

DEEP INELASTIC TRANSFER REACTIONS
AND THE FORMATION OF A DOUBLE NUCLEAR SYSTEM

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Abstract

Experimental data on multi-nucleon transfer reactions, obtained mainly by bombarding ^{232}Th with the ^{16}O , ^{22}Ne and ^{40}Ar ions with an energy of 7-9 MeV/nucleon are discussed. The energy spectra of light reaction products and isotopic production cross sections show some features which are difficult to interpret in the framework of conventional direct processes. The concept of a double nuclear system is proposed, which allows one to explain these features easily.

1. INTRODUCTION.

Heavy ion transfer reactions are usually considered as quasi-elastic direct processes occurring in the grazing collisions of two nuclei. However, lately experimental data have been obtained, especially for multi-nucleon transfer reactions, which cannot be described in this traditional framework. Transfer reactions in deep inelastic collisions of two nuclei are meant. Deep inelastic transfer reactions (DITR) have been observed for the first time by the authors of refs.¹⁻³). However, the peculiarity of the mechanism of these reactions and their close relation to the interaction of two nuclei have become evident only recently. Now the experiments aimed at studying DITR are under way in Dubna⁴⁻¹⁰), Orsay¹¹⁻¹⁵) and Berkeley^{16,17}). The theoretical analysis of DITR is being carried out elsewhere¹⁸⁻³⁵).

There are some reasons why these reactions attract the attention of physicists. DITR allow one to obtain unique information on the interactions of nuclei. Indeed, the compound nucleus forgets the history of its formation. Quasi-elastic processes, both elastic and inelastic scattering, give information on nuclear interaction in peripheral collisions when the nuclear surfaces overlap inconsiderably. On the contrary, DITR provide information on nuclear interaction just with considerable overlapping of nuclear surfaces, when collisions turn out

to be close to the head-on ones. DITR allow deep reconstruction of interacting nuclei and the obtaining of such exotic isotopes as ^8He , ^{11}Li , ^{14}Be , ^{15}B , ^{20}C , ^{21}N , and ^{24}O . The transfer reactions of this type may prove useful for superheavy element synthesis as well. Similarly to amphoteric elements in chemistry, the DITR mechanism itself is combining the properties of two opposite processes: direct reactions and compound nucleus formation.

Here the peculiarities of DITR are considered, basing mainly on experimental data obtained in Dubna ⁵⁻¹⁰) *). An attempt has been made to interpret these peculiarities qualitatively on the basis of the concept of a double nuclear system (DNS) formed in deep inelastic collisions of two nuclei. In DNS the nuclear surfaces considerably overlap, while the velocity of their relative motion is small. As a DNS has a considerable angular momentum, it rotates as a whole and evolves in time, coming from one state to another. The DNS lifetime turns out to be much larger than the characteristic nuclear time (10^{-22} sec).

2. EXPERIMENTAL DATA

2.1. Energy spectra of transfer reactions and nuclear viscosity.

Figs. 1-3 show the elemental energy spectra of the light products of transfer reactions in the $^{232}\text{Th}+^{40}\text{Ar}$ system at 388 MeV ⁹). The spectra are given in the lab. system. The $\Delta E, E$ method has been used for measurements without separating isotopes. The spectra have revealed the following peculiarities:

- a broad range spectrum extends to 200 MeV and that means the transfer of considerable amount of kinetic energy to excitation,
- the spectra are divided into two parts in the case of few-nucleon transfer reactions and at large emission angles,
- the spectra maxima are reduced with decreasing emission angle for few-nucleon transfer reactions,
- the spectra shape becomes symmetric with increasing number of stripped nuclei mainly due to the damping of the high energy part,
- the spectra maxima of multi-nucleon transfer reactions turn out to be close to the exit Coulomb barrier. A noticeable amount of products have energies much lower than the exit Coulomb barrier.

Fig. 4 shows a comparison of the energy spectra of S, P, Si and Al at three emission angles and at two ^{40}Ar projectile energies, 297

* DITR have been studied experimentally by a team of Dubna physicists, namely, A.G.Artukh, G.F.Gridnev, V.L.Mikheev, V.V.Volkov and J. Wilczynski of the Krakow University, Poland.

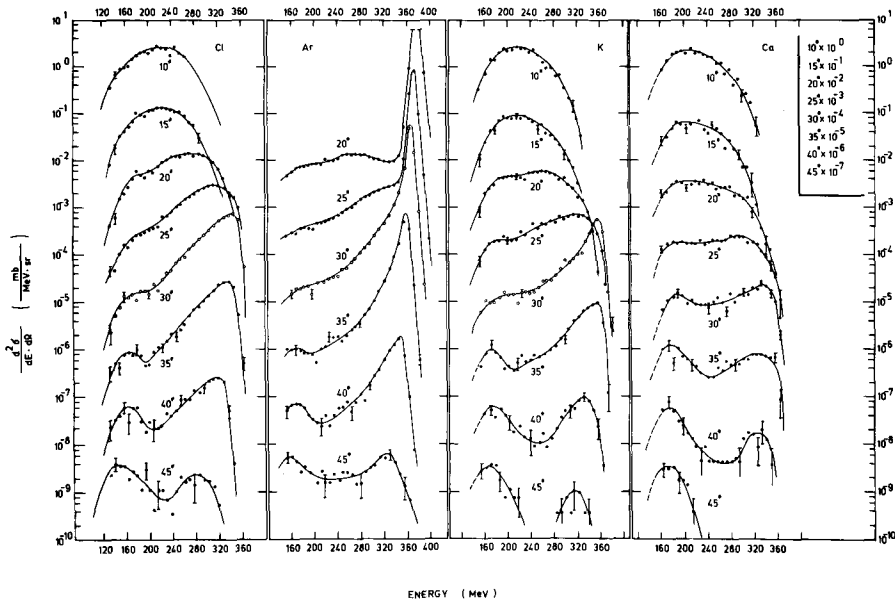


Fig. 1. Energy spectra of Ca, K, Ar and Cl transfer reaction products obtained by bombarding ^{232}Th with ^{40}Ar of 388 MeV (lab.system).

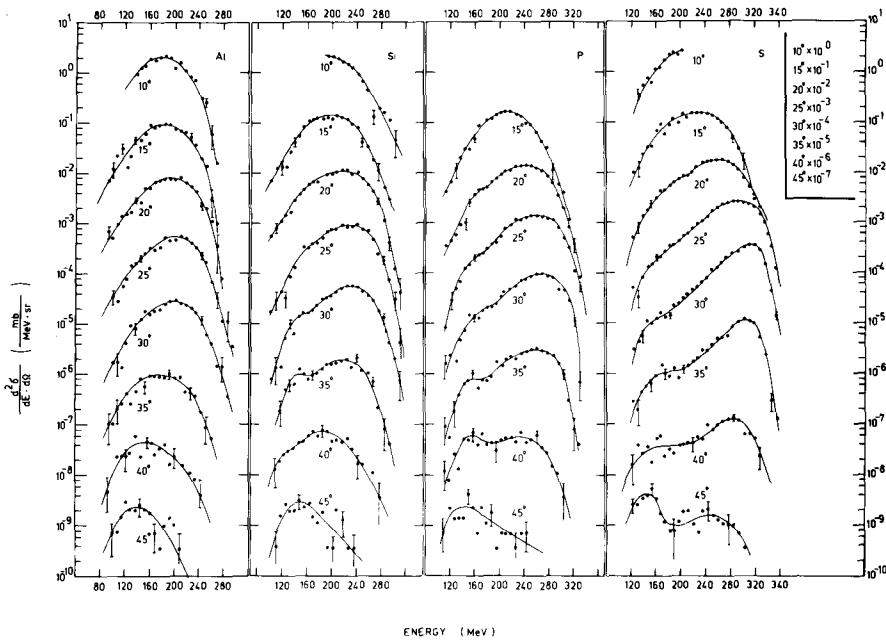


Fig. 2. Energy spectra of S, P, Si and Al transfer reaction products obtained by bombarding ^{232}Th with ^{40}Ar of 388 MeV (lab. system).

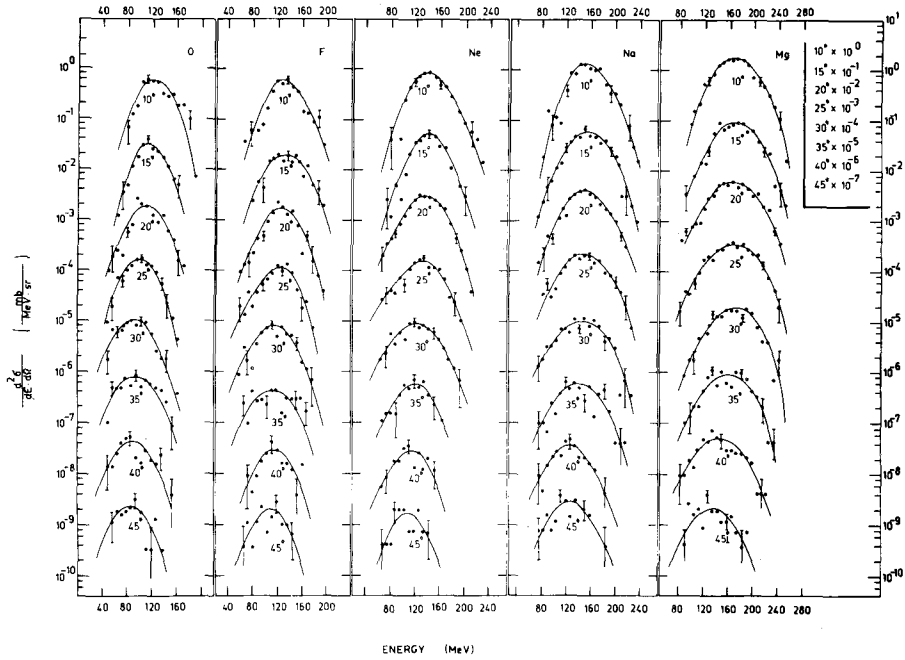


Fig. 3. Energy spectra of Mg, Na, Ne, F and O transfer reaction products obtained by bombarding ^{232}Th with ^{40}Ar of 388 MeV (lab.system).

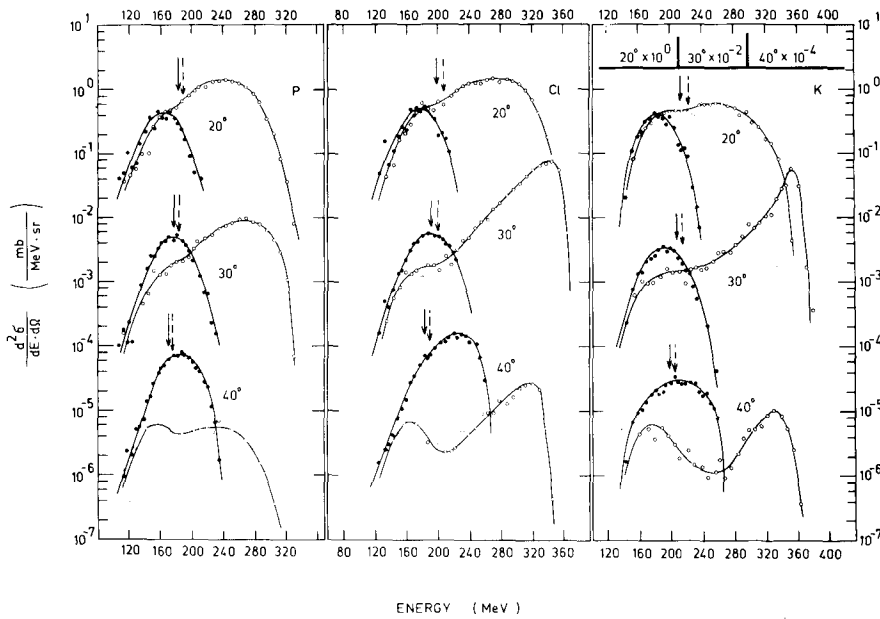


Fig. 4. Comparison of the energy spectra of P, Cl and K obtained by bombarding ^{232}Th with ^{40}Ar of 279 and 388 MeV.

and 388 MeV. Arrows show the exit Coulomb barrier: the solid and dashed arrows correspond to 297 and 388 MeV, respectively. The spectrum width greatly increases with increasing projectile energy. However, the low energy parts of the spectra, especially at small angles, coincide. For an angle of 20° the greater part of the energy spectrum at 288 MeV is lower than the exit Coulomb barrier.

Fig. 5 shows the Q_m value of reactions for the maxima of the energy spectra with respect to Z and the emission angle of the reaction light product, θ . They have been calculated on the basis of the kinetic energy of light reaction products under the assumption of a two-body reaction mechanism. Some facts give evidence for the two-body character of transfer reactions. The most important of them is that the peculiarities of the energy spectra and angular distributions observed in nucleon stripping are conserved in pick-up reactions when the dissociation of the bombarding nucleus in collisions is cancelled out. Potassium and chlorine nuclei produced in proton pick-up reactions and proton stripping may be considered as the "labeled" argon since the particle charge and mass are varied in this case slightly. The deviation to smaller angles with energy loss may be due to only nuclear attraction. The larger the nuclear surface overlapping in collisions, the greater is the nuclear attraction effect. The Q_m behaviour for Cl and K allows one to draw the conclusion that kinetic energy losses greatly increase with increasing overlap between the nuclei. The losses amount to about 150 MeV at a narrow angular interval of about 20° (at 379 MeV). This implies that nuclear behaviour in collisions is that of quite viscous objects.

Fig. 6 shows a comparison of kinetic energies of two final nuclei and their exit Coulomb barriers. The abscissa is the emission angle for a light product in the c.m.s. The ordinate is the decay kinetic energy at the maximum of the energy spectrum reduced by the height of the exit Coulomb barrier. The mark "0" at the ordinate axis implies in this case a situation when reaction products gain all their kinetic energy due to Coulomb repulsion. As it follows from data of Fig. 6, essential nuclear viscosity may result in total dissipation of kinetic energy in collisions and the reduction of the relative velocity of two nuclei to small values. Low energy maxima of few-nucleon transfer reactions and the maxima of multi-nucleon transfer reactions lie dozens of MeV lower than the exit Coulomb barrier. If one makes a mirror reflection of low energy maxima of few-nucleon transfer reactions onto the negative angle region, one obtains a good conjugation with their high energy maxima.

2.2. Angular Distributions, Element Production Cross Sections.

Fig. 7 shows the differential cross section for the production

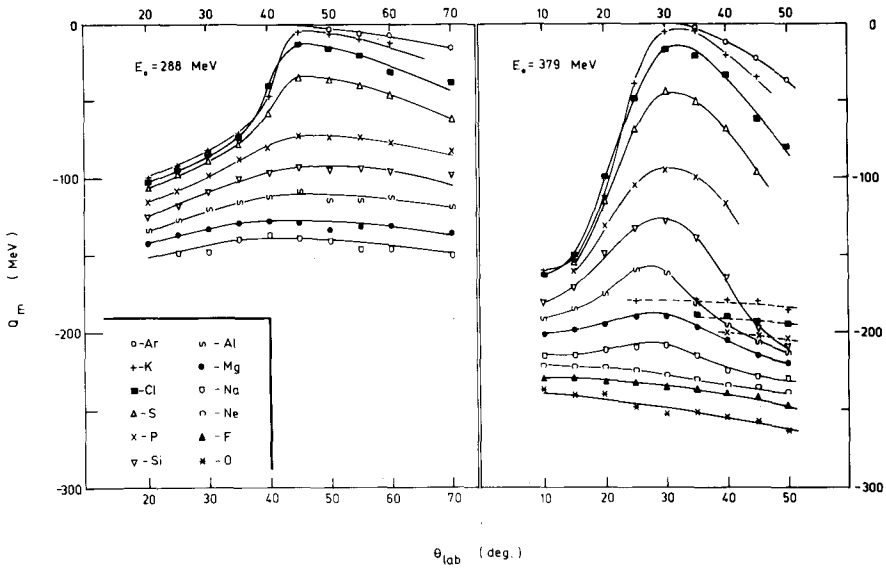


Fig. 5. Dependence of $Q_m(Z, Q)$ upon Z and θ of reaction light products (lab. system).

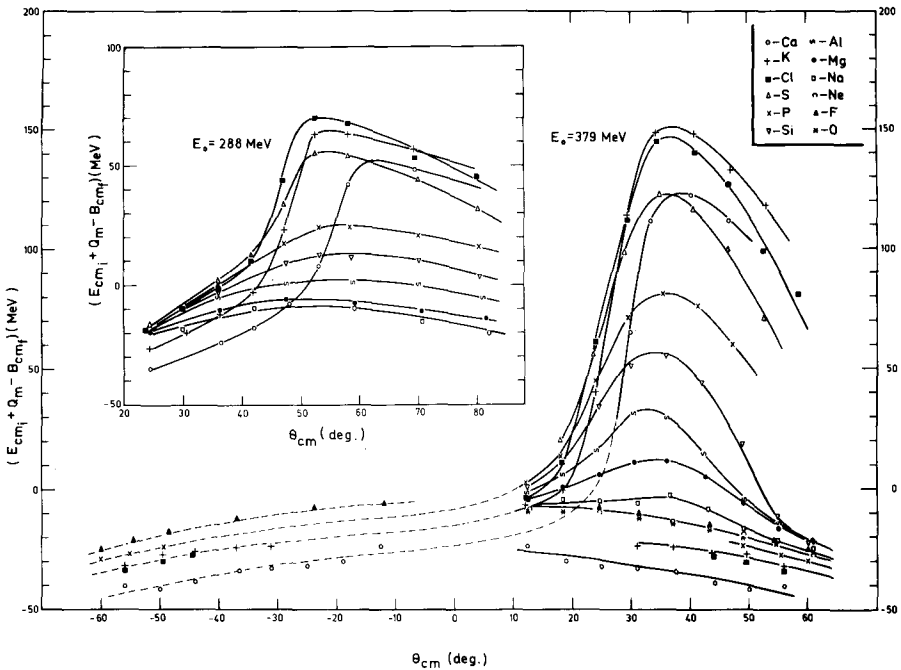


Fig. 6. Relation of the total kinetic energy of reaction products to the exit Coulomb barrier with respect to Z and the emission angle of the light product.

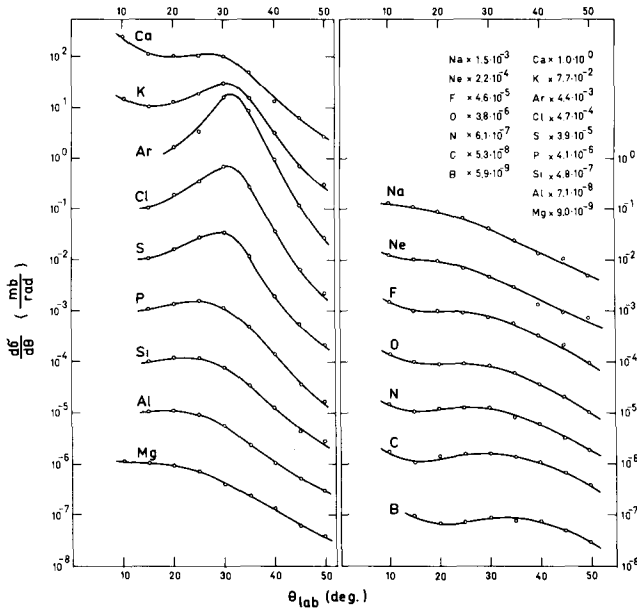


Fig. 7. Differential cross sections $d\sigma/d\theta$ of transfer reaction light products obtained by bombarding ^{232}Th with ^{40}Ar ions of 379 MeV (lab. system).

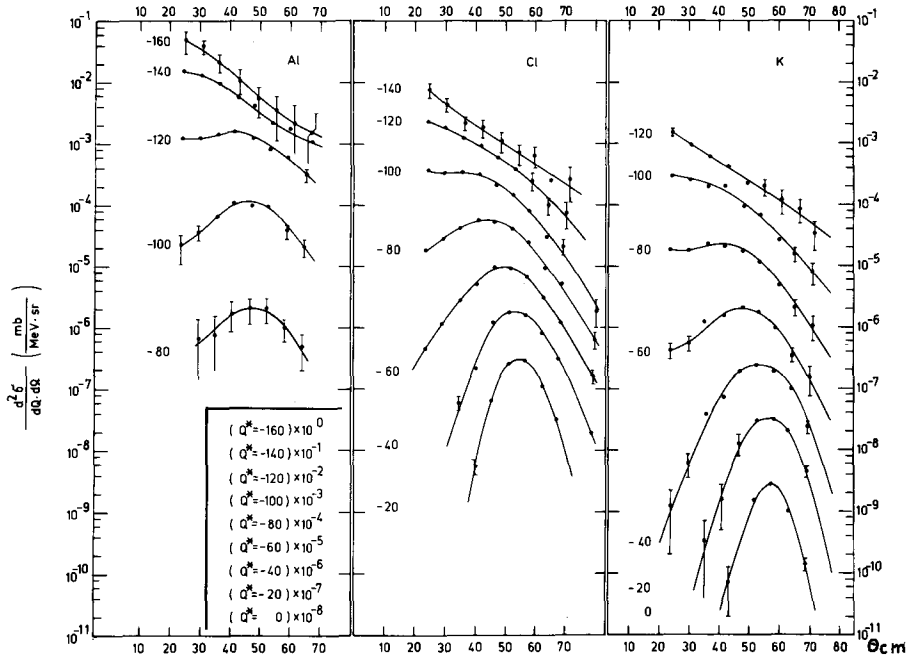


Fig. 8. Partial angular distributions of Al, Cl and K for various $Q^* \equiv Q$ values obtained by bombarding ^{232}Th with ^{40}Ar of 288 MeV.

of light elements - transfer reaction products in the bombardment of ^{232}Th with 379 MeV ^{40}Ar ions. The shape of the angular distributions varies regularly with the number of nucleons transferred. The peculiar maximum at the grazing angle is quite pronounced only for few-nucleon transfer reactions. With an increase in the number of nucleons transferred, its half-width increases and the maximum is shifted towards smaller angles. For multi-nucleon transfer reactions $d\sigma / d\Omega$ increases at first with decreasing emission angle. However, when the largest number of nucleons are transferred, there appears a broad maximum at an angle of 30° - 35° . Fig. 8 shows the partial angular distributions $d^2\sigma / d\Omega dQ$ for Al, Cl and K for various values of $Q^x = Q$. The data have been calculated for the system $^{232}\text{Th}+^{40}\text{Ar}$ at 288 MeV in the c.m. system. The shape of partial angular distributions extremely changes with increasing inelasticity of interaction. It is worth noting that the maximum at a "grazing" angle for quasi-elastic transfer reactions rapidly decreases towards smaller and larger angles. Thus, at small and large angles the main contribution to the cross section comes from inelastic processes.

Fig. 9 shows the cross sections of light element production in bombarding ^{232}Th with ^{40}Ar and ^{22}Ne ions. The abscissa is the number of protons stripped from the incident nucleus or picked up by it. The data obtained for isotopic yields show that nearly the same number of neutrons is transferred together with protons. It is seen that at first the reaction cross section rather quickly decreases with an increase in the number of protons transferred. However, in the case of ^{40}Ar at 379 MeV this reduction will be moderated (from O to B). A similar behaviour of the element cross section for the $^{232}\text{Th}+^{40}\text{Ar}$ system (379 MeV) is also observed in pick-up reactions¹⁰⁾. For instance, the production cross section for Fe exceeds 10 mb. On summing up the cross sections for direct processes, it is 800 mb for the $^{232}\text{Th}+^{22}\text{Ne}$ system at $\sigma_R = 1960$ mb, 1.7 b for the $^{232}\text{Th}+^{40}\text{Ar}$ system at 297 MeV and 2.4 b at 388 MeV. The σ_R values are equal to 1.9 and 2.9 b, respectively. With increasing projectile energy and mass, transfer reactions become a dominating process in the inelastic interaction of nuclei.

2.3. Isotope Production Cross Sections.

The cross sections of isotope production in transfer reactions vary from dozens of millibarns to fractions of a microbarn. For multi-nucleon transfers involving proton stripping from the bombarding nucleus, the authors of ref.⁵⁾ have found systematics for the cross sections. For the $^{232}\text{Th}+^{16}\text{O}$ system at 137 MeV it is shown in Fig. 10. The abscis-

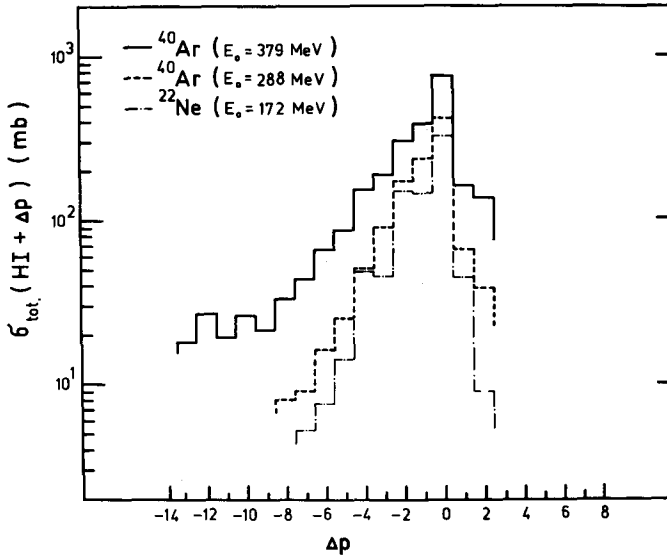


Fig. 9. Cross section of light element production by bombarding ^{232}Th with ^{22}Ne (174 MeV) and ^{40}Ar ions (288 MeV and 379 MeV). The abscissa is the number of stripped or picked-up protons.

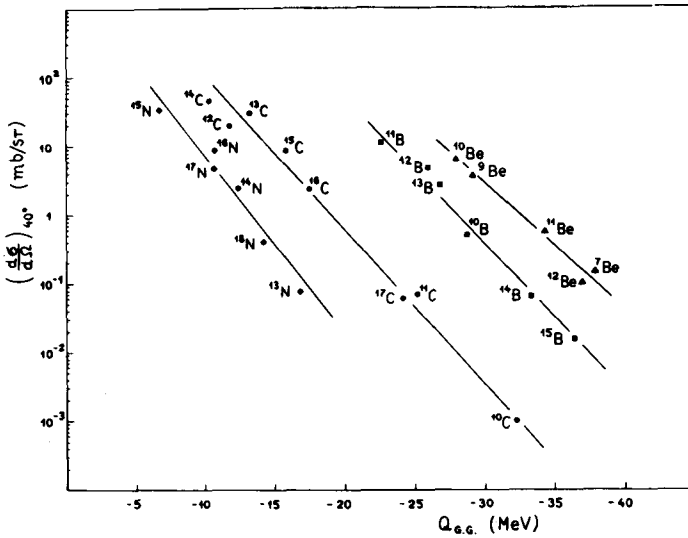


Fig. 10. Systematics of the differential cross section for isotope production for 40° obtained by bombarding ^{232}Th with ^{40}Ar at 137 MeV (lab.system). The target is 20 mg/cm^2 thick.

sa is Q_{gg} , $Q_{gg} = (M_1 + M_2) - (M_3 + M_4)$ being the energy required for accomplishing the reaction when the final nuclei turn out to be in the ground state. The ordinate is $d\sigma / d\Omega$. It is seen that the production cross sections of the isotopes of each element lie fairly well on the straight elemental lines. The systematics has been obtained for some combinations of targets and projectiles and emission angles of 40° and 12° . Figs. 11-13 show the systematics for the $^{232}\text{Th} + ^{15}\text{N}$ (40°) (ref.⁶), $^{232}\text{Th} + ^{22}\text{Ne}$ (12°) (ref.¹⁰) and $^{94}\text{Zr} + ^{22}\text{Ne}$ (12°) (ref.¹⁰) systems. It is seen that the systematics is fairly good and is fulfilled the better, the deeper the incident nucleus reconstruction.

The systematics is characterized by the exponential dependence $d\sigma / d\Omega$ upon Q_{gg} and the displacement of elemental lines towards the Q_{gg} axis with an increase in the number of stripped protons. The slope of elemental lines varies with Z of reaction products.

2.4. Difficulties in Interpreting Experimental Data within the Traditional Scheme of Direct Reactions

In classical direct reactions the energy of light products in the lab. system increases with decreasing emission angle as a result of a more favourable summation over the vectors of transfer velocity and that in the c.m.s. The spectra shown in Figs. 1-3 reveal the reverse dependence. The spectra are divided into two parts and the appearance of particles of energy lower than the Coulomb barrier is also difficult to explain. In transfer reactions the centrifugal barrier amounts to several dozens of MeV, while in the potential of two nuclei interaction, $V(R)$, the potential well is either absent or not deep. Therefore, it is difficult to explain the appearance of a low energy particle by the penetrability of the potential barrier.

The cross section of direct reactions is determined by the properties of the quantum states between which nucleon transfer occurs, and by the appropriate values of Q . The multi-nucleon transfer reactions are accompanied by considerable excitation of the final nuclei, and the probability of their production in the ground state is extremely small. From this point of view the interpretation of the Q_{gg} systematics involves serious difficulties. It has first been discussed in ref.²⁰). It has also been pointed out there that the Q_{gg} dependence of isotope production cross section shows that in two-body collisions the conditions are fulfilled which are close to the statistical equilibrium. The authors of ref.²⁰) have proposed the concept of partial statistical equilibrium for the states in which nucleons most easily pass from nucleus to nucleus through the contact region.

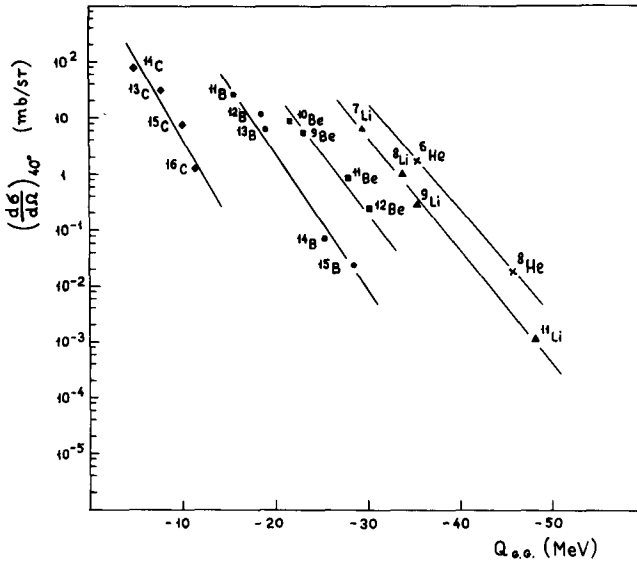


Fig. 11. Systematics of the differential cross section of isotope production for 40° obtained by bombarding ^{232}Th with ^{15}N at 145 MeV (lab. system). The target is 20 mg/cm^2 thick.

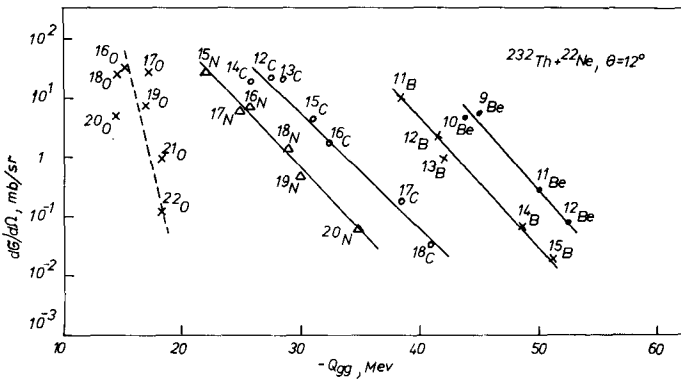


Fig. 12. Systematics of the differential cross sections of isotope production for 12° obtained by bombarding ^{232}Th with ^{22}Ne at 174 MeV (lab. system). The target is 2.5 mg/cm^2 thick.

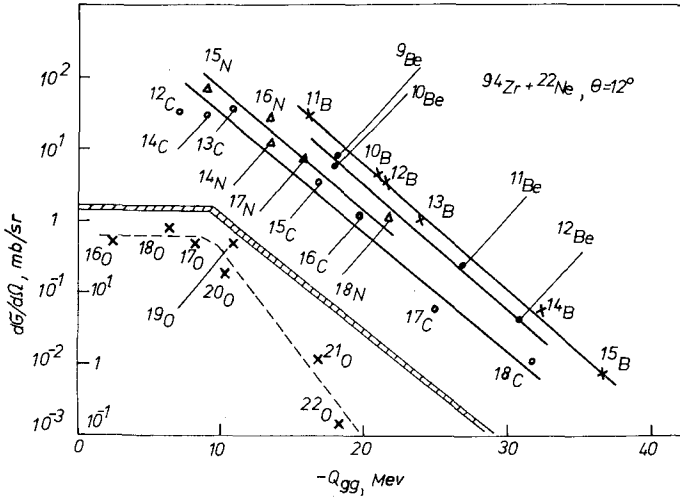


Fig. 13. Systematics of the differential cross sections for isotope production for 12° obtained by bombarding ^{94}Zr with ^{22}Ne of 174 MeV (lab. system). The target is 2.5 mg/cm^2 thick.

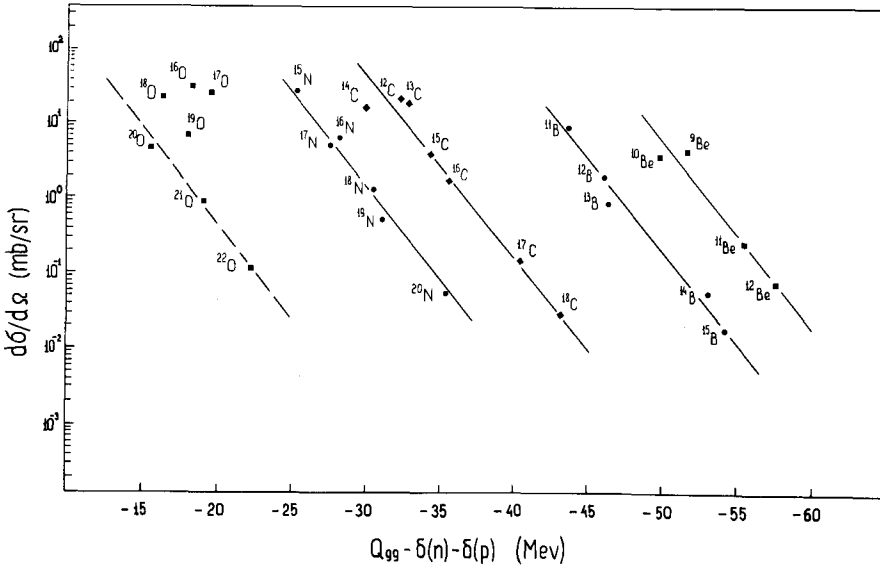


Fig. 14. The Q_{gg} systematics for the $^{232}\text{Th} + ^{22}\text{Ne}$ system, $E = 174 \text{ MeV}$, $\theta = 12^\circ$ (lab. system) after introducing corrections taking into account the effect of neutron and proton pairing.

3. POSSIBLE INTERPRETATION OF DEEP INELASTIC TRANSFER REACTIONS IN TERMS OF THE DOUBLE NUCLEAR SYSTEM CONCEPT

3.1. Formation, Evolution and Disintegration of the Double Nuclear System (DNS)

The formation of a double nuclear system is a natural consequence of strong nuclear viscosity and strong incompressibility of nuclear matter. The analysis of the interaction potential of two nuclei

$$V(R) = V_n(R) + V_c(R) + V_{\text{rot}}(R),$$

where $V_n(R)$, $V_c(R)$ and $V_{\text{rot}}(R)$ are the nuclear, Coulomb and centrifugal potentials, respectively, has been performed in refs. 24,25,36). It has been shown that at small radii a rise is observed in the $V_n(R)$ potential which shows that repulsive forces, instead of attractive ones, become active. The appearance of repulsive forces has been interpreted as a result of the Pauli principle effect and strong incompressibility of saturated nuclear matter.

We consider the collision of two nuclei (Z_1, A_1) and (Z_2, A_2) (c.m.s.) at energies exceeding the Coulomb barrier, $E_0 > B_0$, the orbital momentum ℓ being close to the critical angular momentum ℓ_{cr} . The spins of both nuclei are assumed to be equal to zero. At the moment of contact between the nuclear surfaces the kinetic energy is $E_0 - B_0$. We divide it into two parts: the radial part E_R and the tangential one E_t . They are as follows

$$E_t = \frac{\hbar^2 \ell(\ell+1)}{2\mu R^2} \quad \text{and} \quad E_R = E_0 - B_0 - \frac{\hbar^2 \ell(\ell+1)}{2\mu R^2}.$$

Here μ is the reduced mass, $R = r_0(A_1^{1/3} + A_2^{1/3})$ and $r_0 = 1.5$ fm. Due to the radial portion of the kinetic energy and nuclear attraction, the nuclei start to penetrate into each other energetically. It can be expected that under conditions of strong nuclear viscosity the tangential motion practically damps near the trajectory turning point, where the radial velocity is reduced to zero, and the overlapping of nuclear surfaces is maximally large. E_t is partly converted into excitation energy, partly to the rotation of the system of two tightly bound nuclei. The ratio of these two parts depends upon the variation of the moment of inertia of the system. At the first stage of the process $\mathcal{J} = \mu R^2$. After the damping of the relative motion $\mathcal{J} = \mathcal{J}_1 + \mathcal{J}_2 + \mu R_*^2$, where \mathcal{J}_1 and \mathcal{J}_2 are the intrinsic moments of inertia of the nuclei, and R_* is the distance between the centres of the nuclei at the turning point. The intrinsic moments of inertia \mathcal{J}_1 and \mathcal{J}_2 are close to those of the rigid body ones, since their excitation energy is about several tens of an MeV.

The radial part of the kinetic energy E_R also greatly dissipates. It may be assumed that a larger portion of E_R is converted into nuclear excitation. After the turning point the light nucleus possessing some reverse potential energy starts "to slide down" along the radius following the $V(R)$ potential. This resembles the pendulum motion in a viscous liquid. The light nucleus may be slightly accelerated under the effect of the Coulomb field when passing nuclear periphery where the stopping effect of nuclear viscosity weakens due to smaller density of nuclear matter.

A major part of collision kinetic energy dissipates within the period from the moment of contact to the turning point. At the collision energy of several MeV per nucleon, this time is about $1-2 \times 10^{-22}$ sec. This time is too short for the nuclei to become strongly deformed and change their structure to a great extent.

Thus, as a result of strong nuclear viscosity and repulsion at small radii at the beginning of collision, a double nuclear system is formed at the turning point. The nuclear surfaces of DNS are considerably overlapping and their relative velocity is small. The DNS has an angular momentum $\hbar \ell$ and the moment of inertia corresponding to the common rotation of two tightly bound nuclei. The DNS has its rotation energy $E_{\text{rot}} = \frac{\hbar^2 \ell(\ell + 1)}{2J}$ and the excitation energy $E^* = E_0 - V^*(R_*)$, where V^* is the potential of the nuclear interaction, in which the centrifugal potential $V_{\text{rot}}(R)$ is taken to be that for a rotating DNS.

What happens to DNS later? If $\ell < \ell_{\text{cr}}$, the interaction potential $V^*(R)$ has a minimum to which the system slides down along R . However, this is a local minimum since the shape of DNS does not correspond to that of the potential energy. Therefore, the system starts evolving by exchanging nucleons and changing its shape for the one corresponding to the potential energy minimum. If the Z and A values of the DNS are not very large, the excited compound nucleus of equilibrium deformation comes as a final result.

With $\ell > \ell_{\text{cr}}$, the Coulomb and centrifugal forces exceed nuclear attraction (the interaction potential $V^*(R)$ has no minimum) and the DNS starts disintegrating. However, since with $\ell = \ell_{\text{cr}}$ the three forces are balanced, the domination of repulsion over attraction may be assumed to be small if ℓ is somewhat larger than ℓ_{cr} . As a result, the disintegration of the DNS under the conditions of high nuclear viscosity will proceed slowly compared with the characteristic nuclear time. In the course of disintegration the system may turn by a considerable angle, and the emission of light products will take place in the region of negative angles. The comparatively long lifetime of the DNS

provides the possibility of transferring a large number of nucleons from one nucleus to the other. During this period of time the nuclei incorporating the DNS may undergo noticeable deformation.

3.2. Interpretation of Experimental Data.

The concept of a double nuclear system permits a natural interpretation of the peculiarities of transfer reactions. The double peak in the energy spectra of few-nucleon transfers results from the fact that a transfer of a small number of nucleons takes place in two different processes, namely in the quasielastic and deep inelastic ones. In the former case the ion is scattered mainly in the Coulomb field with the emission into the region of positive angles, and most of the kinetic energy is conserved. In the latter case the turning double system passes through 0° and disintegrates by emitting a light product with an energy close to the Coulomb barrier in the region of negative angles.

Multi-nucleon transfer reactions mainly occur in deep inelastic processes, since the transfer of a considerable number of nucleons requires a longer contact time and higher excitation of the nuclei. The development of deformations in the double nuclear system reduces the exit Coulomb barrier and makes possible the emission of particles with energies substantially lower than the Coulomb barrier for non-deformed nuclei. The shape and width of the energy spectra of deep inelastic transfers can be interpreted in terms of the spread of the lifetime of the double nuclear system. The distribution of specific lifetimes t over an average time τ may be assumed to be characterized by the Gaussian $t - \exp - (\frac{t - \tau}{\sigma})^2$. The deformation of the double nuclear system will increase proportionally to time at first approximation. Correspondingly, the Coulomb barrier will decrease. As a result, the shape of the energy spectrum may be described by the Gaussian, while its width will be proportional to $Z_3 Z_4$, the atomic numbers of the reaction products. The possible dependence of τ on the Z_3/Z_4 ratio can also affect the spectrum width.

An analysis of the angular distribution was carried out in the quasielastic approach, according to which all partial waves corresponding to surface collisions take part in the interference³⁷⁾. However, under the real conditions the inelasticity of the interaction increases rapidly as l goes from l_s to l_{cr} . This leads to the destruction of the coherence of partial waves if one takes the entire interval $l_{cr} - l_s$. In the exit channels only the groups of partial waves close in the l values interfere. The width of the packet Δl decreases with the increasing gradient of energy changes dE/dl . The elemental angular

distributions are a complicated superposition of partial angular distributions differing both in shape and intensity. The analysis made in ref. ⁹⁾ has shown that the quasielastic part of the angular distributions of few-nucleon transfers (the Q_{π} values are small) is well described by the Strutinsky model ³⁷⁾ provided use is made of the Gaussian distribution of partial wave amplitudes. However, this model is incapable of describing the angular distributions at larger energy losses. It has recently been shown in ref. ³⁴⁾ that some progress can be made by using a modified version of the Strutinsky model and introducing a more complicated ℓ dependence of the amplitudes and phases of partial waves.

The angular distributions of deep inelastic transfers are to be analysed separately since the methods developed for direct processes are hardly applicable here. The disintegration of the double nuclear system resembles the fission of a compound nucleus with a large angular momentum, but the basic difference between them is that the disintegration of the double system takes a shorter time than required for one revolution. Nucleon transfer in the double nuclear system can be regarded as one of the aspects of its evolution in time. In this case there should exist a relationship between the lifetime of the double nuclear system and the number of nucleons transferred. As this system rotates, this correlation should manifest itself in the fact that the average emission angle of a light product (in the region of negative angles) will somehow increase with the number of transferred nucleons.

The disintegration of the double nuclear system is accompanied by the emission of a light product in the region of negative angles. This implies that the average turning angle of the system prior to its disintegration is no less than $\pi/2$. The estimates of the double nuclear system lifetime for $\ell \sim \ell_{cr}$ and the rigid body moment of inertia give a value of about $2-3 \times 10^{-21}$ sec, which much exceeds the characteristic nuclear time, $\sim 10^{-22}$ sec. During the turning time of the system, conditions close to the statistical equilibrium with respect to energy and nucleon exchange between the nuclei can be established ²⁰⁾.

The excitation energy of the DNS at the turning point is equal to $U_i(R_{\pi}) = E_0 - V^{\pi}(R_{\pi}) - \Delta(p, n)$, where $\Delta(p, n)$ is an energy consumed to break proton and neutron pairs in both nuclei. The DNS can disintegrate in many directions, since the exchange of energy and nucleons between the nuclei is a process of statistical nature.

We assume the probability for the disintegration of the DNS with the production of two nuclei (3 and 4) in the exit channel to be proportional to the product of the level densities in these nuclei,

i.e. $\rho_3 \cdot \rho_4$. The level densities are determined by the final excitation energy U_f and its distribution between the nuclei. Since the Q_{gg} systematics describes the cross sections for the formation of light reaction products in bound states, the ρ value for a light product should be understood to be the number of bound states.

We shall express U_f in a form, which clearly reflects the influence of the nucleon transfer process on the value of the final excitation energy

$$U_f = U_i + Q_{gg} + \Delta E_c + \Delta E_{rot} - \delta(n) - \delta(p).$$

Here ΔE_c is a change in the Coulomb energy of the interaction in the exit channel as compared with the entrance one, ΔE_{rot} is a change in the rotational energy of the double nuclear system at nucleon transfer, which is due to a change of the moment of inertia, and $\delta(n)$ and $\delta(p)$ are corrections taking account of the effect of neutron and proton pairing at nucleon transfer.

The Q_{gg} factor automatically includes the energy consumption on the breaking of pairs in the donor-nucleus for those nucleons that were transferred to the acceptor-nucleus. The transferred nucleons occupy, as a rule, the excited levels in the acceptor-nucleus and turn out to be unpaired. However, the Q_{gg} factor, which characterizes the energy consumption for the transfer of nucleons from the ground state of the donor-nucleus to the ground state of the acceptor-nucleus, neglects this fact. As a result, the excitation energy U_f appears to be overestimated. The over-all pairing correction for a given reaction channel (for a definite isotope) is equal to the sum of the pairing energies in the acceptor-nucleus of the additional nucleon pairs formed in the acceptor-nucleus as a result of nucleon transfer. The exception of this rule are the channels, in which extremely neutron-rich light nuclei with an even number of neutrons are formed. Such nuclei may not have excited bound states corresponding to the breaking of a neutron pair. If such nuclei are formed as a result of a pick-up of two neutrons, these neutrons may be transferred only in the form of a pair, for these two neutrons no pairing correction is introduced.

In accordance with the hypothesis about the partial statistical equilibrium with respect to energy and particle exchange, we shall assume the final excitation energy U_f to be distributed between both nuclei proportionally to their level densities. In order to describe the level density ρ , we make use of the expression for ρ at a constant temperature

$$\rho \sim \exp \frac{U}{T}.$$

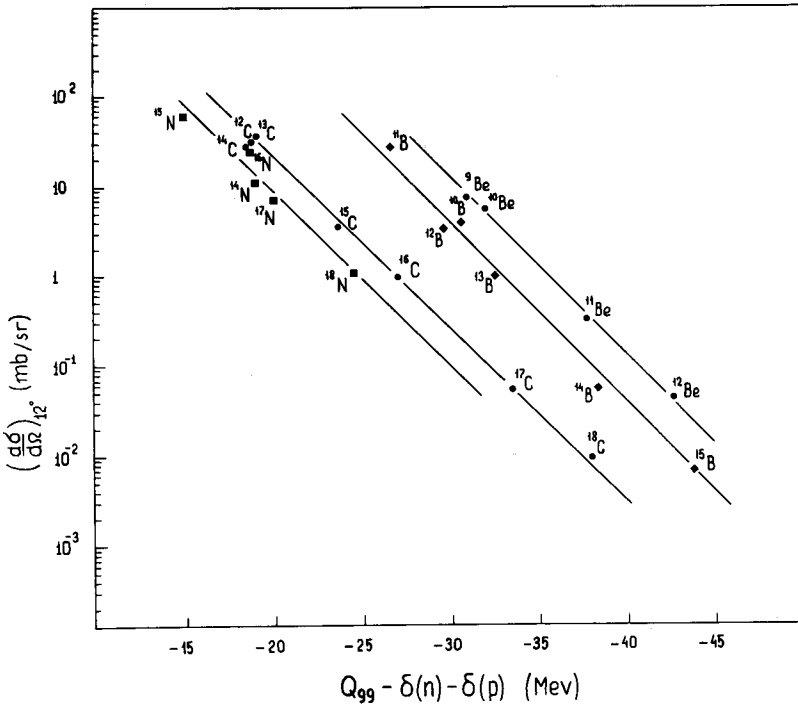


Fig. 15. The Q_{gg} systematics for the $^{94}\text{Zr} + ^{22}\text{Ne}$ system, $E = 174$ MeV, $\theta = 12^\circ$ (lab. system) after introducing corrections taking into account the effect of neutron and proton pairing.

It should, however, be noted that T can noticeably differ from the temperature of the corresponding compound nucleus, since the double nuclear system does not reach the state of complete statistical equilibrium. This quantity can be regarded as the temperature of a partial statistical equilibrium or simply as a parameter. Generally, the T values are the same for both nuclei forming the DNS. However, if one of the reaction products is a light nucleus with large neutron excess and a small number of bound states, practically the entire excitation energy will then be concentrated in the heavy nucleus. The light nucleus will remain unexcited. For the general case, the product of the level densities of the final nuclei $\rho_3 \cdot \rho_4$ can be written as follows:

$$\rho_3 \cdot \rho_4 \sim \exp \frac{U}{T}.$$

The energy spectra of the isotopes produced by deep inelastic transfers differ inconsiderably (for a given Z_f). The range of angular momenta l_{cr} , $l_{cr} + \Delta l$ for deep inelastic transfers is comparatively narrow, and in calculating U_f one can use some average value

of l . Thus, the isotopic production cross section is mainly determined by the final excitation energy U_f , i.e.

$$\sigma \sim \exp \left(-\frac{U_f}{T} \right).$$

On heavy nuclei, the main contribution to the changes in excitation energy U is made by Q_{gg} and ΔE_c , the Q_{gg} value reaching tens of MeV and ΔE_c being equal to 5-10 MeV per transferred proton. The value of ΔE_{rot} does not exceed several hundred keV per transferred nucleon, and the pairing energy in heavy nuclei is about 1 MeV. Therefore, in the first approximation one can leave only the main terms in the expression for U_f . This will give the following expression for the cross section:

$$\sigma \sim \exp \left(-\frac{Q_{gg} + \Delta E_c}{T} \right).$$

This is just the expression that describes the empirical Q_{gg} systematics of isotopic production cross sections in multi-nucleon transfer reactions.

In the empirical Q_{gg} systematics, the slope of the isotopic lines changes to some extent as one progresses from one element to another. The introduction of corrections for neutron pairing (in this case the abscissa corresponds to $Q_{gg} - \delta(n)$) results in the identity of the slopes. The role of the pairing corrections manifests itself most vividly in the case of the bombardments of ^{94}Zr with ^{22}Ne . In ^{94}Zr , the pairing energy increases and the Coulomb energy decreases compared with ^{232}Th . As a result, nitrogen isotopes appear to be located to the right of the carbon isotopes, while boron isotopes are to the right of berillium ones. Corrections for the pairing of neutrons and protons permit the reestablishment of the normal sequence of the isotopic lines in accordance with the Z value (Fig. 15).

4. CONCLUSION

The experimental information presented in this paper and its analysis allow to conclude that transfer reactions in the deep inelastic collisions of two complex nuclei are characterized by a new, in principle, mechanism of nuclear reactions, which is unknown for light bombarding particles. The characteristic feature of this mechanism is the production of a double nuclear system, in which, in spite of the strong interaction, the nuclei retain most of their individual properties. The originality of these reactions consists in the fact that they combine the features typical both for classical direct processes and a compound nucleus. The light products "forget" neither the initial direction of the projectile motion, nor its characteristics; in other

words, their angular distribution is directed forward and the maximum yield corresponds to isotopes close to the initial nucleus both in A and Z. At the same time, the production cross sections for some isotopes are determined by the statistical equilibrium conditions characteristic of a compound nucleus. These conditions allow the transfer of a considerable number of nucleons from one nucleus to the other. Under equilibrium conditions, the heavy nucleus possessing a high level density absorbs practically the entire excitation energy. This fact provides the possibility of producing neutron-excessive isotopes of light elements with an extremely low neutron (or neutron pair) binding energy in transfer reactions.

The experimental investigations described in this paper were possible due to the high parameters of heavy ion beams from the U-300 cyclotron of the JINR Laboratory of Nuclear Reactions. The author is deeply thankful to Academician G.N.Flerov, Director of the Laboratory of Nuclear Reactions, for his every support and valuable advice, which largely contributed to the success of the work. The author is grateful to his colleagues A.G.Artukh, G.F.Gridnev and V.L.Mikheev for fruitful discussions.

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