# *SOME TRANSFER REACTIONS IN THE BOMBARDMENT OF THORIUM BY $Ne^{22}$ IONS*

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Reactions in which a large number (from 5 to 8) of nucleons are transferred under the action of heavy ions were investigated. Targets of $Th^{232}$ were bombarded by $Ne^{22}$ ions and the $\alpha$-active products $Th^{227}$, $Ac^{226}$, $Ac^{225}$ and $Ac^{224}$ were recorded. The dependence of the cross sections for the production of these isotopes on the incident ion energies was measured and was found to rise gradually from $\sim 10^{-30}$ cm$^2$ near the Coulomb barrier to $\sim 10^{-27}$ cm$^2$ at 154 MeV. The angular distributions of the recoil nuclei of these isotopes were measured at 150 and 120 MeV. They are peaked near the Rutherford angle. The positions of the peaks for the various isotopes are different; the larger the number of transferred nucleons, the larger the angle corresponding to the maximum of the cross section. The observed dependences cannot be described by existing models of the mechanism of transfer reactions.

## 1. INTRODUCTION

SHORTLY after beams of accelerated heavy ions became available, it was found that not all reactions produced by such beams proceed with the production of compound nuclei. In England, [1] the U.S.S.R., [2] and the U.S.A. [3] mass numbers differing little from the mass numbers of targets or incident particles were found among the products of the bombardment of isotopes. Recently, a number of papers have been devoted to transfer reactions of one two, and also several nucleons in reactions with heavy ions. [4,5]

In order to explain reactions of incomplete fusion and "transfer" reactions a number of approaches have been developed, but their regions of applicability are not yet clear. Reactions in which one nucleon is transferred are described by the theory based on the tunnel effect. [6] In the first papers of Fremlin et al [7] the hypothesis was proposed according to which the particle breaks up in the field of the nucleus and the nucleus captures one of its particles (the so-called shrapnel effect); the intermediate compound nucleus thus produced can then evaporate nucleons, as a result of which products heavier than the target nucleus arise.

In order to explain the occurrence of products with masses close to the mass of the incident particles, Kaufmann and Wolfgang [8] proposed a "grazing collision model." These authors observed light radioactive products when rhodium was bombarded by $C^{12}$, $N^{14}$, $O^{16}$, and $F^{19}$ at an energy of 10 MeV/nucleon. They found that the angular distribution of the products has a very distinct maximum in the direction of the beam. The cross section rises monotonically with the energy. Wolfgang and Kaufmann [8] suggested that these products arise in grazing collisions in which the volumes of the particles and the nucleus somewhat overlap. Owing to friction, the substance in the overlapping region is excited, so that the nuclei are not fully fused. During the contact the nucleons can pass from the nucleus to the particle and vice versa. In the process of motion the centrifugal and Coulomb forces again break apart this system. In [8] the range vs energy distributions of nuclei emitted at a given angle (18°) display a large spread ($\sim$ 30 MeV). This clearly indicates that unbound nucleons or complexes of nucleons also arise in the reactions. [9]

An important premise of the grazing collision model is that the energy of the bombarding particle is high in comparison with the Coulomb barrier. However, the considerable yield of actinium isotopes in the bombardment of thorium by $Ne^{22}$ ions already observed close to the Coulomb barrier [10] does not correspond to the model described by Kaufmann and Wolfgang. [8]

In the present experiment we studied the reactions in which $Th^{227}$, $Ac^{226}$, $Ac^{225}$, and $Ac^{224}$ are produced in the bombardment of $Th^{232}$ by $Ne^{22}$ ions. Such reactions correspond to the stripping of several nucleons (5n, p5n, p6n, and p7n) from the target nucleus. The fact that use was made of a heavy target consisting of thorium and a heavy $Ne^{22}$ particle of energy considerably exceeding the Coulomb barrier gives support to the assumption that the obtained dependence reflects certain

| Radioactive family | $4n+3$ | $4n+2$ | $4n+1$ | | $4n$ | |
|---|---|---|---|---|---|---|
| Observed parent nucleus | $Th^{227}$ | $Ac^{226}$ | $Ac^{225}$ | $Ra^{225}$ | $Ac^{224}$ | $Ra^{224}$ |
| Periods determining the nucleus decay | 18d, 11d | 28 h | 10d | 14d, 10d | 3 h<br>3.6d | 3.6d |
| Energy of observed α line, MeV | 7.35 | 7.68 | 8.35 | 8.35 | 8.78 | 8.78 |
| Nucleons emitted from $Th^{232}$ | $5n$ | $p5n$ | $p6n$ | $2p5n$ | $p7n$ | $2p6n, 4n\alpha$ |
| Q-value estimate, MeV | −6 | +3 | +2 | +15 | −3 | +18 |
| Cross section σ at 143 MeV, $10^{-28}$ cm² | 10 | 6.6 | 5.5 | <1.5 | 5.3 | <2 |

general properties of the transfer reaction, since the production of unbound nucleons or their complexes is restricted energetically.

The method of recording α-radioactive products with an ionization chamber affords a high sensitivity.

The experiment was carried out with an internal beam of accelerated $Ne^{22}$ ions from the multiply-charged-ion cyclotron of the Joint Institute of Nuclear Research.

## 2. RECORDING METHOD

The isotopes $Th^{227}$, $Ac^{226}$, $Ac^{225}$, and $Ac^{224}$ produced in the $Th^{232} + Ne^{22}$ reaction are easy to record. They all give series of α and β-active daughter products which end in the α decay of one of the polonium isotopes with a high α-particle energy (see the table). By measuring the intensity of these lines with the aid of an ionization chamber, we can determine the number of nuclei of the initial parent isotope in a given sample. Since there are very few emitters with α-particle energies above 7 MeV, the isotopes in the table can be identified from the energy and half-life without the use of chemical methods. The targets were usually measured four or five times at different periods, so that the amount of each isotope was determined by at least two independent measurements. In the case of some thin targets all the remaining lines of these series were also identified. The $Th^{227}$ and $Ac^{226}$ nuclei were effectively screened. The isotope $Ac^{225}$ could be produced from $Th^{225}$, which, in 10% of the cases, experiences K-capture. The isotopes $Ac^{224}$ and $Ra^{224}$ could not be separated quantitatively.

The measurements were made with an ionization chamber which had two grids and was filled with argon with a small admixture of acetylene. The pulses were applied to an AI-100 100-channel analyzer through a preamplifier, amplifier, and expander. In the case of measurements of very active samples we used an electron collimation block based on the principle proposed by Facchini et al.[11] The chamber resolution (~ 25 keV with an effective 2π geometry) was not realized in full in these measurements, since the products of the reaction were "driven" deep into the collectors. The chamber was fitted with a valve for the introduction of the sample without the replacement of the gas in the working volume.

## 3. CROSS SECTIONS

To determine the dependence of the cross sections for the production of various isotopes of Th and Ac on the energy of the $Ne^{22}$ ions the latter was used to bombard a stack of $Th_2O_3$ targets (~ 100 μg/cm²) deposited on aluminum bases 5 μ thick and stacks of aluminum collectors of different thickness. The targets and collectors were counted in the ionization chamber. Here we could also determine the amount of deposited thorium from the α counts. Owing to the strong β activity of the collectors and targets, the first measurements were begun no earlier than ~ 15 h after the end of the bombardment, by which time the short-lived β emitters had already decayed. The results are shown in Figs. 1 and 2. The errors shown include the contributions from the complete separation of the α lines and the statistical errors. The relative quantities are, however, more accurate, since all spectra were analyzed in the same way. The uncertainty in the energy scale is less than ± 5 MeV. In the total cross section measure-

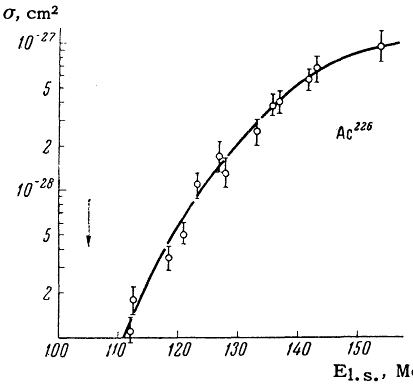


FIG. 1. Cross section for the production of $Ac^{226}$ in the bombardment of thorium by $Ne^{22}$ ions as a function of the bombarding-particle energy (in the laboratory system). The arrow indicates the Coulomb barrier energy.

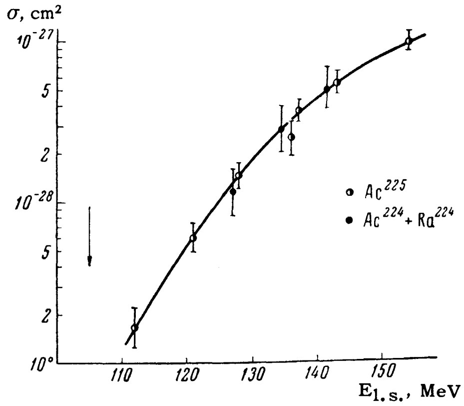


FIG. 2. Energy dependence of the $Ac^{225}$ and $Ac^{224}$ production cross sections.

ments the $Ac^{224}$ yield was determined with a considerable error, since the 8.78-MeV line is present in the spectrum of the thorium family.

Moreover, we were not able to separate $Ra^{224}$ from $Ac^{224}$, the latter decaying into $Ra^{224}$ with a half-life of 2.8 h, since the measurements were begun only ~ 15 h after the bombardment. However in the angular distribution measurements the collectors were not activated by the beam and the activity was therefore recorded immediately after the bombardment. Although we were not able to determine quantitatively the $Ra^{224}$ to $Ac^{224}$ ratio, owing to the length of the bombardment (3–5 h), we found that the amount of $Ac^{224}$ was at least 3 times as great as that of $Ra^{224}$. In the table the production cross sections at 143 MeV and estimates of the values of Q for the reaction (according to Cameron's tables) are given.

## 4. ANGULAR DISTRIBUTIONS

The angular distributions of the $Th^{227}$, $Ac^{226}$, $Ac^{225}$, and $Ac^{224}$ recoil nuclei in the 40–180° range were measured with the aid of a simple attachment to the probe for the measurement of the ion current of the internal beam of the cyclotron (see Fig. 3). A $Th_2O_3$ target 15 $\mu$g/cm$^2$ thick was deposited by electrophoresis [12] on a thick molybdenum base placed at an angle of 40° to the beam. The target was bombarded ~ 5 h by a current of ~ 15 $\mu$A. For a check of the ion current a small part of it passed by the target and reached the collector. Around the target was another collector consisting of an aluminum foil in the form of a semi-cylinder, so that the beam passed along the cylinder axis. After the irradiation the foil was cut along the lines $\theta$ = const and the individual strips were counted in the ionization chamber.

The angular distribution in the range from 0 to 70° was measured with the aid of a similar arrangement. A $Th_2O_3$ target 60 $\mu$g/cm$^2$ thick was placed on an aluminum foil (5 $\mu$) and was set perpendicular to the beam.

Curves for the backward (40–180°) and forward (0–70°) angles were matched in the overlapping region. This matching gave consistent results for all four distributions within the limits of experimental error. The angular distributions in the laboratory system for an ion energy of 150 MeV are shown in Fig. 4. The angular resolution was determined by the distance between the points. The finite dimensions of the target gave only a slight broadening of the angular resolution.

Figure 5a shows the c.m.s. differential cross sections $d\sigma/d\Omega$. The transformation from the l.s. to the c.m.s. was made under the assumption that in the reaction all the nucleons are transferred to the incident particle while the final products arise in the ground state. However the transformation is not very sensitive to these assumptions. Even if several unbound nucleons are produced in the reaction, the character of the curves does not change.

The width of the observed $\alpha$ lines, which is due to the depth to which the Th and Ac isotopes pen-

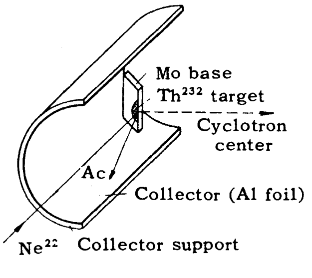


FIG. 3. Device for measurement of the angular distribution of recoil nuclei (in the angular range 180 to 40°).

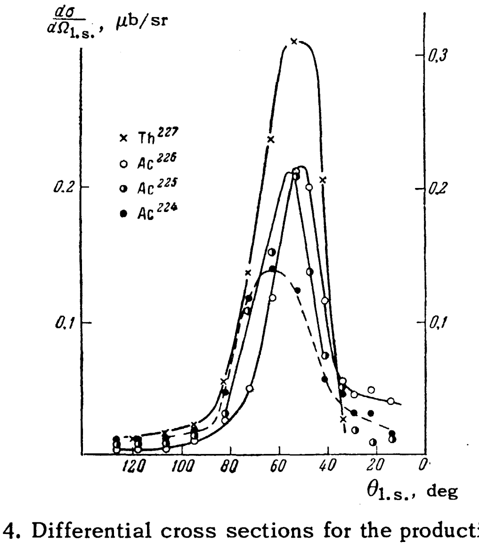


FIG. 4. Differential cross sections for the production of $Th^{227}$, $Ac^{226}$, $Ac^{225}$, and $Ac^{224}$ in the l.s. for the bombardment of $Th^{232}$ by 150-Mev $Ne^{22}$ ions ($\theta$ is the angle of emission of the recoil nucleus).

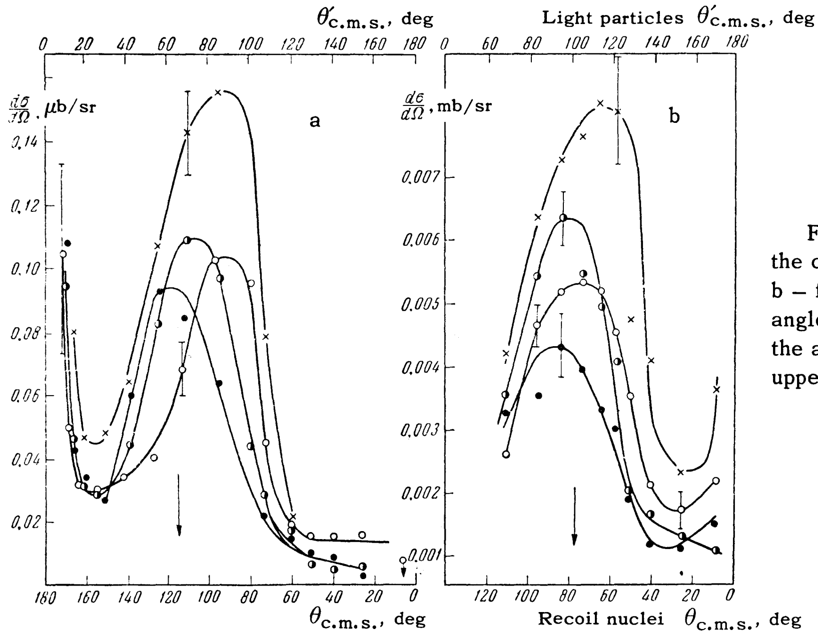


FIG. 5. The same cross sections as in Fig. 4, but in the c.m.s.: a – for bombardment by 150-MeV $Ne^{22}$ ions; b – for 120-MeV $Ne^{22}$ ions. The recoil nucleus emission angle is given on the lower scale of the abscissa axis; the angle of emission of light particles is given on the upper scale. The notation is the same as in Fig. 4.

etrate into the nucleus, decreases monotonically with increasing angle $\theta$, since the recoil energy decreases. Although the energy of the recoil nucleus emitted at an angle greater than 150° is very small (~ 300 keV), this segment of the curves can also be considered reliable in view of the fact that a very thin target was used. But since the partial cross section for $\theta \geq 150°$ is ~ 5% of the total cross section, the statistical errors in this range are quite large. All experiments were repeated with the same results. In particular, the displacement of the peaks for the individual isotopes was confirmed.

Figure 5b shows the same differential cross sections $d\sigma/d\Omega$ for the bombardment of a thorium foil 1.0 $mg/cm^2$ thick by 120-MeV $Ne^{22}$ ions. The measurements were not made to obtain the backward angles, since it was found that most of the recoil nuclei are emitted from the target.

## 5. DISCUSSION OF RESULTS

As is seen from the figures, the maxima in the angular distributions are to the right of the Rutherford angle [angle of deflection of an elastically scattered particle with the smallest collision parameter $r_0(A_1^{1/3} + A_2^{1/3})$, where $r_0 = 1.35$ F] and are shifted with it when the ion energy is changed. This indicates that the particles move primarily in Coulomb orbits and the nuclear interaction deflects them very little from their initial direction. This only confirms the fact that the reaction proceeds on the nuclear surface. At the same time, the shift in the position of the maxima for the individual isotopes signifies that a nuclear interaction occurs and that it is different for different numbers of transferred nucleons, where the larger the number of transferred nucleons, the more effective the nuclear interaction.

It should be stressed that the obtained dependence cannot be explained by existing models for the mechanism of the transfer reactions. It is quite impossible to describe the transfer of eight nucleons by a model based on the tunnel effect, although the behavior of the excitation functions and the differential cross sections is similar to that in the case of a one-nucleon transfer. But the "grazing collision model" can hardly describe the observed phenomenon, since its basic assumption—a high energy in comparison with the Coulomb barrier—is not fulfilled. Even close to the barrier, where the nuclei approach each other at a negligible velocity, the reaction in which a large number of nucleons is transferred proceeds with an appreciable cross section. Of course, a compound nucleus is not always produced in central collisions, as has been believed till now.

In the fusion of two nuclei the greater part of the excitation energy is in the form of a deformation energy and rotational energy. It is possible that the transition of the energy of these collective degrees of freedom into the energy of the statistical motion of the nucleons in the compound nucleus is somewhat inhibited and the system can split apart. The fact that the neutrons are transferred with a greater probability than protons (see table) can signify that it is primarily the neutron external shells which overlap.

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