Transfer reactions induced by heavy ions

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The experimental data on transfer reactions induced by heavy ions are reviewed. It is shown that in these reactions there is a new mechanism of nuclear reactions which combines the characteristic features of direct processes and the decay of an excited compound nucleus. The concept of a double nuclear system formed in the deep inelastic collisions of two complex nuclei is proposed.

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INTRODUCTION

Research on transfer reactions, especially those in which several nucleons are transferred, is one of the most rapidly developing directions in the physics of heavy ions.[1)] In practically every laboratory with a heavy-ion accelerator these types of reactions between complex nuclei are being studied. Many-nucleon transfers are interesting because they open up the possibility of obtaining new nuclear information which is inaccessible with light bombarding particles. In nuclear spectroscopy, they can be used to obtain data about the many-particle components of nuclear states, particular interest attaching here to the excitation of α-cluster and quasimolecular states. Since the transfer of nucleons takes place in peripheral collisions of two nuclei and is accompanied by the transfer of appreciable angular momentum, a transfer reaction can be used successfully to excite nuclear states with very high spin.

Many-nucleon transfers are very effective for obtaining isotopes far removed from the β-stability region. The first emitter of delayed protons—^{17}Ne—was detected in the reaction of stripping of three neutrons from the ^{20}Ne nucleus.[12] In reactions involving the capture of neutrons, the stripping of protons, and the exchange of nucleons it has been possible to obtain and demonstrate the nuclear stability of about 30 new neutron-rich isotopes of light elements.[13,14] When the ^{40}Ar nucleus collides with a medium or heavy target nucleus, it can transfer to it more than 30 nucleons. This means that many-nucleon transfers can be used to synthesize different isotopes of transuranium elements. It is possible that these reactions could also be used to synthesize superheavy nuclei in the conjectured new stability region.

With increasing mass and energy of the bombarding ion, the cross section for production of a compound nucleus decreases, while the transfer-reaction cross section increases. For the heaviest of the ions currently used—the ions of krypton and xenon—the cross section for production of a compound nucleus on medium and heavy nuclei does not exceed a few percent of the total reaction cross section.[15,16] The overwhelming part of the cross section is accounted for by transfer reactions, which are the dominant nuclear process for these ions.

In heavy-ion reactions, two complex nuclear systems are involved, and the transfer-reaction mechanism therefore entails features unknown for light bombarding particles. Indeed, it is the particular features of direct reactions with heavy ions which are the main concern of this review. On the basis of the experimental data, one can show that heavy-ion transfer reactions involve a new mechanism which combines the characteristic features of two antipodal processes: classical direct reactions and decay of an excited compound nucleus.

Usually, heavy-ion transfer reactions have been regarded as a quasielastic direct process that occurs in a grazing collision of two nuclei. This picture was suggested by the study of the angular distributions and energy spectra of one- and few-nucleon transfers. It was these reactions on which experimenters concentrated in the first stage. As a rule, the energies of the light products of these reactions were found to be near the energy of the incident nucleus, and the angular distribution corresponded to scattering of the heavy ion in a peripheral grazing collision with the target nucleus. These notions form the basis of a whole series of theoretical models[17–21] which succeeded in giving a satisfactory description of the angular distributions of transfer reactions. However, in more recent years the study of transfer reactions has yielded experimental data that do not fit into this now almost traditional scheme of direct processes induced by heavy ions. These are the data on transfer reactions in deep inelastic collisions of two nuclei. In these collisions, all or the overwhelming part of the kinetic energy of the collision is expended on exciting the nuclei, and the energy of the light reaction products is near that of the exit Coulomb barrier. Moreover, among the light products of the transfer reactions one observes particles with an energy tens of MeV below the exit Coulomb barrier. Their appearance cannot be explained by penetrability of the potential barrier. Transfer reactions are real-

[1)]Transfer reactions induced by heavy ions are reviewed in Refs. 1–5 and in the corresponding sections of the reports of the latest international conferences and symposia on reactions between complex nuclei.[6–11] ized in collisions with large angular momentum. In these collisions, the centrifugal potential reaches several tens of MeV and the probability of reaction products being emitted with an energy appreciably lower than the exit Coulomb barrier is negligibly small.

Nor can the low-energy products be attributed to processes involving the dissociation of the incident nucleus when it collides with the target nucleus, since the low-energy particles are also observed among the products of nucleon pickup by the incident nucleus. The cross sections for the production of isotopes in many-nucleon transfer reactions were found to exhibit features that can be explained only under the assumption of statistical equilibrium with respect to the exchange of energy and nucleons between the nuclei. However, in direct processes the time of contact between the nuclei is short and it would be hardly possible for statistical equilibrium to be established.

Deep inelastic transfers in reactions induced by heavy ions were observed for the first time in Refs. 22–24. However, the distinctive feature of the mechanism of these reactions and the importance of studying them for understanding the nature of the interaction between complex nuclei were recognized only recently. This came about largely as the result of new experiments made at Dubna,[25–31] Orsay,[32–36] and Berkeley[16,37–39] with Ar, Cu, Kr, and Xe ions as bombarding particles. It was found that the deep inelastic transfer reactions have a direct bearing on the problem of synthesizing superheavy elements since they enable one to obtain unique information about the viscosity of nuclear matter and the mechanism by which nuclei interact when their surfaces overlap strongly. For a compound nucleus forgets the history of its formation, and elastic and inelastic processes give information about the interaction of nuclei in peripheral collisions when the surfaces of the nuclei overlap only slightly. It is the deep inelastic transfers that contain information about the interaction of nuclei in nearly head-on collisions.

The study of deep inelastic transfers stimulated the development of a theoretical approach to the description of the interaction of two complex nuclei in which wide use is made of the concepts of classical macroscopic physics: friction, viscosity, diffusion, and evolution of the properties of a nuclear system in time. The possibility and value of such an approach were discussed at the conference in Aix en Provence.[40] A whole series of theoretical papers[41–50] have since been published in which the interaction of two complex nuclei and deep inelastic transfer reactions are analyzed in the framework of this approach.

In this paper, the experimental data on deep inelastic transfer reactions, and especially the material obtained at the Nuclear Reactions Laboratory at Dubna,[22–31] are reviewed. An attempt is also made to interpret them qualitatively on the basis of the notion of formation of a specific double nuclear system in the deep inelastic collisions of two nuclei. Such collisions are the result of the high viscosity of nuclear matter and its low compressibility in the saturated state. It is these properties that lead to the rapid dissipation of kinetic energy in a collision. In the double nuclear system, the surfaces of the nuclei overlap strongly, and the velocity of their relative motion is low. Despite the strong interaction, the nuclei retain their individuality to a considerable extent, largely because of the strongly bound nucleons of the inner shells. Possessing an appreciable angular momentum, the double nuclear system rotates as a whole. In the case of transfer reactions for which the angular momentum of the collision is greater than the critical[2)] value $\hbar l_{cr}$, the double nuclear system decays before completing a revolution. Nevertheless, because of the increase in the moment of inertial and the comparatively large angle of revolution, the lifetime of the system before decay is much greater than the characteristic nuclear time ($\sim 10^{-22}$ sec), so that conditions nearly corresponding to statistical equilibrium are established for the exchange of energy and nucleons between the nuclei. During the interaction time, an appreciable number of nucleons can be transferred from nucleus to nucleus, and the nuclei themselves can undergo appreciable deformation. The concept of a double nuclear system is also helpful when one is considering the formation of a compound nucleus in reactions induced by heavy ions. In this case, the double nuclear system is formed in the first stage of collision of the two nuclei, when nuclear forces participate in the interaction. Subsequently, the double nuclear system evolves by exchanging nucleons and energy and by changing its shape toward an equilibrium state by minimizing the potential energy.

1. EXPERIMENTAL DATA

Detection of transfer-reaction products. In transfer reactions induced by heavy ions with energy appreciably exceeding the Coulomb barrier, a large number of reaction channels are open and tens of different isotopes are formed as products. Under these conditions, severe conditions are imposed on the resolution of the experimental apparatus if the individual reaction channels are to be distinguished.

In the first stage of investigations, when the first aim was to study the spectrum of transfer reactions, radiochemical methods were used to separate and identify individual isotopes.[51,25] These methods guaranteed good selectivity, but all stable and short- or long-lived isotopes escaped detection. However, just these isotopes were of particular interest since the maximal reaction yields were associated with them, or they were the ones furthest removed from the β-stability region. The radio-chemical method is convenient in measurements of total cross sections for production of individual isotopes but is of little use for measuring energy spectra. Because of these shortcomings, it gave way to improved methods of detecting reaction products. However, when the heaviest ions—those of krypton and xenon—are used and the other methods fail to distinguish in-

2) The critical angular momentum $\hbar l_{cr}$ places a division in the entrance channel between collisions leading to the formation of a compound nucleus and to direct nuclear reactions.

dividual reaction channels, the radiochemical method continues to be used with success.[15–16]

For light bombarding particles, the $(\Delta E, E)$ method is popular; in it, one measures the specific ionization and the energy of the reaction products. It has also been widely used in experiments with heavy ions. Its use is restricted to reaction-product mass numbers of about 16–20. For reliable identification of large masses the resolution of the ΔE detector is inadequate. The use of this method also encounters serious difficulties in the detection of isotopes with a large excess or deficit of neutrons or isotopes whose production cross section is small. In many cases, it is impossible to distinguish the pulses from a neutron-rich isotope of element Z and a neutron-deficient isotope of element $Z+1$. Small reaction cross sections require the use of heavy-ion beams of maximal intensity, but the detectors are then overloaded by the intense flux of elastically scattered particles, which spoils their resolution, and they may even be damaged. These difficulties can be eliminated by combining the $(\Delta E, E)$ method with others. If the $(\Delta E, E)$ method is used in conjunction with the time-of-flight method, the resolution can be significantly improved for measurement of the mass number of a reaction product. In this case, the resolution is determined by the statistical spread, not in the ΔE, but in the E detector, in which it is several times smaller. The atomic number of the product is determined by the ΔE detector. In Ref. 34, Gatty *et al.*, who used a 1-*m* flight path, succeeded in reliably distinguishing isotopes with mass number of about 40.

The proposal made in Ref. 52 by Artukh *et al.* to combine magnetic analysis with the $(\Delta E, E)$ method has proved very effective. In the focal plane of a magnetic spectrometer one places a $(\Delta E, E)$ telescope made of a thin semiconductor detector and a total absorption detector. With this arrangement, one can reliably distinguish isotopes with mass 40–50. Because of the difference between the magnetic rigidities of the reaction products and the elastically scattered ions, the detectors are not overloaded, and the target can be irradiated with a beam of maximal intensity. This guarantees a high sensitivity of the apparatus; with it, one can measure cross sections right down to several nanobarns.[53] Since this combined method enables one to detect simultaneously only a small part of the energy spectrum, the measurement of the cross sections for production of a large number of isotopes at many angles requires the expenditure of much accelerator time. This problem was overcome by combining two types of measurement. The angular distributions and energy spectra of light elements produced in the transfer reactions were measured by the $(\Delta E, E)$ method at many angles but without separation of the isotopes. For a small number of angles, "isotope cuts" were made. The $(\Delta E, E)$ method enables one to identify light elements with Z up to 30 reliably. By means of combined measurements of this kind, it proved possible to obtain in a short time extensive experimental information about the mechanism of transfer reactions. In the "element" approach, some aspects of many-nucleon transfer reactions were used. The overwhelming contribution to the cross section for the production of a given element is made by two or three isotopes in the case of bombardment with neon ions and three or four isotopes in the case of bombardment with argon ions. The energy spectra in many-nucleon transfers have smooth bell-shaped profiles with half-width of several tens of MeV. The profiles of the spectra and the positions of the maxima for the isotopes that make the main contribution to the element production cross section differ only slightly, so that their summation does not significantly deform the spectrum or shift the maximum. This means that the energy spectra of the elements contain information about the interaction of nuclei in transfer reactions. A similar situation exists for the angular distributions.

It is usually assumed that transfer reactions take place as a two-body process. However, this important assumption requires experimental verification, for which one uses the correlation method known from heavy-nucleus fission experiments. In it, two fragments are detected in coincidence and their energy measured. The method enables one to test the balance of the masses and energies for two-body decay. For this purpose, Peter *et al.*[32] used two movable surface-barrier detectors, which measured the energy of two conjugate transfer-reaction products. In Ref. 39, one of the detectors was made position-sensitive in order to increase the efficiency. It covered an angular interval of 26°.

The first experiments. At the present time, the interest of experimenters and theoreticians concerned with deep inelastic transfers is concentrated on reactions in which the heaviest ions and heaviest target nuclei are used. However, deep inelastic transfers are observed for almost any combination of a heavy ion and target if the collision energy appreciably exceeds the Coulomb barrier. Therefore, a brief description of the first experiments is of interest not only historically but also as proof of the wide occurrence of this class of reactions. Deep inelastic transfers are one of the main mechanisms of interaction of two complex nuclei.

The first indications that transfer reactions may take place not only in the form of a quasielastic process but also may be accompanied by a large loss of the collision kinetic energy were obtained from study of the energy spectra of light reaction products. The important thing in the experiments was the possibility of detecting the low-energy part of the spectrum. In the $(\Delta E, E)$ method this was achieved by using a fairly thin (~10 μm) ΔE detector,[23] and in the radiochemical method by using collectors of reaction products in the form a stack of thin aluminum foils.[22] The choice of pickup reactions made it easier to interpret the results. In this case, one can ignore the contribution from processes of dissociation of the incident nucleus.

Figure 1, which is taken from Ref. 22, shows the energy spectra of ^{18}F from the reaction ^{27}Al(^{14}N, ^{18}F) measured from the distribution of the ^{18}F activity in the stacks of thin aluminum foils. The measurements were made for several angles and four energies of the

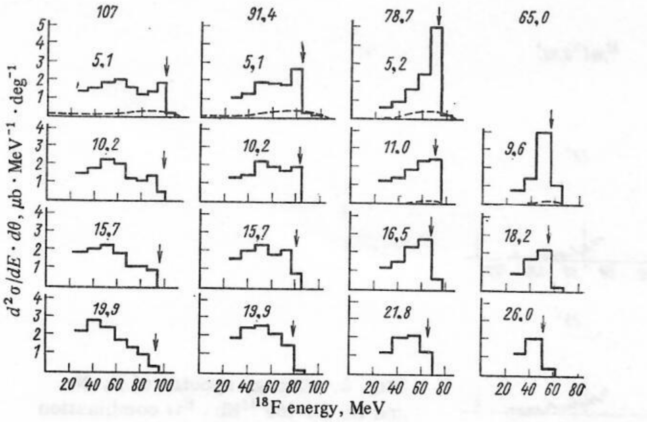

FIG. 1. Energy spectra of ^{18}F from the reaction $^{27}Al(^{14}N, ^{18}F)$ for four energies of the ^{14}N ions in the laboratory system. The numbers above the arrows indicate the emission angle of ^{18}F; the arrows indicate the energy of ^{18}F for the case of formation of final nuclei in ground states; the dashed curves are the contribution from the interaction of elastically scattered ^{14}N ions with the aluminum collectors.[22]

bombarding ions. Despite the crudeness of the measurements, the spectra clearly reveal two parts, especially at high energies. The quasielastic part corresponds to α-particle pickup in the case of weak excitation of the final nuclei. The maximum of the broad inelastic part is at an energy near the exit Coulomb barrier. An appreciable part of the energy spectrum lies below the Coulomb barrier. The angular distributions of the two parts of the spectrum are very different (Fig. 2). The differential cross section $d\sigma/d\theta$ of the quasielastic part increases monotonically with decreasing emission angle. The angular distributions of the inelastic part are nearly isotropic in the measured range of angles.

In Ref. 23, studies were made of reactions with the pickup of one to three protons when ^{27}Al, ^{51}V, and ^{93}Nb are irradiated by ^{16}O ions. The energy of the ions was chosen in such a way as to ensure the same kinematic conditions for all three targets (67 MeV above the Coulomb barrier in the center-of-mass system). The light transfer-reaction products (F, Ne, Na) were detected by a $(\Delta E, E)$ detector telescope. The semiconductor ΔE detector was 10μm thick. The products were distinguished only by Z.

Figure 3 shows the results of bombarding ^{93}Nb. In the F energy spectra one can clearly distinguish the quasielastic and the inelastic part. Once again, the maxima of the inelastic part lie near the exit Coulomb barriers and significant parts of the spectra lie in the range of energies below the Coulomb barrier. Figure 4 shows the angular distributions of the quasielastic part of the F spectra and the inelastic parts of the F, Ne, and Na spectra. It can be seen that the angular distributions in the case of inelastic transfers are more isotropic. Similar results were obtained when ^{27}Al and ^{51}V were irradiated.

Transfer-reaction products with low energy were also observed at Orsay[24] when Ag was bombarded with ^{12}C and ^{14}N ions. Unfortunately, the great thickness of the ΔE detectors (35 and 47 μm) made it impossible to establish a complete picture of the low-energy parts of the spectrum. This investigation demonstrated, for many transfer-reaction products, that the profile of the angular distributions changes strongly with varying inelasticity of the process. For few-nucleon transfers, the angular distributions of the quasielastic parts of the spectrum have the characteristic profile of curves with a maximum at the angle of Rutherford scattering for grazing collisions. For the inelastic parts of the spectrum, the angular distribution was peaked forward sharply. When a few nucleons were transferred, angular distributions of the second type were basically observed.

The characteristic features of the energy spectra and angular distributions of the transfer-reaction products obtained in Refs. 22 and 23 were the basis of the suggestion made by the two groups that they had observed a new reaction mechanism intermediate between direct processes and processes leading to formation of a compound nucleus. It was suggested[22] that quasielastic transfers are associated with peripheral surface collisions, whereas inelastic transfers are associated with collisions near the critical angular momentum $\hbar l_{cr}$. The production of low-energy particles was explained as follows. If the surfaces of the two nuclei overlap strongly, the strong interaction leads to transfer of an appreciable fraction of the kinetic energy to the target nucleus and formation of a system of two strongly interacting nuclei. However, in collisions with a greater than critical angular momentum the Coulomb and centrifugal forces exceed the attraction of the nuclei, preventing their coalescing, and the system therefore breaks up after a short interval of time.

The energy spectra and angular distributions obtained in Refs. 22 and 23 were very different from those obtained by Kaufman and Wolfgang[54] when they studied few-nucleon transfers. In fact, Kaufman and Wolfgang observed only quasielastic transfers. The maxima of the energy spectra (one only for each product) corresponded to an energy that, per nucleon, amounted to approximately 90% of the energy per nucleon in the incident nucleus. The angular distributions obtained in Ref. 54 were strongly anisotropic. The overwhelming part of the cross section was concentrated at small angles appreciably smaller than the angle of Rutherford scattering for grazing collisions. The theoretical anal-

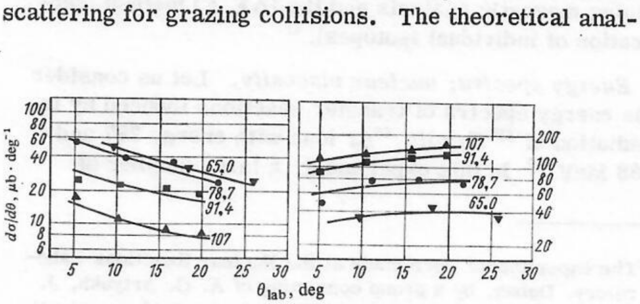

FIG. 2. Differential cross sections of the reaction $^{27}Al(^{14}N, ^{18}F)$ for the quasielastic and inelastic parts of the energy spectrum. The quasielastic part corresponds to Q values of the reaction in the range $Q_{gg} < Q < Q_{gg} + 11$ MeV (Ref. 22).

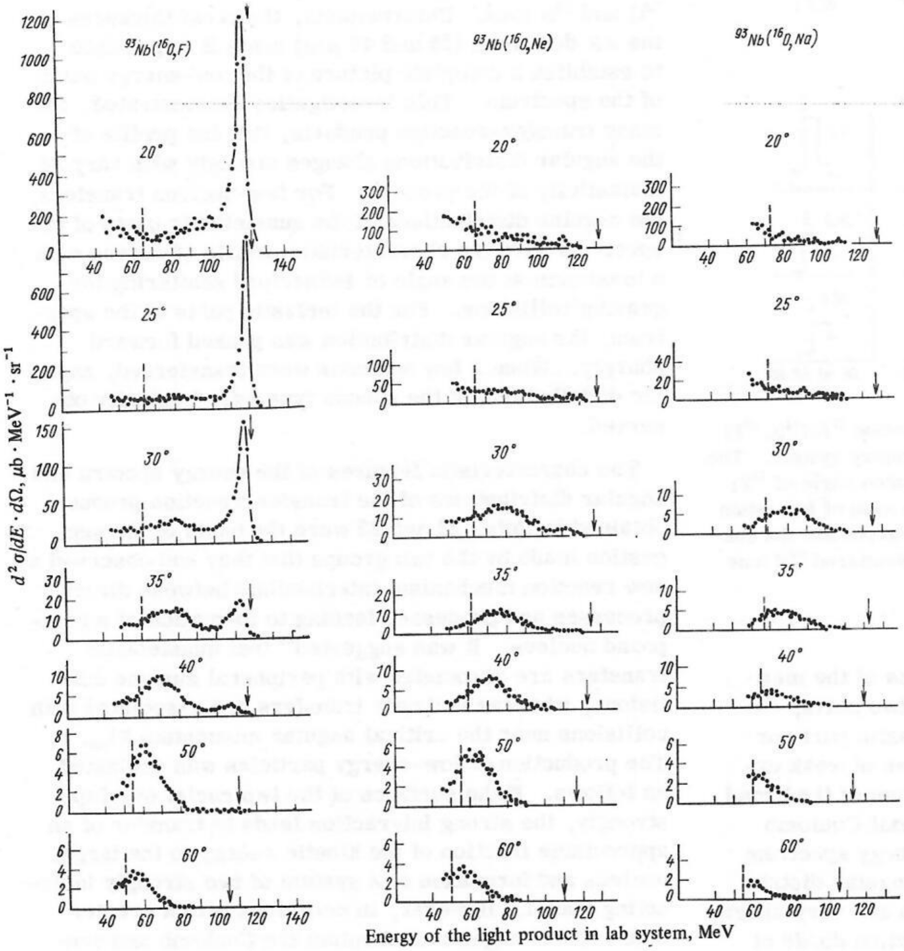

FIG. 3. Energy spectra of F, Ne, and Na for the $^{93}Nb + ^{16}O$ combination at an ion energy 131 MeV in the laboratory system. The dashed line is the energy corresponding to the exit Coulomb barrier of the final nuclei with $r_0 = 1.5$ F; the arrows indicate the energy corresponding to the formation of unexcited final nuclei.[23]

ysis of Ref. 19 showed that the angular distributions of Ref. 54 can be successfully described in the framework of a model of quasielastic surface direct reactions and do not require any additional assumptions about the reaction mechanism.

Below, we shall consider in more detail the energy spectra, angular distributions, and production cross sections of individual isotopes in transfer reactions induced by heavy ions. Here, we shall dwell mainly on the experimental data obtained by bombarding ^{232}Th with ^{15}N, ^{16}O, ^{22}Ne, and ^{40}Ar ions with energy 9.7–7 MeV per nucleon.[25–31] The reaction products were detected by the $(\Delta E, E)$ method (element approach) and by combining magnetic analysis and the $(\Delta E, E)$ method (separation of individual isotopes).[3)]

Energy spectra; nuclear viscosity. Let us consider the energy spectra of transfer reactions induced by irradiation of ^{232}Th with ^{40}Ar ions with energy 297 and 388 MeV.[30] In this experiment, a large number of transfer-reaction products with Z from 5 (B) to 26 (Fe) were observed. The measurements were made at many angles by the $(\Delta E, E)$ method in the "element" approach. The data obtained made it possible to follow the evolution of the profile of the energy spectra as a function of the emission angle of a light reaction product and the number of nucleons transferred in the reaction.

In Fig. 5, we show the energy spectra of Cl, Ar, K, and Ca at an irradiation energy 388 MeV. When a proton is stripped from the ^{40}Ar nucleus, Cl is formed, while K and Ca are formed when one and two protons, respectively, are picked up. One notes immediately the tremendous widths of the energy spectra: They extend over more than 200 MeV. The collision energy is 170 MeV above the Coulomb barrier for ^{40}Ar. This means that the kinetic energy of the collision can be

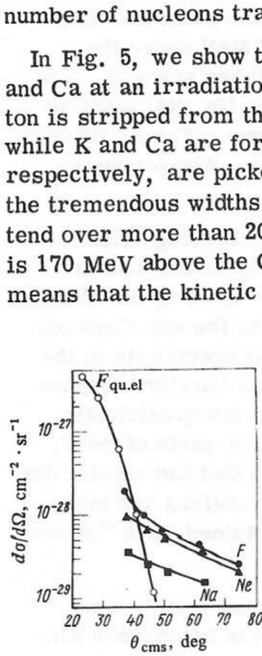

FIG. 4. Differential cross sections $d\sigma/d\Omega$ of the quasielastic part of the F spectrum and of the inelastic parts of the F, Ne, and Na spectra for the combination $^{93}Nb + ^{16}O$ (Ref. 23).

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3) The experiments were made at the Nuclear Reactions Laboratory, Dubna, by a group consisting of A. G. Artyukh, J. Wilczynski (Cracow), V. V. Volkov, G. F. Gridnev, and V. L. Mikheev. V. V. Avdeĭchikov (V. G. Khlopin Radium Institute, Academy of Sciences of the USSR, Leningrad) participated in the investigations Refs. 26 and 27; J. Erö (Budapest) participated in Ref. 26.

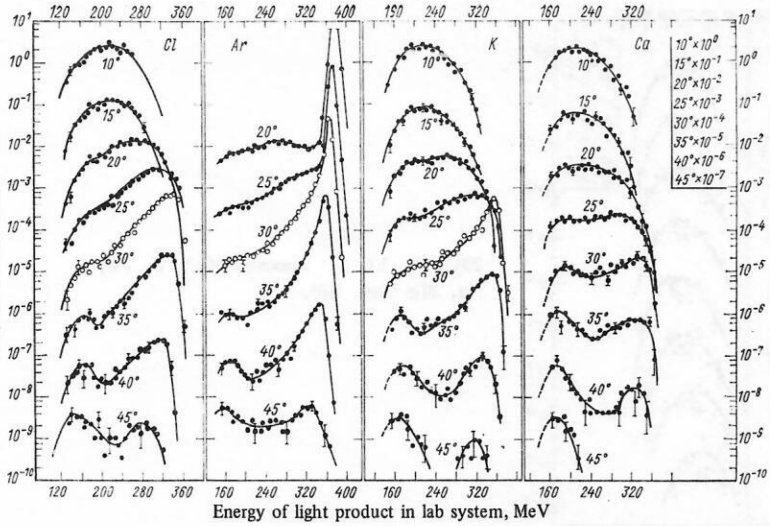

FIG. 5. Energy spectra of Cl, Ar, K, and Ca from bombardment of ^{232}Th with 388-MeV ^{40}Ar ions. Allowance is made for the energy loss in the thin target for the ^{40}Ar ions and the reaction products. The data for each angle are multiplied by the coefficients given at the top right.[30]

completely dissipated if one or several nucleons are transferred and also in the case of inelastic scattering.

The angle of Rutherford scattering for peripheral grazing collisions of Th and Ar nuclei at an energy 388 MeV is 36° in the laboratory system. For this angle, the energies at the maxima of the Cl, Ar, and K spectra are similar, i.e., the pickup and stripping of a proton in grazing collisions take place essentially as inelastic processes. At the same time, in the energy spectra of these reaction products one can also observe features that are unusual for direct processes: With decreasing emission angle, the energy of the products decreases, and at large angles the energy spectrum decomposes into two parts. In classical direct processes, the energy of light reaction products in the laboratory system increases with decreasing emission angle because of the more favorable addition of the vectors of the transport velocity and the cms velocity. The opposite tendency is observed in the Cl, K, and Ca spectrum. The decrease in the energy reaches a very appreciable amount, 120–140 MeV, for the maxima of the spectra. A decomposition of the energy spectrum into two parts was also observed in the more recent Refs. 22 and 23, although for the ^{232}Th + ^{40}Ar combination it is particularly clear. Note that with increasing emission angle the high-energy part of the spectrum decreases much more rapidly than the low-energy part.

Let us consider the change in the profile of the energy spectra with increasing number of protons stripped from the incident nucleus. The spectra of Al, Si, P, and S, corresponding to stripping from the ^{40}Ar nucleus of from two to five protons, are shown in Fig. 6. Data on the yield of different isotopes resulting from bombarding of ^{232}Th by ^{40}Ar ions[55] indicate that not only protons but, on the average, about the same number of neutrons are stripped. The spectra in Fig. 6 exhibit a tendency to symmetrization of the profile and reduction in the half-width of the spectrum with increasing number of stripped nucleons. Note the more rapid decrease with increasing Z of the high-energy part of the spectrum. The energy spectra from Mg to O (Z from 12 to 8) are shown in Fig. 7. They have an already symmetric profile. The half-width of the spectrum decreases with decreasing Z of the reaction product.

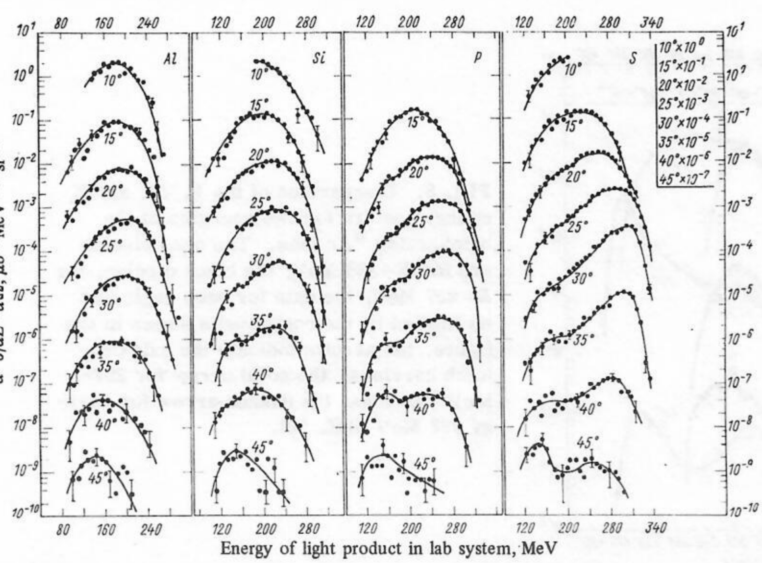

FIG. 6. Energy spectra of Al, Si, P, S (Ref. 30).

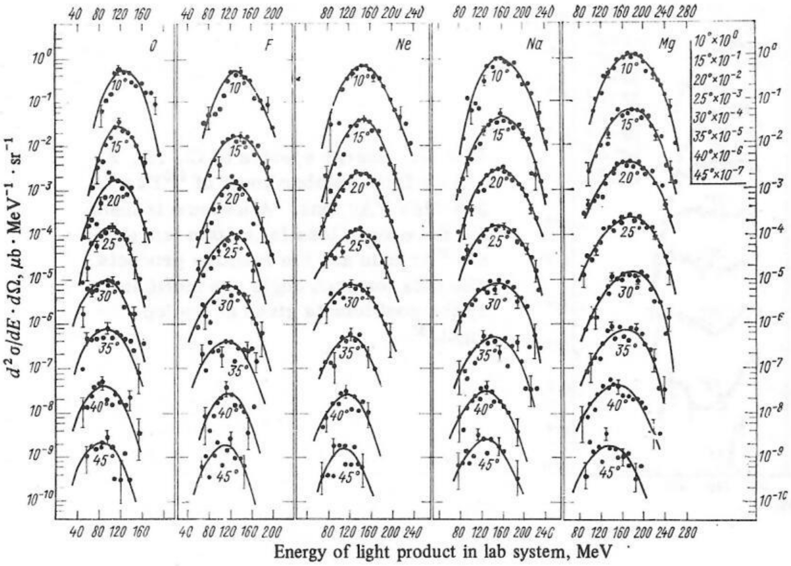

FIG. 7. Energy spectra of O, F, Ne, Na, Mg (Ref. 30).

The dependence of the energy at the maximum on the emission angle becomes monotonic: The energy increases with decreasing emission angle of the light reaction product.

The energy spectra of P, Cl, and K for three emission angles and the two energies 297 and 388 MeV of the bombarding particles are compared in Fig. 8. The arrows indicate the energies which these transfer-reaction products would have if they had "rolled down" from the tops of the exit Coulomb barriers from zero initial velocity and zero orbital angular momentum ($r_0 = 1.46$ F). It can be seen that the width of the spectrum increases appreciably with increasing energy of the bombarding ion, although the low-energy parts of the spectra, especially at small angles, virtually coincide. Note the fact that for the angle 20° and for 288-MeV ^{40}Ar the greater part of the energy spectra lie below the exit Coulomb barriers.

We now represent the experimental data in a form that more clearly reveals the features of the interaction of the ^{232}Th and ^{40}Ar nuclei and the transfer-reaction mechanism. In Fig. 9, we give the energies released in the reactions for the maxima of the energy spectra $Q_m(\theta, Z)$ as a function of the atomic number Z and the emission angle θ of the light reaction product. In the cases when the energy spectrum has two maxima, they are both shown in the figure. Dashed curves are drawn through the points corresponding to the low-energy maxima. The value of Q_m was calculated under the assumption of a two-body reaction for the mass numbers of the isotopes that make the largest contribution to the element production cross section. We may mention in passing that variations in the mass of the isotope have very little influence on the value of Q_m. Below, after presenting the main experimental facts, I shall turn to the justification of assuming that the observed reactions are two-body reactions. Let us note for the time being that one of the arguments in favor of such an assumption is that the characteristic features of the energy spectra and the angular distributions observed when nucleons are stripped are also retained in pickup reactions when the contribution to the cross section from dissociation of the incident nucleus can be

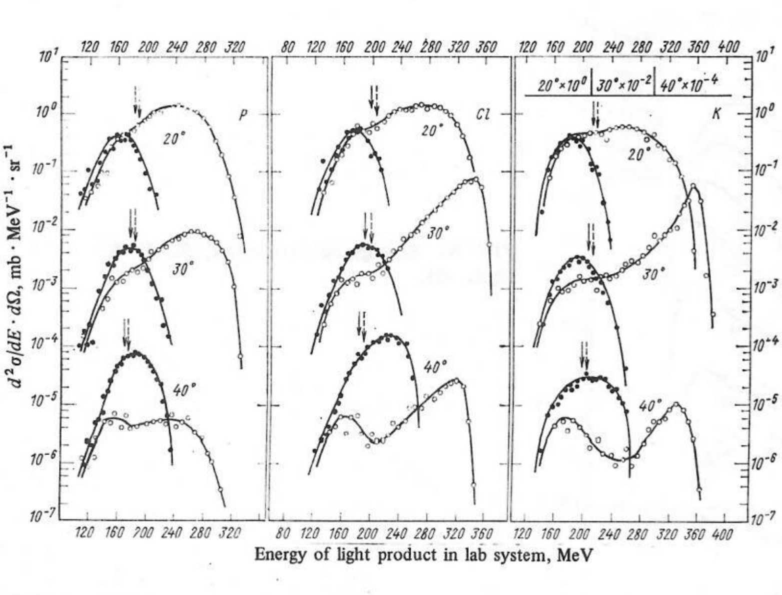

FIG. 8. Comparison of the P, Cl, and K energy spectra for two energies of the bombarding ^{40}Ar ions. The open circles are for $E = 388$ MeV; the black circles, for $E = 297$ MeV; the data for each angle are multiplied by the coefficients shown in the figure; the arrows indicate the exit Coulomb barriers: the solid arrow for 297-MeV ^{40}Ar ions, the dashed arrow for energy 388 MeV (Ref. 30).

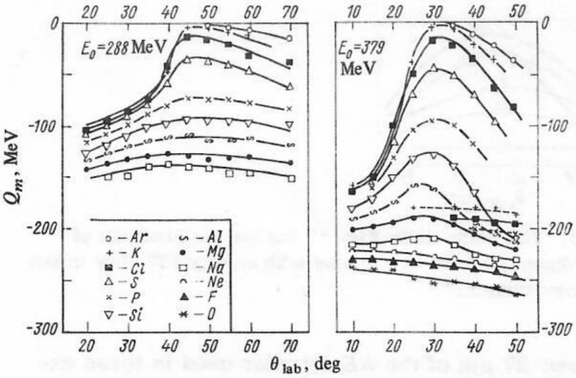

FIG. 9. Dependence of Q_m on the emission angle θ of the light reaction product in the laboratory system and on the number of transferred protons. The ^{40}Ar energies are indicated for the middle of the target; the dashed curve is drawn through the points corresponding to the low-energy maxima of the spectra.[30]

ignored in practice. The quantity Q_m is the difference between the kinetic energies in the entrance and exit reaction channels ($T_{en} - T_{ex}$). This energy is expended on rearrangement of the nuclei from the initial to the final states, Q_{gg}, and on their excitation E^*:

$$|Q_m| = T_{en} - T_{ex} = |Q_{gg}| + E^*. \qquad (1)$$

For few-nucleon transfers, Q_{gg} is large and $|Q_m| \approx E^*$. Conversely, for the combination $^{232}Th + {}^{40}Ar$ in few-nucleon strippings Q_m may reach tens of MeV.

The K and Cl formed by the pickup and stripping of a proton can, in a way, be regarded as "labeled argon" since the atomic number and mass number of the bombarding nucleus are changed little. The paths of the Cl and K nuclei when they interact with the target nucleus are similar to those of the ^{40}Ar nuclei. Note that the use of classical ideas about the motion of nuclei along paths is fully justified in our case since the de Broglie wavelength of the ^{40}Ar nucleus is less than 0.1 F, i.e., much less than the dimensions of the nuclei themselves or the widths of their surface layers. Only nuclear interaction can give a deflection to small angles with loss of kinetic energy. The interaction acts more strongly, the more the surfaces of the nuclei overlap during the collision. But it then follows from the dependence of Q_m on the emission angle for Cl and K that an increase in the overlapping zone between the nuclei leads to a sharp increase in the loss of the collision kinetic energy. For ^{40}Ar ions with energy 379 MeV this loss reaches 150 MeV for a relatively small change ~20° in the emission angle. If one uses the language of classical macroscopic physics, this indicates that in the relative motion with overlapping of the surfaces the nuclei behave as objects with a high viscosity. This property of nuclear matter has fundamental importance for understanding the interaction mechanism of two complex nuclei, the formation of a compound nucleus, and the possibilities of synthesizing superheavy elements in reactions using the heaviest ions.[40–56] It should be emphasized that the first reliable proofs of a high viscosity of nuclei in the excited state were obtained in deep inelastic transfer reactions. These experimental results are the basis of the modern theoretical models[41–50] in which attempts are made to describe quantitatively the interaction of two complex nuclei in deep inelastic collisions.

The total kinetic energy of the reaction products (conjugate pairs of nuclei) is compared with the exit Coulomb barriers corresponding to them in Fig. 10. The zero marked on the ordinate in this representation means that the reaction products obtained all their kinetic energy from Coulomb repulsion. To calculate the Coulomb barriers, the nuclear parameter r_0 was set equal to 1.46 F. Let us now return to "labeled argon," i.e., the Cl and K nuclei. It follows from the data shown in Fig. 10 that the high nuclear viscosity almost completely decelerates the relative motion of the nuclei. At the emission angle 10° for 379-MeV ^{40}Ar ions the kinetic energy of all the transfer-reaction products is close to the height of the exit Coulomb barriers. At

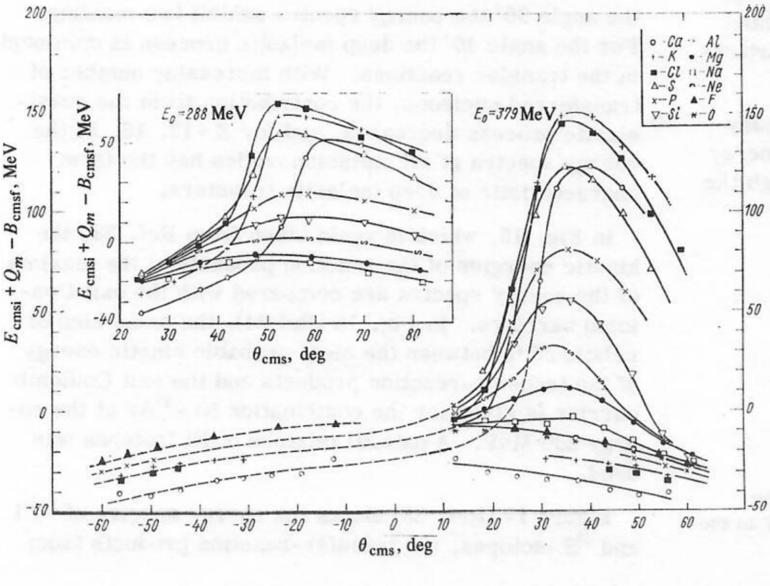

FIG. 10. Ratio of the kinetic energy of the final products $E_{cmsi} + Q_m$ at the maxima of the energy spectra to the exit Coulomb barriers B_{cmsf} as a function of the angle of emission θ_{cms} and the atomic number of the light reaction product. The dashed curves are drawn through the points corresponding to the low-energy maxima in the spectra of few-nucleon transfers after their reflection onto the region of negative values. The data refer to two energies of the ^{40}Ar ions in the middle of the target: 288 and 379 MeV (Ref. 30).

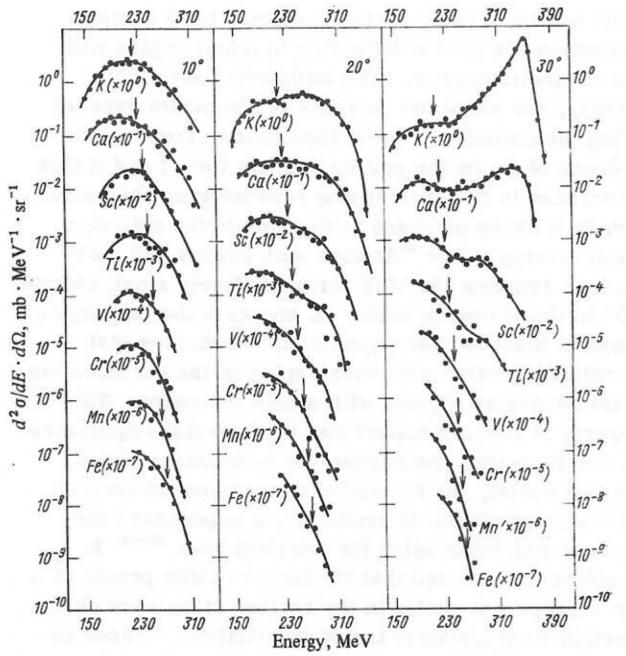

FIG. 11. Energy spectra of K, Ca, Sc, Ti, V, Cr, Mn, Fe. The arrows indicate the exit Coulomb barriers for the final products.[31]

energy 297 MeV the kinetic energies of the products at small angles are even lower than the exit Coulomb barriers, by 20–30 MeV.

In the behavior of the low-energy maxima in the Ca, K, Cl, and P spectra one observes a different angular dependence: The energy decreases with increasing emission angle. The maxima themselves are 30–40 MeV below the exit Coulomb barriers. The energy spectra of reactions in which an appreciable number of nucleons is transferred (the elements Ne, F, O) behave similarly. In Fig. 10, the low-energy maxima of few-nucleon transfers have been mirror reflected onto the region of negative angles. It can be seen that this gives good connection of the data for the high- and low-energy maxima of few-nucleon transfers. It can also be seen from Fig. 10 that with increasing Z of the reaction product the deviation (reduction) of the kinetic energy of the products compared with the exit Coulomb barriers increases. This tendency is manifested particularly clearly in the pickup reactions.

The energy spectra of pickup reactions accompanying the bombardment of ^{232}Th by ^{40}Ar ions with energy 388 MeV (Ref. 31) are shown in Fig. 11. Although the

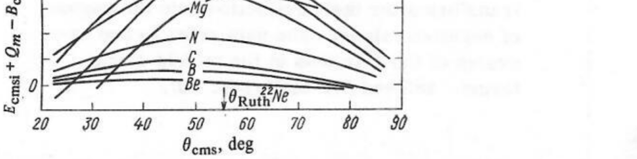

FIG. 12. The same as in Fig. 10 but for products of the bombardment of ^{232}Th by ^{22}Ne ions with energy 174 MeV in the laboratory system.[29]

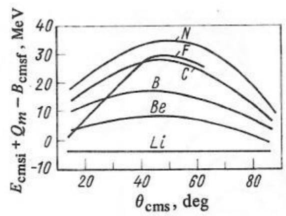

FIG. 13. The same as in Fig. 10 but for the products of bombardment of ^{232}Th by ^{16}O ions with energy 137 MeV in the laboratory system.[47]

thickness 27 μm of the ΔE detector used in these experiments made it impossible to obtain a complete picture of the energy spectra, the tendency can be followed quite clearly. In Fig, 11 for the pickup reactions, the same evolution in the profile of the energy spectra is exhibited as in the stripping reactions: With increasing number of transferred nucleons there is rapid damping of the contribution to the cross section from quasielastic processes. The cross section of deep inelastic transfers at small angles decreases with increasing Z rather slowly.

The characteristic manner in which the kinetic energy of conjugate pairs of transfer-reaction products changes relative to the exit Coulomb barrier when the emission angle θ_{cms} of the light reaction product and its atomic number Z change is observed in the case of bombardment of ^{232}Th by other ions as well. Figures 12 and 13 show the corresponding data, that is, averaging curves drawn through the experimental points, for 174-MeV ^{22}Ne ions[29] and 137-MeV ^{16}O ions.[57]

These features in the energy spectra of many-nucleon transfers were observed in the experiments made at Berkeley and Orsay. Figure 14, taken from Ref. 38, shows the element energy spectra obtained by irradiating targets of natural silver with 228-MeV ^{40}Ar ions. The spectra were converted to the center of mass system under the assumption of a two-body reaction. The scattering angle for grazing collisions in this case is 28°. For few-nucleon transfers ($Z=17$, 16) at angle 15° the main contribution to the element production cross section is made by the quasielastic process. At the angle 30° the energy spectra exhibit two maxima. For the angle 40° the deep inelastic process is dominant in the transfer reactions. With increasing number of transferred nucleons, the contribution from the quasielastic process decreases, and for $Z=12$, 13, 14 the energy spectra at all emission angles has the form characteristic of deep inelastic transfers.

In Fig. 15, which is again taken from Ref. 38, the kinetic energies of the reaction products at the maxima of the energy spectra are compared with the exit Coulomb barriers. In Fig. 16 (Ref 34), the same kind of relationship between the most probable kinetic energy of the transfer-reaction products and the exit Coulomb barrier is given for the combination Ni + ^{40}Ar at the energy 280 MeV. A natural mixture of Ni isotopes was used.

Figure 17 (Ref. 35) shows the energy spectra of ^{39}Cl and ^{36}S isotopes, the transfer-reaction products from

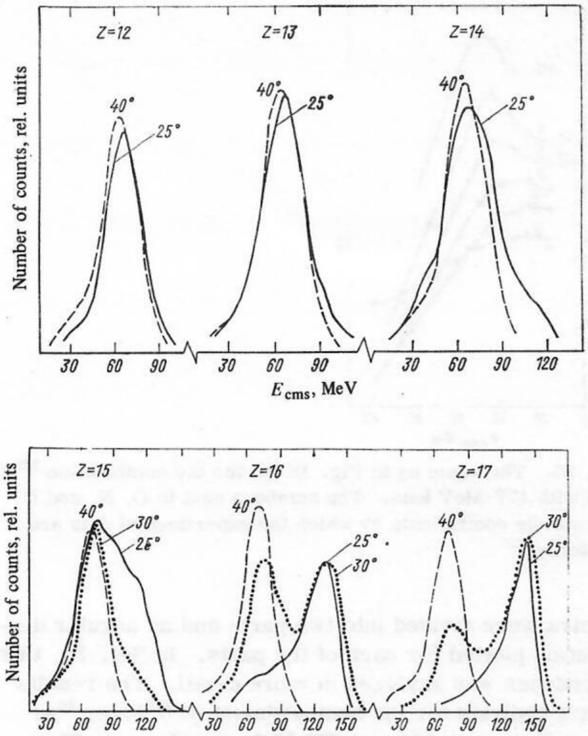

FIG. 14. Energy spectra of Cl, S, P, Si, Al, and Mg for different emission angles after bombardment of As (natural mixture of isotopes) by 288-MeV ^{40}Ar ions.[38]

bombardment of ^{232}Th by 295-MeV ^{40}Ar ions. The spectra were measured at 18 and 40°. It can be seen that in the first case virtually the whole spectrum lies below the exit Coulomb barrier. The profile of the spectra changes with decreasing angle and increasing number of nucleons stripped from the bombarding nucleus in much the same way as in the element energy spectra already discussed.

Angular distributions. The differential cross sections for the production of light elements as transfer-reaction products obtained in Refs. 30, 29, and 57 by bombarding ^{232}Th with ions of ^{40}Ar (288 and 379 MeV), ^{22}Ne (174 MeV), and ^{16}O (137 MeV), are shown in Figs. 18–20. It can be seen that the profile of the angular distributions changes regularly with increasing number of transferred nucleons. The maximum characteristic of transfer reactions at the Rutherford scattering angle

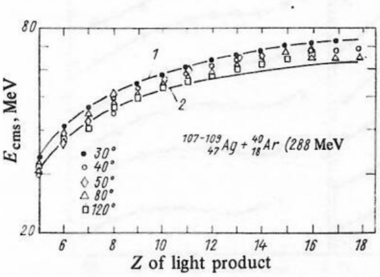

FIG. 15. Relation between the energy at the maxima of the energy spectra and the exit Coulomb barriers in the center-of-mass system: 1) Coulomb energy of two touching charged spheres; 2) of two touching spheroids in the case of equilibrium deformation.[38]

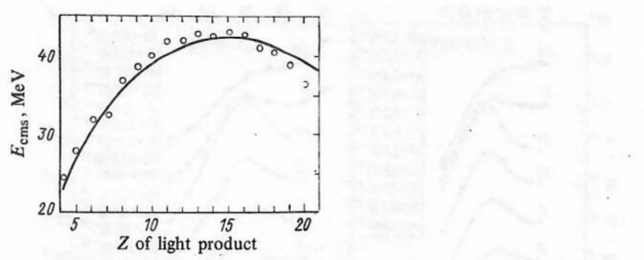

FIG. 16. The same as in Fig. 15 but for products of bombardment of Ni (natural mixture of isotopes) by 280-MeV ^{40}Ar ions.[34] The open circles are the experimental points, and the curve is calculated.

for grazing collisions of the nuclei is seen clearly only for few-nucleon transfers. With increasing number of transferred nucleons, the width of the maximum increases, and the maximum itself is shifted to smaller angles. The differential cross sections of many-nucleon transfers increase monotonically with decreasing emission angle. Note also that for few-nucleon transfers, expecially for proton pickup, one observes a hump in the cross section at small angles. For the transfers involving the most nucleons (bombardment with 379-MeV ^{40}Ar) the anisotropy in the angular distribution is reduced. This feature is revealed more clearly by going over from $d\sigma/d\Omega$ to $d\sigma/d\theta$ (Fig. 21), which eliminates the influence of the factor $1/\sin\theta$. It is well known that for an isotropic angular distribution $d\sigma/d\theta$ is constant. It can be seen from Fig. 21 that the N, C, and B angular distributions exhibit broad flat maxima in the neighborhood of the angles 30–35°. A certain rise in the cross section at the smallest angles

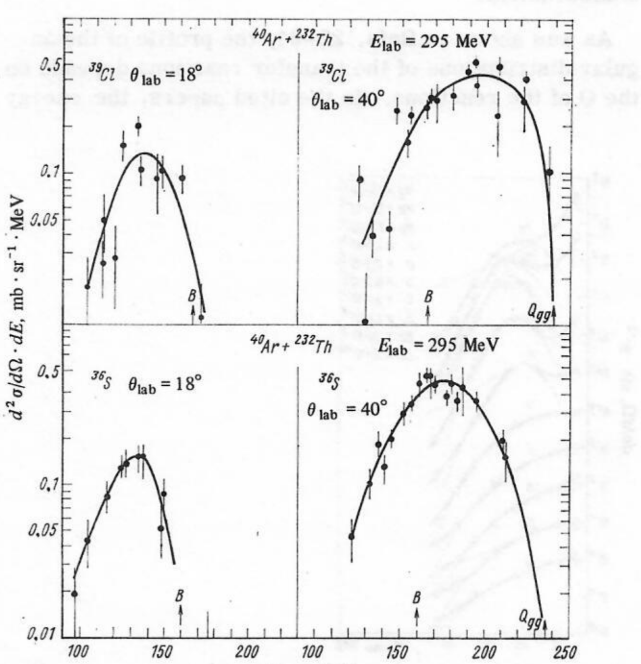

FIG. 17. Energy spectra of the isotopes ^{39}Cl and ^{36}S produced as transfer-reaction products in bombardment of ^{232}Th by ^{40}Ar ions with energy 295 MeV in the laboratory system. The arrows indicate the exit Coulomb barrier *B* and the energy Q_{gg} corresponding to formation of the final nuclei in the ground state.[35]

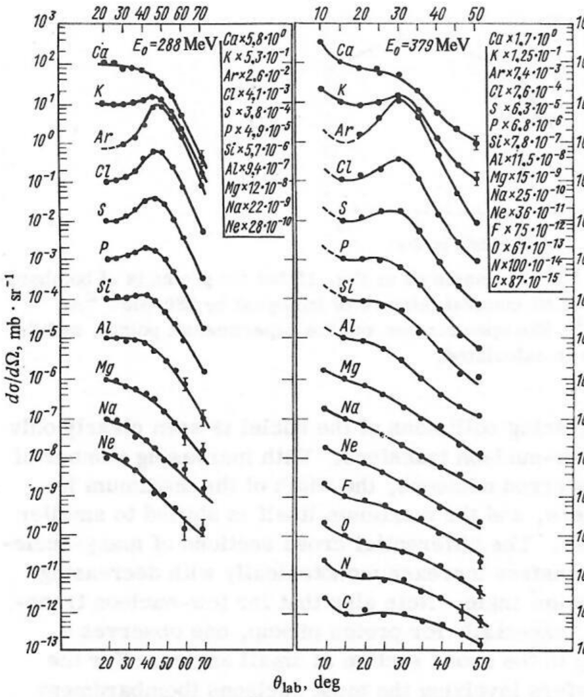

FIG. 18. Angular distributions of light elements produced as transfer-reaction products in bombardment of ^{232}Th by ^{40}Ar ions with energy 288 and 379 MeV (in the center of the target) in the laboratory system. The lines are drawn through the experimental points. The data for each element are multiplied by the coefficient shown at the top right.[30]

for these elements can be attributed to nuclear reactions in the carbon films formed on the target during the bombardment.

As was shown in Refs. 22–24, the profile of the angular distributions of the transfer reactions depends on the Q of the reactions. In the cited papers, the energy

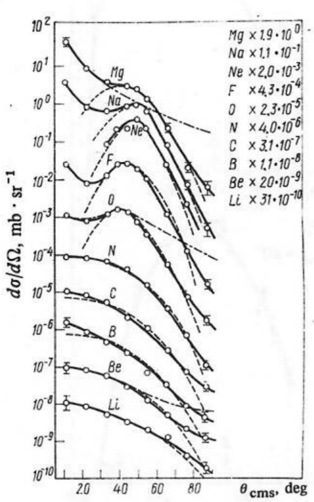

FIG. 19. The same as in Fig. 18 but for the combination ^{232}Th + ^{22}Ne with 174-MeV ^{22}Ne ions. The dot-dash-dot and the dashed curves are the results of calculations in accordance with Strutinskii's model[19] under the assumption, respectively, of an exponential and a Gaussian dependence of the partial-wave reaction amplitudes on the orbital angular momentum of the collision.[29]

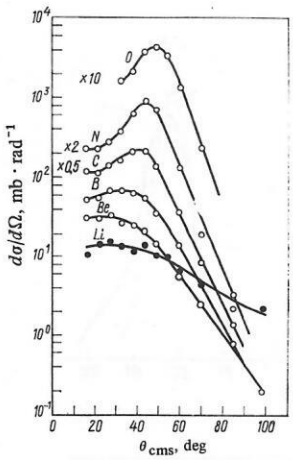

FIG. 20. The same as in Fig. 18 but for the combination ^{232}Th + ^{16}O with 137-MeV ions. The numbers next to O, N, and C indicate the coefficients by which the experimental data are multiplied.[57]

spectra were divided into two parts and an angular distribution plotted for each of the parts. In Ref. 30, this dependence was analyzed in more detail. The results of this analysis for the bombardment of ^{232}Th by ^{40}Ar ions with energy 288 and 379 MeV are shown in Figs. 22 and 23, which present the partial angular distributions $d^2\sigma/dQ\,d\Omega$ with 20-MeV steps in Q. It can be seen that the profile of the partial angular distributions changes radically with increasing inelasticity of the interaction. At low energy loss, the angular distribution has a clearly expressed maximum at the Rutherford scattering angle for grazing collisions. The differential cross section in these cases falls rapidly at both larger and smaller emission angles. With increasing energy loss, the width of the maximum increases and the maximum itself is shifted to smaller angles. At the largest energy loss, the differential cross section changes

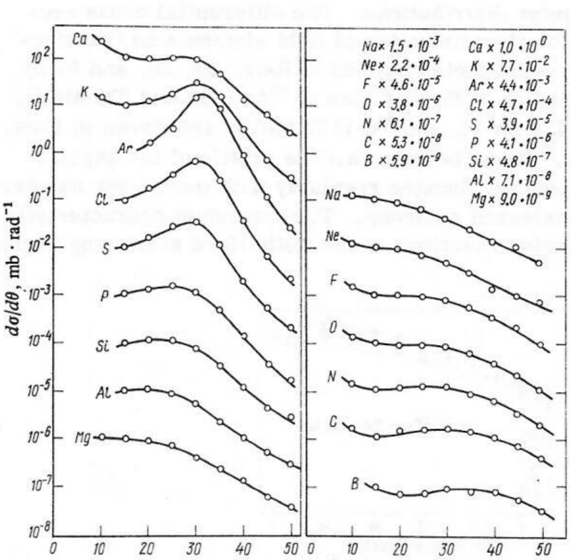

FIG. 21. Differential cross sections $d\sigma/d\theta$ for production of elements for the combination ^{232}Th + ^{40}Ar at energy 379 MeV. The coefficients by which the data are multiplied for each element[31] are indicated in the top right.

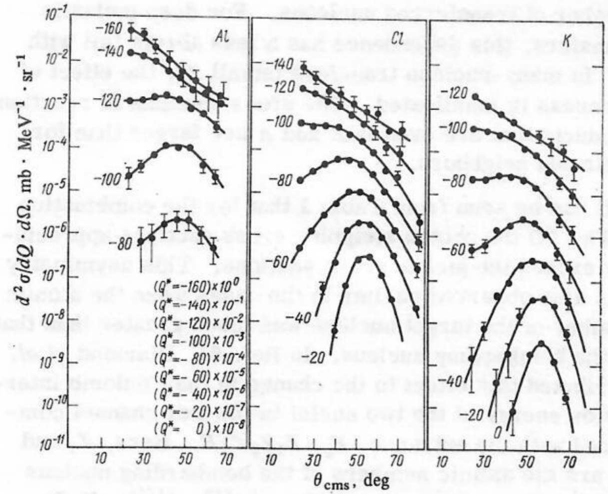

FIG. 22. Partial-wave differential cross sections $d^2\sigma/dQ\,d\Omega$ for the production of K, Cl, and Al for the combination $^{232}Th + ^{40}Ar$ at energy 288 MeV. The Q values of the reaction are put on the left next to the curves; in the table, the coefficients by which the data for each value of Q are multiplied[30] are given.

monotonically, increasing at small angles. Note the similarity of the element angular distributions of many-nucleon transfers and the partial angular distributions of few-nucleon transfers for large negative Q.

Unfortunately, the theoretical models hitherto created to describe the angular distributions of transfer reactions induced by heavy ions[17–21] cannot be used to analyze these experimental data. The models are based on the assumption that the transfer process is quasielastic, though this is the case only for a few of the partial waves, and then only in few-nucleon transfers. Nor can one justify the assumption that the packet Δl of partial waves contributing to the reaction is small compared with the angular momentum of grazing collisions, i.e., $\Delta l/l_0 \ll 1$ (see, for example, Ref. 19). In reality, the range Δl of values contributing to the transfer reactions may be very wide. When ^{232}Th is

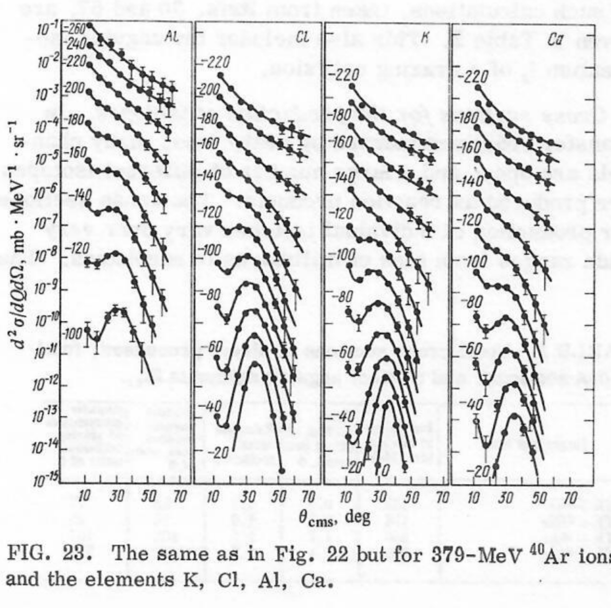

FIG. 23. The same as in Fig. 22 but for 379-MeV ^{40}Ar ions[30] and the elements K, Cl, Al, Ca.

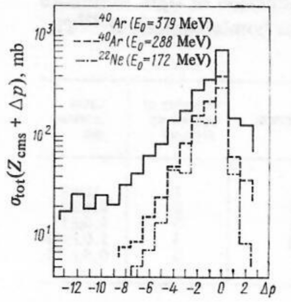

FIG. 24. Cross sections for the production of light elements as transfer-reaction products from bombardment of ^{232}Th by ^{40}Ar ions with energy 379 and 288 MeV and ^{22}Ne ions with energy 174 MeV. The number of stripped or picked up protons is plotted along the abscissa.[20]

bombarded by 389-MeV ^{40}Ar ions it reaches 120–130$\hbar$. Whereas in collisions with $l \approx l_g$ the surfaces of the nuclei hardly touch, for $l = l_{cr}$ the collisions are nearly head-on. The angular momentum l_g for grazing collisions is determined from the relation

$$E_0 = B_0 + \hbar^2 l_g (l_g + 1)/(2\mu R^2),$$

where B_0 is the entry Coulomb barrier; $\mu = M_1 M_2 / (M_1 + M_2)$; $R = r_0(A_1^{1/3} + A_2^{1/3})$; $r_0 = 1.4$–1.5 F.

In the quasielastic approximation, all the partial waves corresponding to surface collisions participate in the interference. However, under real conditions when l increases from l_g to l_{cr} the inelasticity of the interaction increases strongly, destroying the coherence of the partial waves. In the exit channels only small groups of partial waves with nearly equal wave numbers interfere. The width Δl of the packet of interfering partial waves decreases with increasing gradient dE/dl of the energy loss. The element angular distributions are complicated superpositions of partial-wave angular distributions that differ in profile and intensity. The approaches developed in the theoretical models in Refs. 17–21 can be used only to analyze the partial-wave angular distributions corresponding to small Q. And, indeed, good agreement between the calculated curves and the experimental data of Ref. 30 follows from an analysis of the partial-wave angular distributions of K from the $^{232}Th + ^{40}Ar$ reaction made in the framework of Strutinskiĭ's model.[19] In Ref. 58, Aleshin showed that one can advance somewhat further for "moderately" inelastic transfers if one uses the method of summation of partial waves proposed in Ref. 59 and a more complicated dependence of the amplitudes and phase shifts of the partial waves on l.

The angular distributions in deep inelastic transfers require special analysis since the methods developed for classical direct porcesses hardly apply here. The decay of a double nuclear system, whose formation acquires decisive importance in deep inelastic transfers, is reminiscent rather of the fission of a compound nucleus with large angular momentum, with however the fundamental difference that the double nuclear system decays in a time shorter than one revolution.

Cross sections for the production of elements. The cross sections for the production of light elements as transfer-reaction products from the bombardment of ^{232}Th by ^{40}Ar and ^{22}Ne ions[30] are shown in Fig. 24. The element cross sections of transfer reactions for the

TABLE 1 Cross sections for production of light elements as transfer-reaction products from bombardment of ^{232}Th by 137-MeV ^{16}O ions.

Element	Number of stripped protons	Cross section, mb	Element	Number of picked up protons	Cross section, mb
N	1	187±5	Fe	1	11±2
C	2	260±6	Ne	2	6.1±2
B	3	48±3	Na	3	4.3±1
Be	4	24±3	Mg	4	1.0±0.5
Li	5	12±2	Al	5	0.6±0.5

combination ^{232}Th + ^{16}O at an ion energy[57] of 137 MeV are given in Table 1. Similar data obtained at Orsay by bombarding Ni (natural mixture of isotopes) with 280-MeV ^{40}Ar ions[34] are shown in Fig. 25. The total cross sections of the direct processes obtained by summing the measured element cross sections,[30,57] and also the total reaction cross sections and the critical angular momenta l_{cr} calculated from these data, are given in Table 2.

On the basis of the experimental information obtained about the element cross sections one can draw certain conclusions. In transfer reactions, an appreciable fraction of the nucleons of the bombarding nucleus can be transferred to the target nucleus. This means that if heavy nuclei are bombarded by sufficiently heavy ions, transuranium elements can be obtained by means of transfer reactions[60] and possibly also superheavy nuclei in the conjectured new stability region.

In the ^{232}Th + ^{40}Ar combination, the cross sections for production of light elements first decrease rapidly with decreasing Z of the reaction product, but then exhibit a tendency to stabilization. A similar behavior in the variation of the reaction cross sections with increasing number of transferred nucleons was observed in the case of radiochemical separation of the products from tantalum bombarded by ^{136}Xe ions[15] and uranium bombarded by ^{40}Ar and ^{86}Kr ions.[16] If the behavior of the cross sections, energy spectra, and angular distributions with varying number of transferred nucleons are compared, the conclusion can be drawn that the contributions to the cross section for the production of elements due to the quasielastic and the deep inelastic transfer-reaction mechanisms depend differently on the number of transferred nucleons. For deep inelastic transfers, this dependence has a less abrupt fall with Z. In many-nucleon transfers (small Z), the effect of evenness is manifested. The cross sections of reaction products that are even in Z and A are larger than for their odd neighbors.

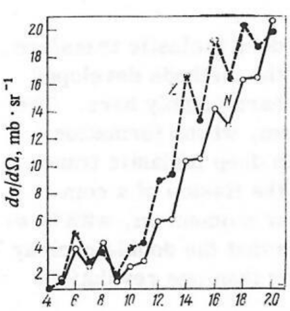

FIG. 25. Production cross section $d\sigma/d\Omega$ of light transfer-reaction products as a function of the atomic number and mass number of the reaction product. Data obtained from the bombardment of Ni (natural mixture of isotopes) by 280-MeV ^{40}Ar ions.[34]

It can be seen from Table 1 that for the combination ^{232}Th + ^{16}O the proton stripping cross sections appreciably exceed the pickup cross sections. This asymmetry was also observed earlier in the cases when the atomic number of the target nucleus was much greater than that of the bombarding nucleus. In Ref. 61, Diamond *et al.* attributed this effect to the change in the Coulomb interaction energy of the two nuclei in the exit channel compared with the entrance, $E_c = Z_1 Z_2 e^2/R$. Here, Z_1 and Z_2 are the atomic numbers of the bombarding nucleus and the target nucleus, and $R = r_0(A_1^{1/3} + A_2^{1/3})$. If $Z_1 \ll Z_2$, the Coulomb energy increases when the bombarding nucleus picks up a proton, and decreases if a proton is stripped. If Z_2 is fixed and Z_1 increased, the proton pickup cross sections will increase. Note that for ^{232}Th with $Z_1 = 18$ (^{40}Ar) equilibrium is established between stripping and pickup: Nucleons are transferred with about equal probabilities from the bombarding nucleus to the target nucleus and vice versa (see Fig. 11 and also the data of Ref. 35).

With increasing mass and energy of the heavy ion, the transfer reactions became the dominant process in the interaction of two complex nuclei and make the main contribution to the reaction cross section σ_R. When ^{181}Ta ions were bombarded by 840-MeV ^{136}Xe ions, it was established that the cross section of complete fusion of the nuclei did not exceed 70 mb, which is 2% of σ_R (Ref. 15). For the combination ^{238}U + ^{84}Kr at an energy 605 MeV the cross section for complete fusion is about 110 mb, or about 3% of σ_R (Fig. 16).

Knowing the total cross section of direct processes and the total reaction cross section, one can calculate the critical angular momentum l_{cr} which in the l space separates the region belonging to the compound (or quasicompound) nucleus and to direct reactions. Data of such calculations, taken from Refs. 30 and 57, are given in Table 2. This also includes the angular momentum l_g of a grazing collision.

Cross sections for the production of isotopes. In transfer reactions induced by heavy ions, many channels are open, and a large number of different isotopes are produced as reaction products. The cross sections for production of individual isotopes vary over very wide ranges from tens of millibarns to nanobarns. The

TABLE 2. Total cross sections of direct processes, total cross sections, and critical angular momenta $\hbar l_{cr}$.

Target and ion	Ion energy in lab system, MeV	Cross section of direct processes, b	Reaction cross section, b	Critical angular momentum, units of $\hbar$	Angular momentum of grazing collisions, units of $\hbar$
^{232}Th + ^{16}O	137	0.8	1.7	53	72
^{232}Th + ^{22}Ne	174	0.8	1.9	74	95
^{232}Th + ^{40}Ar	296	1.1	1.9	102	157
^{232}Th + ^{40}Ar	388	2.4	2.9	94	222

first attempts to systematize the transfer-reaction cross sections were undertaken in Refs. 25 and 51. The cross sections were represented as functions of the number of neutrons lost or picked up by the target nucleus at a fixed number of transferred protons. In this representation, the distribution of the cross sections can be described by a Gaussian function. The variance of the distributions increases with the mass of the bombarding nucleus and the energy of the collision.[25] In these experiments, the transfer-reaction products were separated from the bombarded target by radiochemical methods, so that stable isotopes and long- and short-lived isotopes escaped detection. It was also difficult to take into account the influence of secondary processes, and these had a particularly strong influence on the products of transformation of the target nucleus. These last, having an appreciably greater mass than the bombarding nucleus, received a large part of the excitation energy. The measured yield of isotopes actually reflected a superposition of two processes: transfer of nucleons, and subsequent evaporation of particles (predominantly neutrons) from the excited nucleus. Progress in methods of detecting light transfer-reaction products made it possible to eliminate the restriction on detecting isotopes. Detection of the light products appreciably reduced the influence of secondary reactions. When heavy targets are bombarded, a light product receives an excitation energy that in many cases is below the threshold for the emission of heavy particles.

In Ref. 26, Artukh *et al.* established a new systematic behavior for many-nucleon transfers with proton stripping from the bombarding nucleus. This is demonstrated in Fig. 26a for the case of bombardment of ^{233}Th by 137-MeV ^{16}O ions. The energy Q_{gg} needed to obtain the isotope in the case when both final nuclei are in the ground states is $(M_1+M_2)-(M_3+M_4)$. It can be seen that the cross sections of the isotopes of each element nearly lie on parallel lines. As later experiments at Dubna showed, this tendency is a fairly general characteristic and can be used to systematize the cross sections for the production of isotopes for some combinations of targets and bombarding ions. For brevity, we shall refer to it as the Q_{gg} dependence.

The most characteristic features of the Q_{gg} dependence are the exponential dependence of the differential cross section $d\sigma/d\Omega$ on Q_{gg} and the regular displacement of the lines of the elements (the lines joining isotopes of one element) along the Q_{gg} axis with decreasing atomic number of the isotopes. It should also be noted that the interval between the lines of the elements does not remain constant: It is broader on the transition from even to odd Z and narrower on the transition from odd to even Z. The mean width of the interval between the lines of elements decreases with decreasing Z. The slope of the lines of the elements does not remain constant, and it changes more strongly for elements that have Z near that of the bombarding nucleus.

The Q_{gg} dependence retains its basic features on variation of A and Z of the bombarding particle, the target nucleus, or the emission angle of the reaction products. In Figs. 26b and 26c, the Q_{gg} dependence is represented

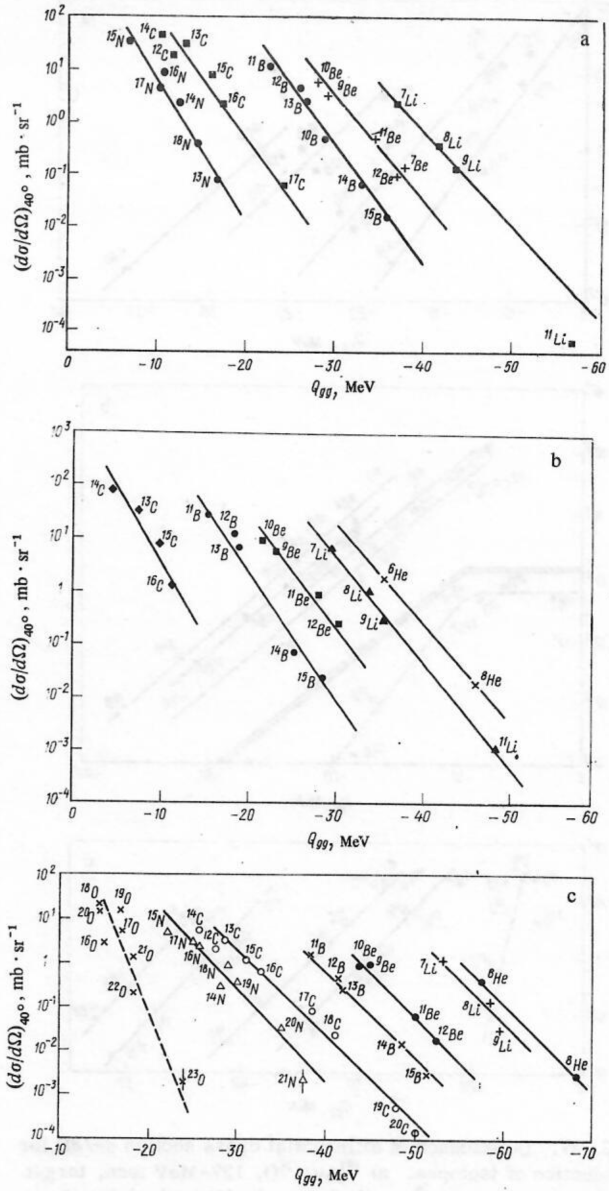

FIG. 26. Dependence of differential cross sections for the production of isotopes, $(d\sigma/d\Omega)_{40°}$, for emission angle 40° in the laboratory system. a) ^{232}Th + ^{16}O, 137-MeV ions, target thickness 20 mg/cm^2 (Ref. 26); b) ^{232}Th + ^{15}N, 145-MeV ions, target thickness 20 mg/cm^2 (Ref. 27); c) ^{232}Th + ^{22}Ne, 174-MeV ions, target thickness 2.5 mg/cm^2 (Ref. 31).

for the cases when ^{232}Th was bombarded by 145-MeV ^{15}N ions[27] and 174-MeV ^{22}Ne ions.[31] Note that the Q_{gg} dependence is exhibited more clearly, the greater the number of protons stripped from the bombarding nucleus in the interaction process. The oxygen isotopes in Fig. 26c do not fit into the dependence. We shall return to a discussion of the reasons for the deviations of cross sections from the Q_{gg} dependence later.

In Figs. 27a and 27b, the Q_{gg} dependence is represented for cases with different targets. For example, instead of ^{232}Th, the 137-MeV ^{16}O ions bombarded ^{197}Au (see Fig. 27a),[26] and the 174-MeV ^{22}Ne ions bombarded ^{94}Zr (see Fig. 27b).[31] In Fig. 27a, one can clearly see how the slope of the element lines changes with de-

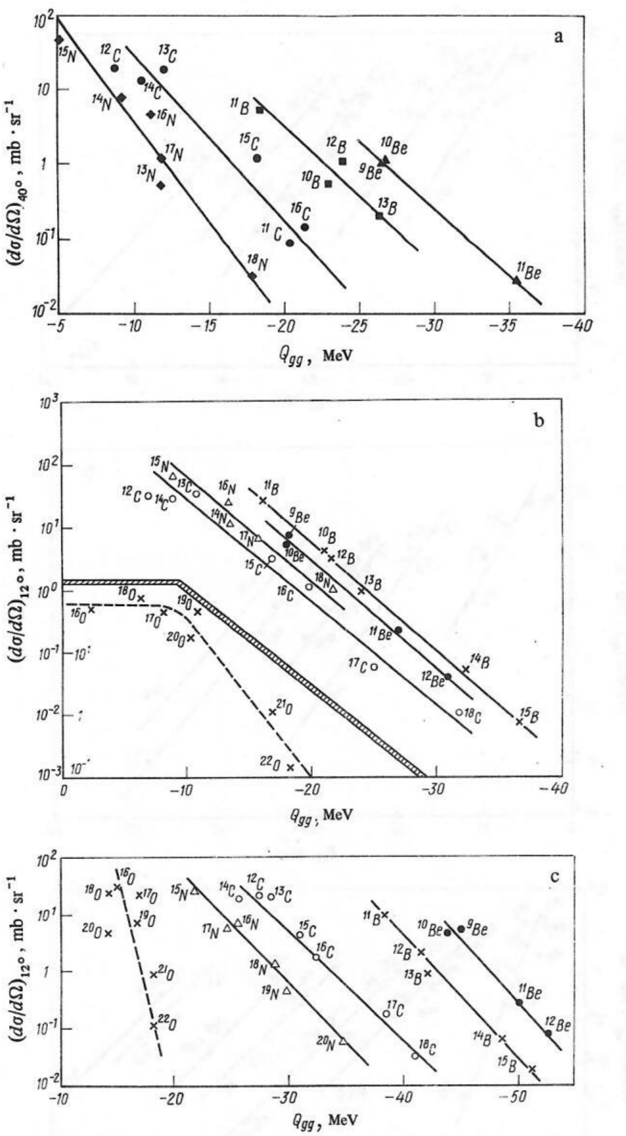

FIG. 27. Dependence of differential cross section $d\sigma/d\Omega$ for production of isotopes. a) $^{197}Au + ^{16}O$, 137-MeV ions, target thickness 2.3 mg/cm^2, emission angle 40° in the laboratory system[26]; b) $^{94}Zr + ^{22}Ne$, 174-MeV ions, target thickness 2.3 mg/cm^2 emission angle 12° in the laboratory system[31]; c) $^{232}Th + ^{22}Ne$, 174-MeV ions, target thickness 2.5 mg/cm^2 emission angle 12° in the laboratory system.[31]

creasing Z and increasing spread of the points about the lines of elements with Z near the bombarding nucleus. In the case of ^{94}Zr, the lines of the elements are much closer together than in the case of heavy target nuclei. In addition, for Zr one can observe a further interesting feature: The sequence in the arrangement of the lines of the elements is charged. The N isotopes lie to the right of the C isotopes, and the B isotopes to the right of the Be isotopes.

In three cases (see Fig. 26) of irradiation of ^{232}Th by different ions the isotopes were detected at an angle of 40° to the beam. In Fig. 27c, the Q_{gg} dependence is represented for the data for the $^{232}Th + ^{22}Ne$ combination at energy 174 MeV, but it is narrower for the emission angle 12°. The general nature of the Q_{gg} dependence is preserved, and the slope of the lines of the elements does not change appreciably.

The Q_{gg} dependence has attracted the interest of theoreticians. Attempts were made to explain it with different approaches. In Ref. 62, Toepfer used Greiner's two-center model[63] in conjunction with Demkov's method of molecular wave functions.[64] In Ref. 66, Abul-Magd *et al.* applied a statistical approach under the assumption that the many-nucleon transfers occur through the stage of formation of a compound nucleus. In Ref. 65, Bondorf *et al.* attempted to combine the statistical approach and the mechanism of classical direct reactions. In Ref. 67, Gudima *et al.* considered the decay of an intermediate nonequilibrium system. Bondorf *et al.*[65] were the first to point out that the nature of the energy spectra in many-nucleon transfers precludes the possibility of explaining the Q_{gg} dependence in the framework of the traditional mechanism of direct reactions. The point is that the cross sections of direct reactions are determined by the properties of the quantum states of the nuclei between which the transfer of the nucleons is made and by the Q values of the reactions corresponding to these transitions. Many-nucleon transfers, as followed from inspection of the energy spectra, are accompanied by very strong excitation of the reaction products. The probability that the final nuclei are formed in the ground state is negligibly small. This can be seen from the example of the measurement of the transfer reactions for ^{21}O and ^{22}O (Ref. 68). In Ref. 65, Bondorf *et al.* noted that the Q_{gg} dependence must be regarded as evidence that conditions near those of statistical equilibrium are realized in transfer reactions. They introduced the idea of partial statistical equilibrium for the nucleon states in which the nucleons can readily pass from the one nucleus to the other through the contact zone. In Ref. 65, they succeeded in obtaining an exponential dependence of the isotope production cross sections on Q_{gg}. However, the theoretically calculated intervals between the element lines were much greater than the experimental. To remove this discrepancy, Bondorf *et al.*[65] were forced to advance the hypothesis that there exists a potential barrier of width of about 2 F for the transferred protons. Since the many-nucleon transfers take place when there is strong overlapping of the nuclear surfaces, this conjecture does not seem plausible.

Direct application to many-nucleon transfers of the methods of analysis developed for the compound nucleus, as was done in Ref. 66, leads to difficulties in explaining the asymmetry of the angular distributions and the symmetric profile of the energy spectra. The difficulties of the theoretical analysis of many-nucleon transfers reside in the dual nature of the mechanism, which combines features inherent in the compound nucleus and classical direct processes. Below I shall attempt to show that the concept of formation of a double nuclear system in deep inelastic collisions enables one to explain naturally the basic features of the Q_{gg} dependence. Indeed, it is the appreciable lifetime (in the nuclear scale) of the double nuclear system that gives rise to conditions near those of statistical equilibrium for the exchange of nucleons and energy between the nuclei and makes possible a statistical approach to the analysis of its decay.

2. FORMATION OF A DOUBLE NUCLEAR SYSTEM, ITS EVOLUTION, AND DECAY

Aspects of the interaction of two complex nuclei. The much larger charges and masses of heavy ions compared with light particles lead to a great increase in the importance of Coulomb and centrifugal forces in the interaction between complex nuclei. Two colliding nuclei do not always fuse even when there is strong overlapping of the nuclear surfaces. It has been shown experimentally that for every pair of nuclei there exists a certain critical value of the orbital angular momentum l_{cr} above which a compound nucleus is not formed. The de Broglie wavelength of heavy ions at energies appreciably exceeding the Coulomb barrier is of the order 0.1 F. This is much less than not only the dimensions of the nuclei themselves but even the width of their surface layer. The nuclear microscope which uses heavy ions as beams of light has a resolution sufficiently high to examine the structure of the nuclear surface. The short de Broglie wavelength of the heavy ions makes it possible to describe the relative motions of two nuclei in the same way as the motion of classical particles. In many cases this simplifies the theoretical analysis and facilitates the interpretation of the experimental data.

Despite this favorable factor, the description of the interaction of two complex nuclei is not a simple problem for the theory. The use of an optical potential does not meet strong objections in the case of elastic and quasielastic collisions, since the nuclei only graze each other in these collisions and one can assume that their individuality is preserved during the interaction. In deep inelastic collisions, when the surfaces of the nuclei overlap strongly and their relative velocity falls to a small value, it is not so obvious that one can use a potential to describe the interaction.

The weakly bound and excited nucleons of both nuclei can readily pass from one nucleus to the other, and the wave functions describing their states actually extend to both nuclei. At the same time, the experimental data show that the most intense exit channel of deep inelastic processes is that of inelastic scattering. The transfer-reaction cross sections decrease with increasing number of nucleons stripped from the bombarding nucleus and with increasing number of nucleons that are picked up. This justifies one in assuming that, despite the strong interaction, the nuclei retain their individuality to a considerable extent, so that one can treat their interaction as a two-body process. The strongly bound nucleons of the lower shells form a fairly strong core whose destruction requires appreciably higher excitation energies than are available in collisions with a kinetic energy of a few MeV per nucleon. For example, for the $^{232}Th + ^{40}Ar$ combination the excitation energy of 100 MeV is only a few percent of the total binding energy of the nuclides. The system of two strongly interacting nuclei formed in the deep inelastic collisions is a distinctive combination of common and individual features. The part in common is the "valence" nucleons belonging to both nuclei; the individual part is the nucleons of the inner shells of each nucleus.

The interaction of two complex nuclei whose surfaces overlap appreciably changes the direction of their motion and dissipates the kinetic energy of the collision. The potential $V(R)$ of the interaction between the nuclei is usually represented as the sum of a nuclear potential $V_n(R)$, a Coulomb potential $V_c(R)$, and a centrifugal potential V_l:

$$V(R) = V_n(R) + V_c(R) + V_l(R). \quad (2)$$

It is not particularly difficult to calculate $V_c(R)$ or $V_l(R)$; the problem is the determination of $V_n(R)$. In some studies[69–71] attempts have been made, on the basis of different approaches, to calculate $V_n(R)$. One of the important results of these calculations is the indication that there are repulsive forces between nuclei at short distances if the nuclei approach each other rapidly. As long as the density in the region in which the volumes of the nuclei overlap is less than the density of saturated nuclear matter, the nuclei attract one another. The attraction is replaced by repulsion when the density in the overlapping region begins to exceed the saturation density. The appearance of repulsive forces in fast collisions of nuclei is interpreted as an effect of the Pauli principle and the weak compressibility of saturated nuclear matter.

Formation of a double nuclear system. Let us consider a model of the collision of two nuclei (Z_1, A_1) and (Z_2, Z_2) at an energy appreciably higher than the Coulomb barrier, $E_0 > B_0$, and with orbital angular momentum $\hbar l$ near the critical $\hbar l_{cr}$. We shall assume that the spins of both nuclei are zero. When the surfaces of the nuclei touch, the kinetic energy of the collision is $E_0 - B_0$. We split it into two parts: radial E_R and tangential E_t:

$$E_t = \hbar^2 l(l+1)/(2\mu R^2); \quad E_R = E_0 - B_0 - \hbar^2 l(l+1)/(2\mu R^2). \quad (3)$$

Here, μ is the reduced mass; $R = r_0(A_1^{1/3} + A_2^{1/3})$, and $r_0 = 1.5$ F. Because of the radial part of the kinetic energy, the nuclei begin to penetrate each other. The tangential part gives rise to a motion of the surface layer of one nucleus through the surface layer of the other. One can expect that under conditions of high nuclear viscosity the velocity of relative motion of the two nuclei is damped near the turning point of the trajectory, where the radial velocity falls to zero and the overlapping of the surfaces of the nuclei is maximal. The tangential energy goes over partly into thermal excitation and partly into the rotational energy of the two tightly bound nuclei. The ratio of these two parts of E_t will be determined by the change in the moment of inertia J of the system. In the first stage of the collision, $J = \mu R^2$. After the damping of the relative motion and the formation of the system of two nuclei rotating together, $J = J_1 + J_2 + \mu R_*^2$, where J_1 and J_2 are the intrinsic moments of inertia of the nuclei and R_* is the distance between the centers of the nuclei at the turning point. The moments of inertia J_1 and J_2 are evidently near the rigid-body values since the excitation energy of the system is a few tens of MeV.

The radial part of the kinetic energy, E_R, is also strongly dissipated. One can assume that a large part of E_R is expended in thermal excitation of the system. After the turning point, the light nucleus, having a certain reserve of potential energy, begins to move along the radius, following the potential $V(R)$ (this is a situation that recalls the motion of a deflected pendulum in a viscous liquid). The light nucleus can be significantly accelerated by the Coulomb and centrifugal forces as it passes the periphery of the target nucleus. where the decelerating action of nuclear friction is weaker because of the lower density of the nuclear matter.

A large part of the kinetic energy of the collision is dissipated between the time at which the nuclei touch and their reaching the turning point. In collisions with an energy of a few MeV per nucleon, this time is near 10^{-22} sec. During this short interval of time, the nuclei cannot be appreciably deformed, but their structure changes appreciably. Thus, as a result of the intensive nuclear friction and the action of powerful repulsive forces at short distances during the first stage of the collision, a double nuclear system is formed at the turning point. The surfaces of the nuclei of the double system overlap strongly, and the relative velocity is low. The double nuclear system has an angular momentum equal to the angular momentum $\hbar l$ of the collision and has a moment of inertia J corresponding to the joint rotation of the two nuclei. The rotational energy of the system is $E_l = \hbar^2 l(l+1)/(2J)$ and the excitation energy $E^* = E_0 - V^*(R_*)$, where $V^*(R)$ is the potential energy of the interaction of the nuclei, in which the centrifugal potential $V_l(R)$ has been taken for the rotating double nuclear system.

What happens then to the double system? If the angular momentum of the collision is less than the critical, $l < l_{cr}$, there is a minimum in the interaction potential $V^*(R)$, and the system may slip into this minimum. However, the minimum is local since the shape of the double nuclear system is not optimal. As a result, it begins to evolve by exchanging nucleons and arrives through deformations at a shape corresponding to a minimum of the potential energy. If $(A_1 + A_2)$, $(Z_1 + Z_2)$ is a light or medium nucleus, the final result of this evolution is an excited compound nucleus in a state of equilibrium deformation.

In collisions with angular momentum greater than the critical $l > l_{cr}$, the Coulomb and centrifugal forces exceed the nuclear attraction [no minimum in the potential $V^*(R)$], and the double nuclear system breaks up. Since however these three forces are in equilibrium when $l = l_{cr}$, the resultant force when l is slightly greater than l_{cr} should be relatively small, and, under conditions of high nuclear viscosity, the double system will break up slowly in the characteristic nuclear time scale ($\sim 1 \cdot 10^{-22}$ sec). Possessing a large angular momentum, the double system will resolve through an appreciable angle during the decay time, and the light reaction products will be emitted in the region of negative angles. The direction of angular deflections due to Coulomb forces is taken to be positive.

The extended lifetime of the double system permits an appreciable number of nucleons to pass from one nucleus to the other. During the same time, the nuclei in the double system may be appreciably deformed.

3. INTERPRETATION OF DEEP INELASTIC TRANSFERS BY THE CONCEPT OF A DOUBLE NUCLEAR SYSTEM

Energy spectra and angular distributions. The idea that a double nuclear system is formed in the deep inelastic collisions of two complex nuclei enables one to interpret the main experimental features of transfer reactions induced by heavy ions.

The double peak in the energy spectrum of few-nucleon transfers is due to the action of the two different reaction mechanisms: quasielastic and deep inelastic. In the first case, the ion is scattered mainly in the Coulomb field of the target nucleus and the product is emitted in the region of positive angles. In this case, a large part of the kinetic energy of the collision is retained.

In the second case, a double nuclear system is formed and this, rotating, passes through 0° and breaks up, emitting a light product in the region of negative angles and with energy near the exit Coulomb barrier.

Many-nucleon transfers are realized preferentially in deep inelastic processes since a greater length of time of contact between the nuclei and a more intense interaction between them are needed for the transfer of an appreciable number of nucleons. The deformation of a double nuclear system that has a large angular momentum reduces the exit Coulomb barrier and makes possible the emission of products with energy below the Coulomb carrier calculated for the undeformed nuclei. Large negative emission angles correspond to large angles of revolution of the double nuclear system and therefore to a longer life of the system. One can suppose that the deformation of the double nuclear system—the increase of the distance between the centers of the nuclei—increases almost linearly with the time. This means that the deviation of the reaction-product energies from the exit Coulomb barriers increases with increasing angle of emission of the light product. Just such a dependence is observed (see Fig. 10).

One can attempt to explain the profile and width of the energy spectra in deep inelastic transfers by a spread of the lifetimes of the double nuclear system. Since the decay of the system is a statistical process, one can assume that the distribution of the individual lifetimes t about the mean lifetime τ of the system is described by the Gaussian function $t = \tau \exp\{-[(t-\tau)/\sigma]^2\}$. In the case of a linear increase in the deformation of the system with time, the energy spectrum of the reaction products will also be described by a Gaussian function. If the lifetime of the double nuclear system does not depend on the proton distribution in the final nuclei, the width of the energy spectrum in deep inelastic transfers must be proportional to $Z_3 \cdot Z_4$, the product of the atomic numbers of the reaction products. This relation is satisfied to within certain limits.

As can be seen from the experimental data (see Figs. 22 and 23), the angular distributions of the reaction products are the result of a fairly complicated superposition of partial-wave angular distributions corresponding to different Q values of the reaction.

In the range of collision angular momenta from l_{cr} to l_g that contribute to the transfer reactions there is also a qualitative change in the nature of the interaction of the nuclei and of the reaction mechanism itself. For $l \sim l_g$ the surfaces of the nuclei hardly touch and the transfer of nucleons (usually only a few) exhibits the features of the classical direct process, but in collisions with $l \sim l_{cr}$, which lead to formation of a double nuclear system, the reaction mechanism resembles rather the decay of a compound nucleus. Therefore, in the framework of a single theoretical model one can hardly combine the whole gamut of interactions of nuclei in transfer reactions and construct equations capable of describing the element angular distributions.

Indeed, Artukh *et al.* showed[30] that Strutinskii's model,[19] in which transfer reactions are treated as a quasielastic surface process, gives a good description of the partial-wave angular distributions of few-nucleon transfers for small Q. However, when $|Q|$ increases, none of the various distributions of the partial-wave amplitudes proposed in Ref. 19 (Gaussian, exponential) can describe the experimental data by theoretical curves. A certain advance in the region of "moderately" inelastic few-nucleon transfers can be achieved by introducing a more complicated many-parameter dependence on l of the amplitudes and phase shifts of the partial waves.[58]

Recently, Aleshin[72] proposed a scheme for calculating the angular distributions of deep inelastic transfers based on the concept of formation during the first stage in the collision of the nuclei of a double nuclear system with its subsequent decay under conditions of strong nuclear friction. The model contains two adjustable parameters, one of which characterizes the strength of the nuclear friction (damping coefficient) and the other the probability of transfer of a given number of nucleons. In the framework of this scheme one can satisfactorily describe the partial angular distributions for the largest negative values of Q. One of the important conclusions obtained in Ref. 72 is that the nuclear friction increases by several times the time of interaction between the nuclei compared with the time of elastic collision.

Isotope production cross sections. The double nuclear system breaks up, emitting preferentially a light product in the region of 0° or negative angles. This means that the angle of revolution of the system prior to break up is greater than $\pi/2$. An estimate of the lifetime of the double nuclear system for an angular momentum near the critical, for rigid-body moment of inertia and angle of revolution $\pi/2$, gives $(1-2)\times 10^{-21}$ sec. This is an order of magnitude longer than the characteristic nuclear time (10^{-22} sec). In the nuclear time scale, the double system lives fairly long, and one can therefore attempt to use the statistical approach to analyze its breakup. Of course, in transfer reactions it is impossible to achieve complete statistical equilibrium, though during the lifetime of the double nuclear system partial statistical equilibrium can be realized with respect to the exchange of energy and nucleons between the nuclei.

At the end of the impact stage (at the turning point) the double nuclear system has excitation energy $U_{in}(R^*)$ given by

$$U_{in}(R_*) = E_0 - V^*(R_*) - \Delta(p, n), \tag{4}$$

where $\Delta(p,n)$ is the energy expended on breaking the proton and neutron pairs in both nuclei. From this state, the system can decay in many ways since the exchange of energy and nucleons between the original nuclei is statistical.

In accordance with the statistical conjecture, we shall assume that the probability of the system's breaking up with the formation of two definite nuclei (to which we append the subscripts 3 and 4) in the exit channels is proportional to the product of the densities of their states:

$$w(3.4) \propto \rho_3 \cdot \rho_4. \tag{5}$$

The density of states of the final nuclei is determined in its turn by the final excitation energy U_f and its distribution between the nuclei. Since the Q_{gg} dependence describes the cross section for the production of light reaction products in bound states, ρ for light products must be understood as the number of bound states.

We write U_f in a form that explicitly reflects the influence of the process of transfer of nucleons on the final excitation energy:

$$U_f = U_{in} + Q_{gg} + \Delta E_c + \Delta E_l - \delta(n) - \delta(p), \tag{6}$$

where ΔE_c is the change in the Coulomb interaction energy of the two nuclei in the exit channel due to transfer of protons; ΔE_l is the change in the rotational energy of the double nuclear system when nucleons are transferred, due to the change of the system's moment of inertia; and $\delta(n)$ and $\delta(p)$ are corrections that take into account the effect of the pairing of the neutrons and protons when nucleons are transferred.

The factor Q_{gg} automatically takes into account the expenditure of energy on pair breaking in the donor nucleus for the nucleons that are transferred to the acceptor nucleus. In the acceptor, the transferred nucleons finish up in the overwhelming majority of cases in excited states and are unpaired. However, the factor Q_{gg}, which characterizes the expenditure of energy on transferring nucleons from the donor's ground state to the acceptor's, does not take into account this feature of the transfer of two nucleons. Therefore, the final excitation energy U_f is overestimated. The corrections $\delta(n)$ and $\delta(p)$ for pairing for a given reaction channel (given isotope) are equal to the sum of the pairing energies in the acceptor for the additional nucleon pairs that the acceptor receives by the transfer reactions. More precisely, the corrections $\delta(n)$ and $\delta(p)$ can be called corrections for nonpairing. Certain light nuclei with maximally large neutron excess (for example, ^{11}Li, ^{14}Be) are an exception to this rule. In these nuclei there may be no bound states corresponding to the breaking of a neutron pair. If these nuclei are formed in reactions with the pickup of two neutrons, for example, (^{11}B, ^{11}Li) and (^{15}N, ^{14}Be), the neutrons can be transferred only as pairs. For such a pair, the pairing corrections are not introduced.

We assume further that the final excitation energy is distributed between the two nuclei in proportion to the density of their states. In order to describe the densities of states ρ as functions of the excitation energy, we use an expression with constant temperature T:

$$\rho \propto \exp(U/T). \tag{7}$$

We mention immediately that T for the double nuclear system can differ appreciably from the temperature of the corresponding compound nucleus since the former does not achieve a state of complete statistical equilibrium. The temperature T can be regarded as the temperature of partial statistical equilibrium, or simply as a parameter. In the general case, T is the same for both nuclei that form the double nuclear system. However, if one of the reaction products is a light nucleus oversaturated by neutrons or protons and with a very small number of weakly bound states, virtually all the excitation energy will be concentrated in the heavier nucleus, and the light nucleus will be cold. In the general case, for the product of densities of states of the final nuclei $\rho_3\rho_4$ one can write

$$\rho_3\rho_4 = \exp(U_f/T). \tag{8}$$

In deep inelastic transfers, the kinetic energy of the reaction product is determined basically by the exit Coulomb barrier, and the variations in the kinetic energies of the different isotopes (for fixed Z) are small. The value of U_f depends on the angular momentum $\hbar l$ of the collision, and in a rigorous treatment of the process it is necessary to sum the contributions from the breakup of the double nuclear system with different angular momenta. However, as a first approximation one can use a certain mean value $\bar{l}$ in the range l_{cr}, $l_{cr}+\Delta l$ where the deep inelastic transfers take place. On this basis, one can assume that the cross section for the production of isotopes is basically determined by the final excitation energy U_f:

$$\sigma \propto \exp(U_f/T). \tag{9}$$

On heavy target nuclei, the main contribution to the change in U_f is made by the factors Q_{gg} and ΔE_c. In many-nucleon transfers, Q_{gg} can reach several tens of MeV and ΔE_c is 5–10 MeV per transferred proton; ΔE_l does not exceed a few hundreds of keV per transferred nucleon, and the pairing energy in heavy nuclei is near 1 MeV. Therefore, in the expression (6) for U_f in a first approximation we can retain only the principal terms and for the isotope production cross section we obtain

$$\sigma \propto \exp[(Q_{gg}+\Delta E_c)/T]. \tag{10}$$

It is this expression that describes the empirically found Q_{gg} dependence. Thus, the statistical approach has made it possible to explain the principal features of the Q_{gg} dependence: the exponential dependence of the isotope production cross sections on Q_{gg} and the shift of the lines of the elements along the Q_{gg} axis with increasing number of protons stripped from the bombarding nucleus.

In the empirical Q_{gg} dependence the slope of the lines of the elements changes slightly with Z (see Figs. 26 and 27). The introduction of corrections for pairing of neutrons [in this case, $Q_{gg}-\delta(n)$ is plotted along the abscissa] makes the lines of the elements have the same slope. Figures 28 and 29 show the Q_{gg} dependences after the introduction of corrections for the pairing of neutrons and protons. The role of pairing corrections is particularly striking for the combination ^{94}Zr + ^{22}Ne (see Figs. 27b and 29c). In ^{94}Zr, as opposed to ^{232}Th, the energy of the Coulomb interaction between the nuclei is smaller, but the pairing energy is greater. As a result, in the empirical Q_{gg} dependence the N isotopes are situated to the right of the C isotopes, and the B isotopes to the right of the Be isotopes. The introduction of corrections for the pairing of neutrons and protons makes it possible to re-establish the normal sequence in the arrangement of the lines of elements. Note that the introduction of the pairing corrections reduces the spread of the experimental points about the lines of the elements.

An important result of the introduction of pairing corrections in the case of ^{94}Zr is the appreciable increase in the intervals between the lines of the elements. Small intervals would mean that the double nuclear system is very strongly deformed before breakup. However, the nature of the energy spectra of the transfer reaction products indicates that this is not the case. For ^{94}Zr, the change in the rotational energy of the system when nucleons are transferred begins to have an appreciable significance in the energy balance; ΔE_l per transferred nucleon is about 0.6 MeV. Therefore, to estimate the deformation of the double nuclear system from the intervals between the lines of the elements this factor must be taken into account.

The change ΔE_c in the Coulomb interaction energy in the case of bombardment of ^{232}Th by ^{15}N, ^{16}O, and ^{22}Ne ions is about 10 MeV per transferred proton. However, the average intervals between the lines of the elements for these target and ion combinations remain appreciably smaller than this value even after the introduction of pairing corrections and allowance for the change in the rotational energy. This difference may be due to

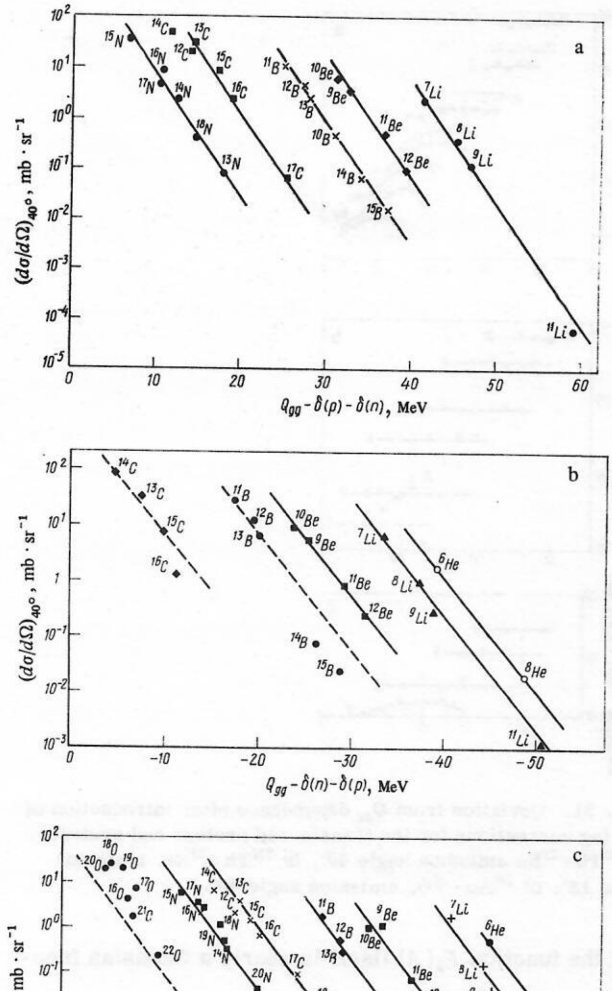

FIG. 28. The Q_{gg} dependence after the introduction of pairing corrections for transferred protons and neutrons. a) $^{232}Th + ^{16}O$ (see Fig. 26a); b) $^{232}Th + ^{15}N$ (see Fig. 26b); c) $^{232}Th + ^{22}Ne$ (see Fig. 26c).

the deformation of the double nuclear system before breakup. The drawing together of the lines of the elements with increasing Z of the light products reflects the fact that the transfer of many nucleons requires a longer interaction time, and this, in its turn, entails a greater deformation of the double nuclear system. Variations in the width of the interval between the lines of the elements on the transition from even to odd Z and from odd to even Z are due to the large difference between the binding energies of even and odd protons in light nuclei.

Table 3 presents the data on the parameter T for the investigated combinations of targets and ions after the introduction of pairing corrections. It also contains the collision energy, i.e., the kinetic energy above the entry Coulomb barrier, and the collision energy per nucleon of the double nuclear system. It can be seen

TABLE 3. Value of the parameter T.

Target and particle	Lab energy of ion, MeV*	Energy above Coulomb barrier in cms, MeV	Energy above Coulomb barrier per nucleon of the system, MeV	T, MeV	Angle of detection in lab system, deg
$^{232}Th + ^{16}O$	125	37	0.149	1.8	40
$^{197}Au + ^{16}O$	136	53	0.241	1.9	40
$^{232}Th + ^{15}N$	137	58	0.235	2.1	40
$^{232}Th + ^{22}Ne$	172	61	0.242	1.9	40
$^{232}Th + ^{22}Ne$	172	61	0.242	1.8	12
$^{94}Zr + ^{22}Ne$	172	85	0.745	2.2	12

*The ion energy corresponds to the middle of the target.

that the parameter T has reasonable values: The temperature of the excited compound nuclei formed in the case of complete fusion of the ^{232}Th and ^{197}Au nuclei and the various ions is about 1.5 MeV. In the case of partial statistical equilibrium there is not time for the excitation energy to be distributed over all the degrees of freedom, and therefore the "temperature" of partial statistical equilibrium is somewhat higher. As can be seen from Table 3, the parameter T is virtually independent of the emission angle of the light reaction product and increases slowly with increasing kinetic energy of the collision per nucleon.

Deviations from the Q_{gg} dependence. In discussing

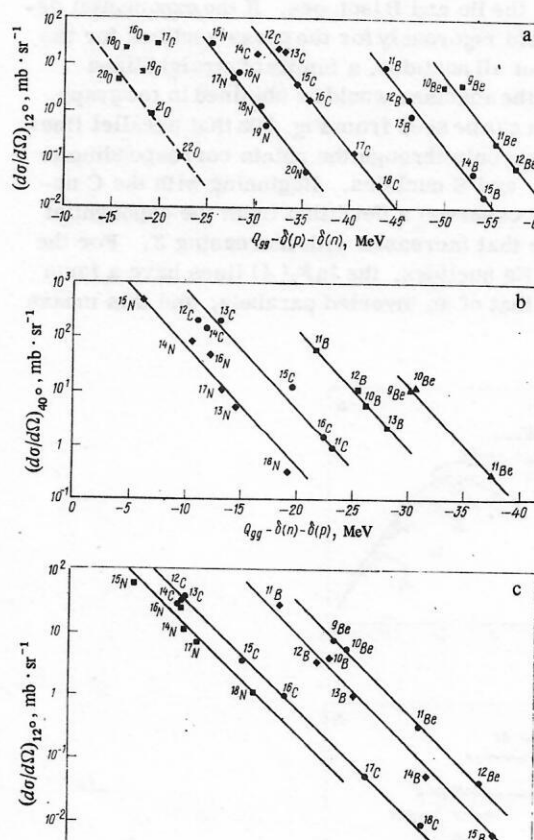

FIG. 29. The Q_{gg} dependence after the introduction of pairing corrections for the transferred protons and neutrons. a) $^{197}Au + ^{16}O$ (see Fig. 27a); b) $^{94}Zr + ^{22}Ne$ (see Fig. 27b); c) $^{232}Th + ^{22}Ne$ (see Fig. 27c).

the properties of the Q_{gg} dependence we noted the increase in the spread of points about the lines of the elements in the cases when the atomic numbers of the reaction products are near the bombarding nucleus's. Following Artukh *et al.*,[28] let us express the deviation from the Q_{gg} dependence explicitly as a function of A and Z of the light reaction product. For the differential cross sections for the production of nuclides, generalizing the expression (10), we can write

$$d\sigma/d\Omega = C\cdot F(A, Z)\exp[(Q_{gg}+\Delta E_c)/T]. \quad (11)$$

The deviation function is $F(A, Z)\equiv 1$ for nuclides whose cross section satisfies the exponential dependence. Taking the logarithm of (10), we obtain

$$\ln(d\sigma/d\Omega) - Q_{gg}/T = \ln F(A, Z) + \Delta E_c/T + \ln C. \quad (12)$$

For fixed Z of the reaction products, $\Delta E_c/T = \text{const}$, and the left-hand side of Eq. (12) characterizes the form of the deviation functions in their dependence on the mass number of the reaction product: $F(A, Z) \equiv F(A, Z)_{Z=\text{const}}$. This relation is represented graphically for the transfer-reaction products for the combination $^{232}Th + {}^{22}Ne$ and detection angle 40° (Ref. 28) in Fig. 30a. The value of T is taken from the slope of the lines of the Be and B isotopes. If the exponential dependence held rigorously for the cross sections for the production of all nuclides, a family of straight lines parallel to the abscissa would be obtained in the graph. However, it can be seen from Fig. 30a that parallel lines can be drawn only through the points corresponding to the Li, Be, and B nuclides. Beginning with the C nuclides, one observes a deviation from the exponential dependence that increases with increasing Z. For the O, F, and Ne nuclides, the $\ln F_2(A)$ lines have a form similar to that of an inverted parabola, and this means

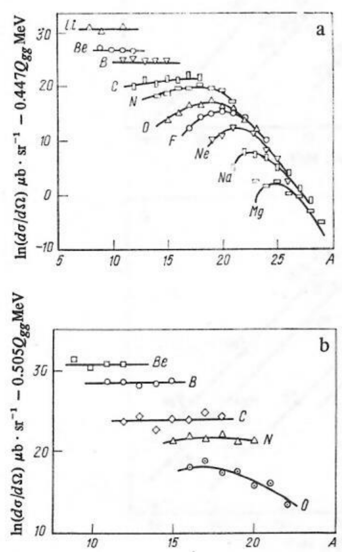

FIG. 30. Deviation of the Q_{gg} dependence as a function of A and Z of the light transfer-reaction product. Pairing corrections not introduced. a) $^{232}Th + {}^{22}Ne$, emission angle 40°; b) $^{232}Th + {}^{22}Ne$, emission angle 11°.

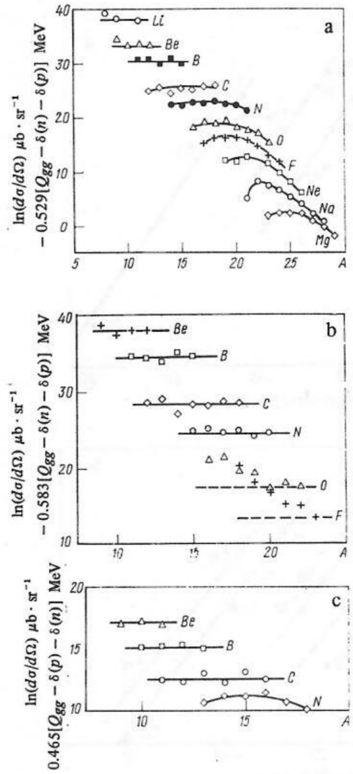

FIG. 31. Deviation from Q_{gg} dependence after introduction of pairing corrections for the transferred protons and neutrons. a) $^{232}Th + {}^{22}Ne$ emission angle 40°; b) $^{232}Th + {}^{22}Ne$, emission angle 12°; c) $^{197}Au + {}^{16}O$, emission angle 40°.

that the function $F_2(A)$ itself is nearly a Gaussian function.

With decreasing emission angle, the range of Z values for which the Q_{gg} dependence holds becomes larger. Figure 30b shows the deviations from the Q_{gg} dependence for the same target and ion combination as in Fig. 30a, but for emission angle 12° (Ref. 31). In Figs. 31a and 31b the deviation functions $F_2(A)$ have been plotted after the introduction of pairing corrections for the transferred nucleons. It can be seen that for 12° the Q_{gg} dependence is satisfied by the C and N isotopes. The deviation function $F_2(A)$ constructed for light transfer-reaction products for the $^{197}Au + {}^{16}O$ combination[26] is given in Fig. 31c.

The deviations from the Q_{gg} dependence, like the previously considered aspects of the energy spectra and the angular distributions of the transfer reactions, indicate that the transfer of nucleons between complex nuclei is realized in two different processes: quasielastic and deep inelastic. In few-nucleon transfers for emission angles corresponding to grazing collisions, the main contribution to the isotope production cross section comes from the quasielastic process. It takes place during times that are short compared with the characteristic nuclear time, and therefore partial statistical equilibrium, which is needed if the Q_{gg} dependence is to be realized, cannot be established. With decreasing emission angle, the quasielastic contribution decreases, but the deep inelastic contribution increases. As a result, the Q_{gg} dependence is extended to a greater number of transfer-reaction products.

Two-body mechanism of transfer reactions and the role of secondary processes. In considering the features of transfer reactions induced by heavy ions, we have assumed throughout that these reactions take place as a two-body process. However, this concept requires serious justification. One asks immediately: Is not the appearance of particles with low energies in the exit channels due to a three-body reaction mechanism? By a three-body mechanism I mean a mechanism in which three particles are formed in the process of interaction of the nuclei. As an example, we can take the dissociation of ^{6}Li into an α particle and a deuteron in a collision with a target nucleus. This mechanism must be distinguished from secondary nuclear reactions such as the evaporation of nucleons and α particles from transfer-reaction products or fission of the products. Usually, the secondary processes take place after the exchange of nucleons has ended and the product nuclei have moved apart to distances at which the interaction between them can be ignored. The secondary processes in the heavy residual nucleus will not affect the kinematic characteristics of the light reaction product at all. With regard to the evaporation of the nucleons and α particles from the light reaction product, it is easy to show that these processes have little influence on the mean energy per nucleon in the product (and therefore on the ratio of the energy of the product to the exit Coulomb barrier) or on its angular distribution.

The weightiest argument for two-body transfer reactions is that features of them such as the large energy loss in the case of a product emitted at a small angle, the double peaks in the energy spectra of few-nucleon transfers, the correlation between the product energy and the exit Coulomb barrier, and the nature of the partial angular distributions are the same in the reactions of stripping or pickup of nucleons by the bombarding nucleus. Naturally, in the case of pickup processes one cannot speak about dissociation of the bombarding nucleus.

Under the assumption that the bombarding nucleus breaks up into two or more fragments, it is hard to explain the correlation observed in deep inelastic transfers between the energy of a light reaction product and its exit Coulomb barrier. For the breakup of ^{40}Ar into two fragments the yields of the conjugate element pairs (B–Al, C–Mg) must be approximately the same. However, this is not observed experimentally. The difference between the cross sections for the production of conjugate elements increases as their Z value increases. The Q_{gg} dependence cannot be explained in the framework of a three-body reaction mechanism. In Ref. 38, Thompson attempted a direct experimental verification of the two-body nature of deep inelastic transfers. Bombarding silver with 280-MeV ^{40}Ar ions, he measured the energies and angular correlations of the conjugate transfer-reaction products. He showed that the emission angle of the products in the center-of-mass system is 180°, and that their energy corresponds to breakup of the intermediate system into two fragments.

In the theoretical paper,[73] Bondorf and Nörenberg attempted to ascribe the great variety of light products observed in the $^{232}Th + ^{22}Ne$ and $^{232}Th + ^{40}Ar$ reactions to the action of secondary processes—the evaporation of nucleons and α particles. In their opinion,[73] the original distribution of light transfer-reaction products has a small dispersion with respect to Z and A, being basically products of few-nucleon transfers. It is then only as a result of the secondary evaporation processes that the great variety of observed nuclides arises. Of course, secondary processes do have an importance in the formation of the final spectrum of masses and charges of the light transfer-reaction products; this is indicated by the observation of "direct" α particles and protons. However, the role of the secondary processes is much more modest than is asserted in Ref. 73. The Q_{gg} dependence enables one to identify directly the isotopes for which a contribution from secondary processes is important. It can be seen from Fig. 29 that the heavy oxygen isotopes ^{20}O, ^{21}O, and ^{22}O satisfy the Q_{gg} dependence. The production of these isotopes as a result of evaporation processes from an inelastically scattered ^{22}Ne nucleus is implausible. On the other hand, the lighter oxygen isotopes ^{16}O, ^{17}O, and ^{18}O clearly do not satisfy the Q_{gg} dependence: Their production cross sections are much larger. But it is precisely these isotopes that will arise as a result of evaporation of α particles and neutrons from excited ^{22}Ne. We recall that in light nuclei the binding energy of an α particle is in many cases appreciably less than a proton's or a neutron's. With regard to the lighter elements (N, C, B, Be, Li), the production cross sections for their isotopes satisfy the Q_{gg} dependence. The probability of production of isotopes with large neutron excess, such as ^{20}N, ^{18}C, ^{15}B, and ^{12}Be as a result of evaporation of nucleons from excited light nuclei is negligibly small. But then it follows from the fact that the Q_{gg} dependence is satisfied by isotopes in the β-stability valley as well as by isotopes strongly oversaturated with neutrons that they are all formed by one and the same reaction mechanism—transfer of nucleons—and the contribution of secondary processes to their production is small. The variety of the observed light products is due basically to the transfer reactions and not to the secondary processes. Of course, for heavy transfer-reaction products, which obtain the overwhelming part of the excitation energy, the secondary processes have a strong influence on the A and Z distribution of the final products.

4. Q_{gg} DEPENDENCE AND EVOLUTION OF A DOUBLE NUCLEAR SYSTEM

The main factors that lead to the formation of a double nuclear system in deep inelastic transfers—the high nuclear viscosity and the low compressibility of saturated nuclear matter—are also operative in collisions with angular momentum smaller than the critical: $l < l_{cr}$. It is therefore natural to assume that in collisions with $l < l_{cr}$ a double nuclear system is also formed and thus becomes the initial stage in the formation of a compound nucleus.

A double nuclear system is an unstable formation. In it, energy and nucleons are continuously being exchanged between the nuclei. The shape of the nuclei, the number of neutrons and protons in each nucleus, and the distance between the centers are changing all the time. The system goes over from one state into another, evolving in time. It is through these features that a double nuclear system differs fundamentally from nuclear molecules, which are characterized by quasistationarity of their states.[74] It should be emphasized that, besides the quasiclassical and quasimacroscopic aspect,[40] evolution in time is a fundamental feature of the interaction of two complex nuclei. It reflects the impossibility of a very rapid (during a characteristic nuclear time) rearrangement of the structure of the two nuclei into a new structure corresponding to an equilibrium compound nucleus. The fusion of two nuclei into a compound nucleus is not to be regarded as a collapse, but as an evolutionary process extending over a comparatively long nuclear time. The statistical nature of the exchange of energy and nucleons between the nuclei gives rise to the Z and A dispersion of the reaction products in the case of deep inelastic transfers.

The question of the direction of evolution of a double nuclear system: Will a heavy nucleus absorb a light one and form a compound nucleus or, conversely, will nucleons pass from the heavy to the light nucleus, tending to symmetrize the double nuclear system? is of particular interest, especially in connection with the synthesis of superheavy elements. In the framework of the liquid-drop model of a nucleus, this problem was analyzed in Refs. 40 and 75. In particular, it was shown that if $(Z_1+Z_2)^2/(A_1+A_2) \gtrsim 40$ and there is zero angular momentum the nuclear drops tend to fuse into a compound nucleus if the original mass asymmetry is large, $A_1 \ll A_2$, but to symmetrize their form if the asymmetry is moderate.

The generalized Q_{gg} dependence (5), in which allowance is made for all the factors influencing the final excitation energy U_f, can be used to estimate the direction of evolution of the double nuclear system and the expected cross sections for the production of definite reaction products. Nucleons will be transferred in the double nuclear system in the direction that increases the final excitation energy U_f and therefore the density of final states. Since the total energy of the system is fixed, this direction of evolution corresponds to minimizing the potential energy of the double nuclear system.

When heavy nuclei (^{238}U, ^{232}Th) are bombarded by ions such as B, C, N, O, Ne, the change in the Coulomb interaction energy ΔE_c when protons are transferred from the light to the heavy nucleus exceeds the total effect of all the other factors $[Q_{gg} - \Delta E_l - \delta(n) - \delta(p)]$ reducing the final excitation energy U_f. As a result, in collisions with angular momentum greater than the critical, $l > l_{cr}$, stripping of nucleons from the bombarding nucleus will dominate over pickups. This is particularly clear from the data in Table 1, which shows the cross sections for stripping and pickup reactions for the combination ^{232}Th + ^{16}O. In collisions with angular momentum less than the critical, $l < l_{cr}$, the heavy target nucleus absorbs the light nucleus and an excited compound nucleus is formed. Extensive experimental material demonstrates the formation of a compound nucleus as the main reaction channel when heavy nuclei are bombarded by the above ions.

With increasing Z of the bombarding nucleus, the change in the Coulomb energy per proton transferred to the target nucleus decreases. Conversely, $|Q_{gg}|$ increases as a result of the increase in the mean binding energy of the nucleons in the bombarding nucleus with increasing A (this continues until $A \sim 90$); ΔE_c and the remaining factors begin to compensate each other, and the two directions of nucleon transfer in transfer reactions ($l > l_{cr}$) become equally probable. A situation close to this obtains for the ^{232}Th + ^{40}Ar combination. As can be seen from the data in Figs. 5–7 and 11, the proton stripping and pickup cross sections are of the same order of magnitude. Thus, the cross section for stripping of eight protons (element Ne) is 33 mb and the cross section for the pickup of eight protons (Fe) is not less than 10 mb. In Ref. 35 it was found that when ^{232}Th is bombarded by 280-MeV ^{40}Ar ions the cross sections for the production of titanium isotopes (pickup of four protons) and Se isotopes (stripping of four protons) are similar.

With a further increase in Z of the bombarding nucleus, it becomes energetically more advantageous for protons to be transferred from the heavy to the light nucleus since the change in the Coulomb energy ΔE_c when protons are stripped no longer compensates the factors reducing the excitation energy. In transfer reactions ($l > l_{cr}$) in this case the nucleon pickup channels will be predominant. For collisions with $l < l_{cr}$, the resulting double nuclear system will evolve in a direction tending to a symmetric dumb-bell shape (Svetetskii's composition system).

The heavy nucleus $^{A_1+A_2}(Z_1+Z_2)$ need not have an equilibrium shape even in the case of weak rotation.[76] In this case, the double nuclear system for $l < l_{cr}$ will break up during evolution from the nonequilibrium state. But if the equilibrium shapes exist right up to some critical value I_{cr} of the spin,[77] collisions with $l < I_{cr}$ will lead basically to the formation of a classical compound nucleus, while collisions with angular momentum in the range $I_{cr} < l < l_{cr}$ will lead to the decay of the double nuclear system from the nonequilibrium state. If for some combination of interacting nuclei the critical angular momentum l_{cr} becomes zero,[78] the Coulomb repulsion even in the absence of rotation exceeds the nuclear attraction and the double nuclear system breaks up without having made a complete revolution.

The nature of the angular distributions of deep inelastic transfers observed in the ^{209}Bi + ^{84}Kr combination[33,39]—the maximum of the cross section at an emission angle near the angle of grazing collisions—may be due to just such a mechanism of interaction between two fairly heavy nuclei.

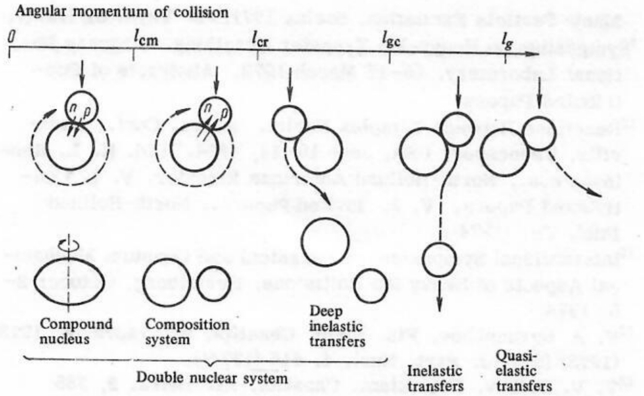

FIG. 32. Interaction of two complex nuclei at different angular momenta of the collision.

The interaction of two complex nuclei with different angular momenta $\hbar l$ of the collision for energies appreciably exceeding the Coulomb barrier are illustrated schematically in Fig. 32. Four characteristic values are plotted along the angular momentum scale: l_{cn}, l_{cr}, l_{gc}, and l_g. The angular momentum of surface (grazing) collisions l_g determines the l value beginning with which nuclear forces are effectively involved in the interaction process. At l_{gc} and below the interaction of two complex nuclei leads to the formation of a double nuclear system, and l_{cn} and l_{cr} divide two different shapes of the double nuclear system.

Deep inelastic transfers occupy the interval $l_{cr} \leq l \leq l_{gc}$. They are characterized by the repulsive Coulomb and centrifugal forces predominating over the nuclear attraction. The double nuclear system in this range of angular momenta breaks up before the completion of a revolution. During the short interaction time only partial statistical equilibrium can be realized.

A composition system is formed in the interval $l_{cn} \leq l \leq l_{cr}$. It is characterized by evolution tending to symmetrize the form. The system may make several revolutions but for these angular momenta an equilibrium form does not exist and the system breaks up (undergoes fission) from nonequilibrium states.

The interval $l \leq l_{cn}$ corresponds to the classical compound nucleus. In this range of angular momenta, complete statistical equilibrium is established, and the double nuclear system attains an equilibrium form during its evolution.

Parallel to the scale of angular momenta, we can represent the time scale of the interaction between nuclei. Collisions with angular momenta in the neighborhood of l_g take place in a time of order 10^{-22} sec. For deep inelastic transfers, the interaction time is increased by an order of magnitude, reaching $(1-2)10^{-21}$ sec. A composition system lives even longer, about 10^{-20} sec. When we come to the compound nucleus, we are here dealing with a time necessary for the double nuclear system to complete its evolution and for an equilibrium form to be established. This requires a special analysis. One could imagine that these times are of order 10^{-20} sec or more.

Although each of these forms of a double nuclear system has its own particular features, I believe that the transition from one form to the other does not take place as an abrupt change, but as a smooth transition, so that the properties of double nuclear systems on the two sides of the characteristic values of the angular momenta are similar. From this point of view, it is worth considering the qualitative change of the transfer reaction mechanism as the angular momentum of the collision decreases from l_g to l_{gc}. In the neighborhood of l_g, the transfer reactions take place as a classical direct process, and they can be described theoretically by an appropriate modification of the distorted-wave method or the coupled-channel method. However, with increasing inelasticity of the process the transfer-reaction mechanism steadily loses the features inherent in the calssical direct process and acquires some of the properties of the mechanism of deep inelastic transfers in which a double nuclear system is formed. Thus, the cross sections for the production of nuclides in these "moderately" inelastic transfers can be described by the Q_{gg} dependence.

The type of interactions of two complex nuclei shown in Fig. 32 correspond to the most general case. Depending on the atomic numbers and the masses of the nuclei and the collision energy, different degenerate cases are possible. For example, at a low collision energy l_g may be less than l_{cr}. In this case, deep inelastic transfers are not realized (the Coulomb and centrifugal forces are not capable of breaking the two nuclei apart if the nuclear surfaces overlap strongly). The interaction is restricted to the formation of a compound nucleus (composition system) and quasielastic transfers. If $l_{cn} = 0$, the classical compound nucleus is absent, and if $l_{cr} = 0$ the composition system is missing.

CONCLUSIONS

The experimental material presented in this review and our analysis suggest that there is an essentially new mechanism of nuclear reactions in the deep inelastic collisions of two complex nuclei. A characteristic feature of this mechanism is the production of a double nuclear system in which the relative velocity of the nuclei is low and the nuclei themselves, despite strong interaction, preserve their individuality to a certain extent. Reactions of this type combine features inherent in both classical direct processes and in the decay of a compound nucleus. The light reaction products forget neither the original direction of the motion of the bombarding nucleus nor its atomic number and mass number. The angular distribution of the products is directed forward, and the maximal yield corresponds to nuclides with Z and A near those of the original nucleus.

At the same time, the lifetime of the double nuclear system is much longer than the characteristic nuclear time, and statistical behavior characteristic of a compound nucleus is manifested in the exchange of energy and nucleons between the nuclei. The prolonged time of contact between the nuclei of the double system makes possible the transfer of an appreciable number of nucleons. Under conditions of partial statistical equilibrium (as regards the exchange of energy and nucleons) the heavy nucleus, which has a very high density of levels, takes virtually the whole of the excitation energy. This creates favorable possibilities for obtaining isotopes of light elements with maximally large neutron excess in transfer reactions.

A feature of the double nuclear system is its evolution in time—the steady change in the state of the system from its time of formation to breakup. The generalized Q_{gg} dependence, which takes into account all factors influencing the final excitation energy when nucleons are transferred, enables one to determine the direction of evolution of the double nuclear system and to estimate the cross section for the production of individual nuclides.

Deep inelastic transfers give unique information about the viscosity of nuclear matter manifested in the relative motion of two complex nuclei with overlapping surfaces. Deep inelastic transfers help one to understand the formation of a compound nucleus when two complex nuclei collide. On the basis of the experimental data obtained in the study of deep inelastic transfers one can conclude with a high probability that the formation of a double nuclear system is a first stage in the formation of a compound nucleus and that a compound nucleus arrives at its equilibrium state as the result of a fairly long—on the nuclear time scale—evolution of a double nuclear system.

The study of deep inelastic transfers has opened up for nuclear physics a new class of physical objects—double nuclear systems evolving in time.

The experiments whose results are presented in this review were made possible above all by the high parameters of the beams of heavy ions of the U-300 cyclotron at the Nuclear Reactions Laboratory at Dubna. I should like to take this opportunity of thanking Academician G. N. Flerov for constant interest in the work, assistance, and support. I thank my colleagues in this work, A. G. Artyukh, J. Wilczynski, G. F. Gridnev, V. L. Mikheev, and A. I. Mezentsev for fruitful discussions in the interpretation of deep inelastic transfers.

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