CROSS SECTION FOR PRODUCTION OF Cm^{240} *BY IRRADIATION OF* Th^{232} *WITH* C^{12} *AND* C^{13} *IONS*

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The dependence of the cross sections for the reactions $Th^{232}(C^{12}, 4n)Cm^{240}$ and $Th^{232}(C^{13}, 5n)Cm^{240}$ on the energy of the bombarding particles was determined by the irradiation of a stack of thin foils followed by radiochemical analysis of the reaction products. The curves of the reaction cross sections exhibit the pronounced peaks that characterize the evaporation of neutrons from an excited compound nucleus. The peak cross sections for the two reactions are 8×10^{-29} cm^2 and 18×10^{-29} cm^2, respectively. It is evident from a comparison with the cross sections for other nuclear reactions that cross sections for neutron evaporation do not depend on Z^2/A in a simple manner.

THE present paper presents results obtained from the investigation of nuclear reactions induced through the irradiation of thorium with accelerated carbon ions. These experiments comprise part of a broader program for the study of the laws of the nuclear reactions that occur when heavy nuclei are bombarded with multiply-charged ions. Specifically, these studies are intended to determine how the cross sections for the formation of different reaction products depend on the atomic number and mass of both the irradiated element and the bombarding particle.

EXPERIMENTAL PROCEDURE

The cross sections for the reactions $Th^{232}(C^{12}, 4n)Cm^{240}$ and $Th^{232}(C^{13}, 5n)Cm^{240}$ were determined as a function of incident-particle energy. We irradiated a stack of thin foils, which were then subjected to radiochemical analysis of the reaction products.

The Th^{232} metal foils, which were rolled to a thickness of $3 - 4$ mg/cm^2, were bombarded at the terminal radius of the 150-cm cyclotron of the U.S.S.R. Academy of Sciences by monoenergetic beams of $^{+4}C^{12}$ and $^{+4}C^{13}$ ions accelerated to 80 and 82 Mev, respectively. After passing through the target the ions entered a collector which was electrically connected to a current integrator. In order to avoid possible overheating and destruction of the target the ion current was limited to a maximum level of $0.2\,\mu$a. The integrated current in all experiments was $0.7 - 1.0\,\mu$a per hour.

A curium fraction was extracted chromatographically from each irradiated foil and was then analyzed by means of an ionization chamber and a 50-channel pulse-height analyzer. Cm^{240} was identified by the energy of the emitted α particles (6.25 Mev) and its half-life (26.8 days). Since the products of Th^{232} decay include Rn^{220} and Bi^{212}, which emit α particles whose energies (6.28 and 6.05 Mev) are close to the energy of α particles from Cm^{240}, the chemical separation of the curium from the thorium had to be accompanied by a sufficiently complete separation from the decay products that could produce an undesirable background. A special technique was developed to separate and purify curium from bombarded thorium. The curium was separated chromatographically from thorium and its decay products. Each bombarded thorium foil was dissolved in concentrated (10.7 N) hydrochloric acid to which a specific amount of Am^{241} had been added, from which the chemical yield of Cm^{240} could be determined. The solution was boiled down to $3 - 5$ drops which were adsorbed in a chromatograph column containing a Dowex-50 cation-exchange resin brought into equilibrium with the concentrated hydrochloric acid. The columns used were 90 mm high and $2 - 3$ mm in diameter. The columns were subsequently washed with concentrated hydrochloric acid, separate fractions of which were collected on platinum plates and analyzed by means of an ionization chamber. The elution curve is shown in Fig. 1.

Measurements of the half-life (~ 10 hours) and energies (6.05 and 8.8 Mev) of the α particles show that the activity eluted with drops Nos. 10 to 40 belongs to products of the thorium series, Bi^{212} and Po^{212}, which are related genetically to Pb^{212}. Curium was eluted with drops Nos. 20 to 100. Thorium and some of its decay products begin to be eluted with the 80th drop. For measurements in

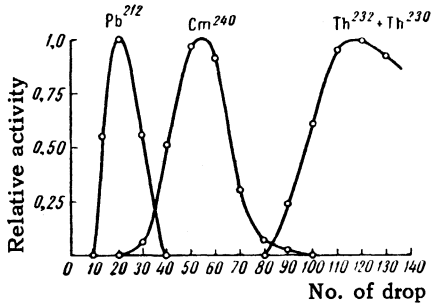

FIG. 1. Chromatographic elution curve.

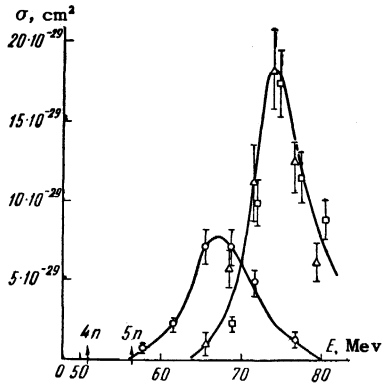

FIG. 2. Reaction cross sections as a function of carbon ion energy. Reaction thresholds are indicated by arrows. o – $Th^{232}(C^{12}, 4n)Cm^{240}$; Δ, □ – $Th^{232}(C^{13}, 5n)Cm^{240}$ (two seperate experiments).

the ionization chamber we selected the fraction in drops Nos. 20 to 80, which contained more than 80% of the curium. The α activity of the Bi^{212} and Po^{212} partially contained in this fraction dropped practically to zero in a few days and did not interfere with measurements of the Cm^{240} content. Purity of the separation of Cm^{240} from thorium was controlled by the content of the thorium-related products Po^{216} and Po^{212}, which emit 6.8- and 8.8-Mev α particles. The counts of 6.8- and 8.8-Mev α particles and consequently also of undesired α particles from Rn^{220} and Bi^{212} did not as a rule exceed 0.2 pulses per minute. This represented ~ 0.001 of the initial amount of thorium and its decay products in the curium fraction. At the peak of the reaction cross section the initial α particle count in the energy range 6.2 – 6.3 Mev was 4 or 5 pulses per minute. The intensity of Cm^{240} α emission was thus 20 – 25 times as great as the background of Rn^{220} α particles. The reaction product Cm^{240} could thus be reliably identified over a broad range of cross-section variation. It was not possible in these experiments to determine the cross sections for the reactions $Th^{232}(C^{12}, 2n)Cm^{242}$ and $Th^{232}(C^{13}, 3n)Cm^{242}$ from the yield of 162-day Cm^{242}, which emits 6.10-Mev α particles. The count of 6.10-Mev α particles in the curium fraction did not appreciably exceed the background of Bi^{212} α particles.

EXPERIMENTAL RESULTS AND DISCUSSION

The cross sections for $Th^{232}(C^{12}, 4n)Cm^{240}$ and $Th^{232}(C^{13}, 5n)Cm^{240}$ as a function of bombarding energy are shown in Fig. 2. The initial carbon-ion energy and the monoenergetic definition of the beam were determined with the aid of an aluminum absorber. The differential distribution curves of C^{12} and C^{13} ion ranges in aluminum are symmetrical Gaussian curves with ~ 3% rms deviation from the mean range. The small spread of carbon-ion ranges indicates sufficient energy homogeneity of the beam, especially if we consider the possible instrumental effects, such as nonuniform aluminum absorber thickness, which would increase the natural range fluctuations. An experimental range-energy curve[1] was used to determine the initial C^{12} ion energy. The initial C^{13} ion energy and the energy variation during passage through the thorium foils were determined from calculations of the C^{13} range in aluminum and the stopping power of thorium.

The indicated experimental errors take into account the statistical errors of Cm^{240} α particle counts and the possible errors in determining the chemical yield of curium, the thickness of the irradiated thorium foils and the integral of ingoing current.

The cross section curves in Fig. 2 exhibit the pronounced peaks that characterize neutron evaporation from excited compound nuclei. The $Th^{232}(C^{12}, 4n)Cm^{240}$ maximum is found at 67 Mev and that of $Th^{232}(C^{13}, 5n)Cm^{240}$ at 74 Mev, with half-widths of 9 and 8 Mev, respectively. The $Th^{232}(C^{13}, 5n)Cm^{240}$ peak is 2.3 times higher than that of $Th^{232}(C^{12}, 4n)Cm^{240}$, as a result of increased cross section for the formation of a compound nucleus when the ion energy rises from 67 to 74 Mev. This effect outweighs the reduction in the yield of the final product for the case of the 5n reaction as a result of the fact that the emission of an additional neutron again involves the competition between nuclear fission and neutron evaporation.

It is interesting to compare the peak cross sections for the evaporation of five neutrons from different nuclides bombarded with heavy particles. In this way an approximate picture is obtained of the way in which the ratio between the neutron-evaporation and fission probabilities varies as a function of Z and A for the compound and intermediate nuclei. Although the cross section for neutron evaporation depends on the cross section for compound-nucleus formation, this factor is unimportant when the cross sections for the evaporation of five neutrons are compared. At the maximum of the 5n-reaction cross section (~ 65 – 70 Mev) the cross section for compound-nucleus

formation has reached a very appreciable fraction of its possible maximum and is approximately independent of the ions used as projectiles.

We present a table of the peak cross sections for the evaporation of five neutrons from gold, thorium and uranium irradiated with carbon and nitrogen ions:

Reaction	σ_{max}, cm²	Reaction	σ_{max}, cm²
$Au^{197}(N^{14}, 5n)\,Ru^{206}$	$2.75\cdot10^{-25}$ [2]	$U^{238}(C^{13}, 5n)\,Cf^{246}$	$1.25\cdot10^{-28}$ [3]
$Th^{232}(C^{13}, 5n)\,Cm^{240}$	$1.80\cdot10^{-28}$	$U^{238}(C^{12}, 5n)\,Cf^{245}$	$9.0\cdot10^{-29}$ [3]

The same data are shown in Fig. 3 as a function of Z^2/A for the compound nucleus. The ratio of the cross sections of gold and thorium is seen to be considerably larger than in the case of thorium compared with uranium. A similar comparison reported by Flerov at the Second International Conference on the Peaceful Uses of Atomic Energy[4] indicated that the neutron-evaporation cross sections decrease monotonically by a factor of about 15 for each unit increase in the value of Z^2/A for the compound nucleus. However, this law was based on data for the evaporation of four neutrons, which is less closely related than the 5n reaction to the competition between neutron evaporation and fission.

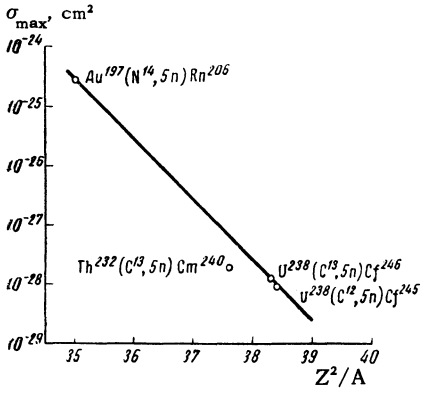

FIG. 3. Cross section for the evaporation of five neutrons as a function of Z^2/A for the compound nucleus.

The comparison of neutron-evaporation cross sections with values of Z^2/A for the compound nucleus[4] was the first attempt to discover a law governing the competition between neutron evaporation and fission in heavy nuclei. It was thus found basically that the cross section decreases as Z increases. The new data obtained from the study of five-neutron evaporation have revealed a more complicated dependence on Z and A than a simple exponential reduction of the cross section as Z^2/A increases.

The competition between neutron evaporation and fission as a function of nuclear parameters can be investigated in greater detail by comparing the values of Γ_n/Γ_f (the ratio of neutron-emission probability to the fission probability of the compound nucleus) for different nuclides. This has been done by Tarantin,[5] using the results presented here and an investigation of certain other nuclear reactions induced by heavy ions.

In conclusion the authors wish to thank Professor G. N. Flerov for directing this investigation, and Professor N. N. Tunitskiĭ and M. V. Tikhomirov for preparing highly enriched C^{13}.

[1] Yu. Ts. Oganesyan, JETP **36**, 936 (1959), Soviet Phys. JETP **9**, 661 (1959).

[2] Gerlit, Karamyan and Myasoedov, Ядерные реакции при малых и средних энергиях (Symp. Nuclear Reactions at Low and Medium Energies), U.S.S.R. Acad. Sci., Moscow, 1958, p. 503.

[3] Volkov, Guseva, Pasyuk, Tarantin, and Filippova, JETP **36**, 762 (1959), Soviet Phys. JETP **9**, 536 (1959).

[4] G. N. Flerov, Second International Conference on the Peaceful Uses of Atomic Energy, Report No. 2299, Geneva, 1958.

[5] N. I. Tarantin, JETP, in press.

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