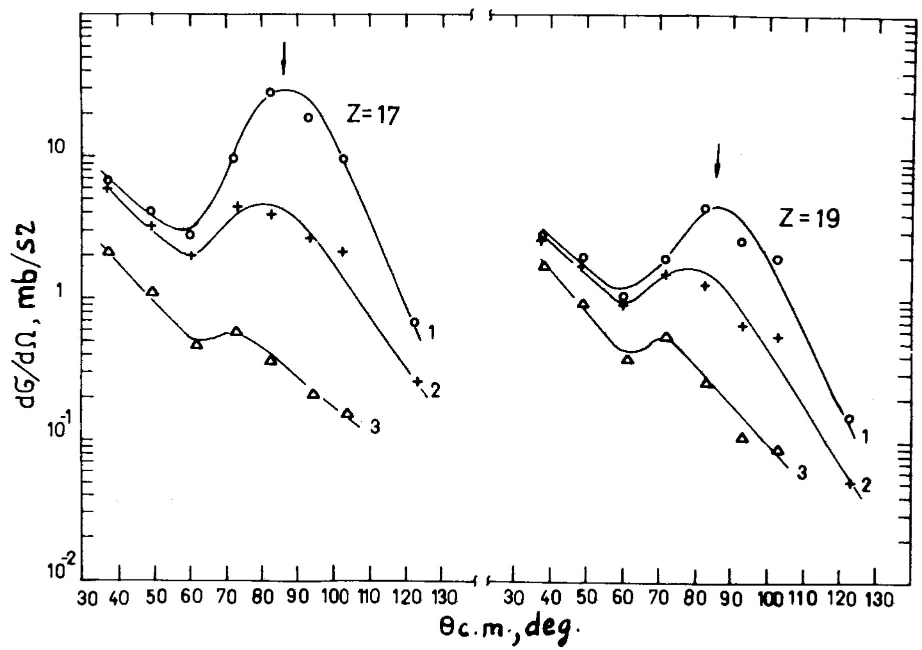

Fig. 5. The angular distributions of the Z=17 and 19 products for different parts of the energy spectrum: (1) for the whole spectrum, (2) for $E < E_{Coul}$, and (3) for $E < E_{Coul} - 20$ MeV . The arrows show the Θ_{Ruth} values.

A comparison of the angular distributions of the same products at bombarding energies of 220 MeV and at 288 and 340MeV shows that in the region of $\Theta_{c.m.} \gtrsim 70°$ the cross section decreases with increasing angle at 220 MeV more sharply than at higher energies, where an increase in cross sections is observed at $\Theta_{c.m.} > 90°$.

Fig. 5 shows the angular distributions of the Z=17 and 19 products, plotted for the whole energy range, for $E < E_{Coul}$ and $E < (E_{Coul} - 20 MeV)$. One can see that the shape of the angular distribution depends considerably on the extent of the initial kinetic energy dissipation.

The data obtained in the present paper allow one to define possible reasons for the difference in the angular distributions of the DIT products, obtained with and without Z-identification of reaction products.

Fig. 3 shows that the maximum dissipation of the initial kinetic energy takes place only in the case of the formation of reaction products differing in Z substantially from the initial particle. As is seen in fig. 4, the angular distributions of such products are forward peaked. If no Z-identification of reaction products is made and the differential cross sections of all "Ar-like" products with energies equal to and lower than the Coulomb barrier are summed up, one can obtain a maximum yield near Θ_{Ruth}. The appearance of this maximum is due to the following two factors: first, the dominating contribution to the total cross section of transfer reactions from few-nucleon transfers (see the table) and, second, the dominating contribution to the few-nucleon transfers and inelastic scattering from quasielastic and moderately inelastic processes.

Thus, to analyze the shape of the angular distributions of the DIT products it is not sufficient to take into account only the initial kinetic energy excess over the reaction barrier and the Z values of the initial nuclei. One should also take into

Table

Cross sections for the formation of light products in the reaction $^{197}Au + ^{40}Ar$ at 220 MeV, obtained by integrating differential angular distributions in the angle interval 30-110° (in the lab. system)

Z	σ, mb	Z	σ, mb	Z	σ, mb
11	0.35	20	6.57	28	1.06
12	0.89	21	3.47	29	0.98
13	2.08	22	2.48	30	0.91
14	7.82	23	1.89	31	0.90
15	16.2	24	1.58	32	0.82
16	63.5	25	1.30	33	0.85
17	92.4	26	1.17	34	1.11
19	18.4	27	1.16	35	0.69

consideration the extent of the dissipation of the initial kinetic energy with nuclear deformation and of the reconstruction of the nuclear nucleon composition.

CONCLUSIONS

(i) The forward peaking in the angular distributions of the DIT products, obtained in the bombardment of ^{197}Au with ^{40}Ar ions is observed down to projectile energies exceeding the interaction barrier by a factor of only 1.15.

(ii) In nucleon transfer reactions at low projectile energies the number of transferred nucleons and the extent of the dissipation of the initial kinetic energy have a considerable effect on the shape of the angular distributions.

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