YIELD OF CALIFORNIUM ISOTOPES PRODUCED IN REACTIONS BETWEEN CARBON IONS AND URANIUM NUCLEI

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The yield of the californium isotopes Cf^{264}, Cf^{245} and Cf^{244} produced in the reaction between 90 Mev carbon ions and a thick uranium target was investigated. The absolute californium yield per incident particle is 1.5×10^{-9} Cf^{246} nuclei, 3.0×10^{-9} Cf^{245} nuclei and 9×10^{-11} Cf^{244} nuclei. Comparison of the obtained results with the cross-section for fission of uranium by carbon ions indicates that fission is 3.8×10^3 times more probable in this case than neutron evaporation from the compound Cf^{250} nucleus.

In the production of transuranic elements by the reaction of multiply charged ions with active elements there is natural interest in data on the yield of nuclei resulting from the complete absorption of the incoming particle by the target nucleus followed by emission of several neutrons. The first experiments on such reactions were carried by Ghiorso et al.[1] in work on the production of californium in irradiations of uranium with carbon ions. More detailed investigations of the reactions of carbon ions with uranium were carried out by Fremlin et al.[2] In both cases carbon ions having a large spread in energy were used. It appeared interesting to investigate such reactions using projectiles having a more narrowly defined spectrum of energies.

In the present work there were determined the yields of isotopes of californium produced in the bombardment of uranium by monoergic carbon ions. The cyclotron accelerated quadruply charged carbon ions, which started at a slit-type source, and had an energy of 90 Mev at a radius of 67 cm. The maximum ion current at this radius was ~ 1μa. The target consisted of metallic uranium sheets having dimensions of 15×7 mm^2 and a thickness of 30μ; they were clamped on a water cooled probe. To avoid possible destruction of the target, carbon-ion currents of ~ 0.1μa were used. The beam current measurement was made by recording the ions passing through the target and impinging on a collector, using a conventional electrometric setup.

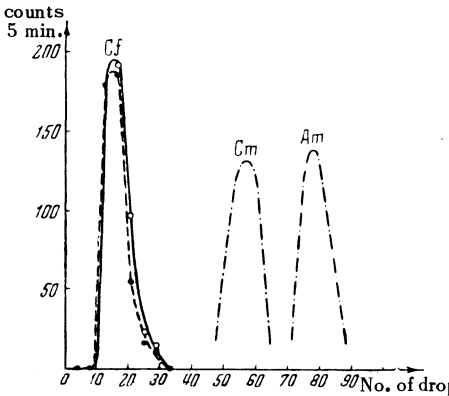

FIG. 1. Elution curves from the chromatographis separation. Solid dots (dashed curve) — Cf^{246}, open points (solid curve) — Cf^{245}.

In calculating the impinging beam current, account was taken of the fact that quadruply charged carbon ions change their effective charge to approximately six elementary charges in passing through a 30μ thick target foil. The irradiation time in different experiments was between 0.5 and 2.5 hours.

The bombarded foil was dissolved in concentrated nitric acid and the actinide fraction was separated from the uranium matrix by precipitation with lanthanum fluoride. The separation of the actinides was carried out on a cation column containing Dowex-50 X-12 at a temperature of 87°C. The complexing solution used consisted of a 0.4 M solution of α-hydroxyisobutyric acid at a pH = 4.1. The chromatographic elution curve of the actinides is presented in Fig. 1. This figure also shows the positions of the maxima of Am and Cm obtained under identical conditions.

The measurement of the energies of the α-particles and the half-lives of the α-active isotopes were carried out using an ionization chamber with a spherical electrode and a 20 channel pulse analyzer.

In the californium fraction there were identified, by means of the energies of the α-particles and the half-lives, the following isotopes of californium: Cf^{246} and Cf^{245}.[3,4] Figure 2 shows the α-particle spec-

trum of the californium fraction at different times. The decay curves of the Cf^{246} and Cf^{245} are presented in Figs. 3 and 4.

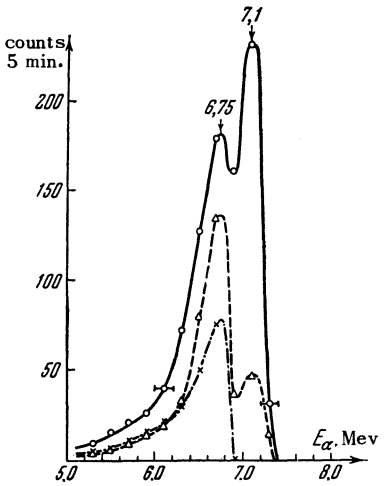

FIG. 2. Spectrum of α-particles in the californium fraction at various times. (Solid curve) — 1 hr. 33 min. after the end of bombardment; (dashed curve) — 3 hrs. 23 min. after the end of bombardment; (dot-dashed curve) — 24 hrs. 49 min. after the end of bombardment.

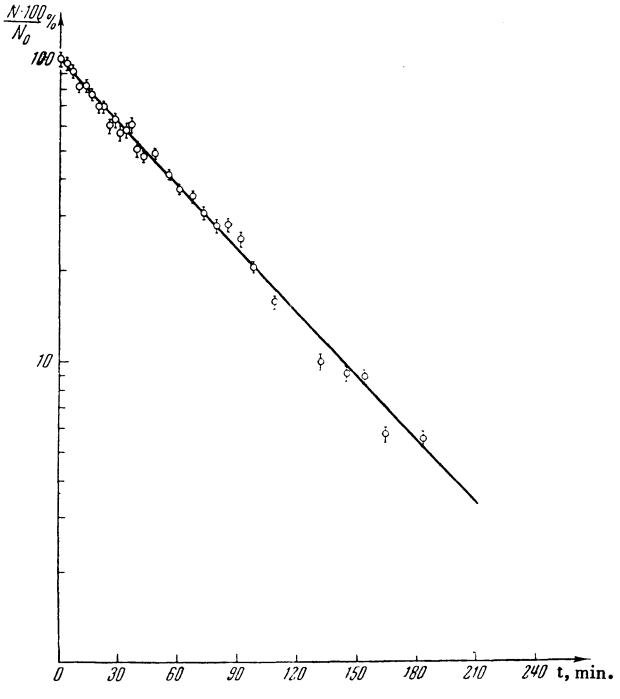

FIG. 4. Decay curve of Cf^{245}. $T_{1/2}$ = 44 min.

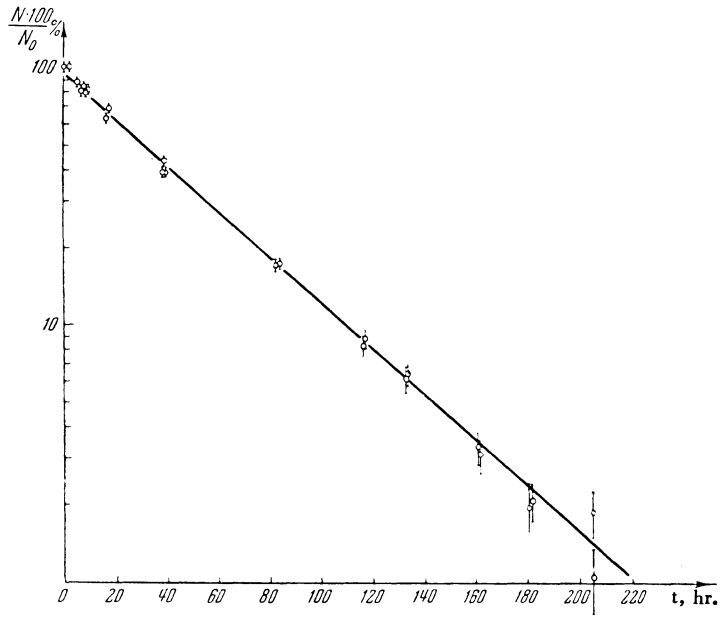

FIG. 3. Decay curve of Cf^{246}. $T_{1/2}$ = 35 hrs.

The 25-min Cf^{244} was not determined in these experiments. One bombardment, in which the α activity of the irradiated metallic uranium was measured directly 5 min after the end of the irradiation, failed likewise to give positive results. An evaluation of the yield of Cf^{244} from the content in the curium fraction of its daughter Cm^{240} formed before the separation of the actinides was not unique since the isotope Cm^{240} can be produced directly by the reaction U(C, α6n).

The results obtained give the yield of α active nuclei of the various isotopes of californium formed in the bombardment of a thick uranium target by 90 Mev carbon ions according to reactions of the type U(C, xn) Cf. The relative yields of these α-active nuclei are presented below. The yield of the α-active isotope Cf^{245} is taken as unity. An upper limit is given for the yield of the isotope Cf^{244}.

Isotope	Cf^{246}	Cf^{245}	Cf^{244}
Production reaction	(C, 4 n)	(C, 5n)	(C, 6n)
Yield of α-active nuclei	1.65 ± 0.15	1.00	$\leqslant 0.1$

The absolute yields of these californium isotopes per incident particle are, 1.5×10^{-9} for Cf^{246}, $\sim 3.0 \times 10^{-9}$ for Cf^{245} and $\leq 9 \times 10^{-11}$ for Cf^{244}. The total yield of these isotopes is equal to $\sim 4.5 \times 10^{-9}$ nuclei per incident carbon particle. In the calcula-

tions of the absolute yield of the californium isotopes account was taken of the fact that the fraction of the nuclei decaying by α emission is 100% for Cf^{246} and Cf^{244} (3)(5) and ~ 30% for Cf^{245}. (5) The yield of californium through all chemical operations and chromatographic separations was taken as 50% on the basis of data on the yields of Am and Cm in identical experiments. The number of californium atoms separated in each experiment was ~ 3×10^5 of Cf^{246} and ~ 1×10^5 of Cf^{245}.

Since the yield of californium isotopes is determined by the probability of formation of the compound nucleus Cf^{250} and subsequent competition between neutron emission and fission, it appeared interesting to compare the probabilities of these two last processes. In order to evaluate the probability of fission of californium nuclei there were utilized unpublished data on the dependence of the fission cross-section of uranium, σ_f, by carbon ions as a function of the energy of the particles. These data were obtained by V. A. Druinyi, S. M. Polikanov, and G. N. Flerov:

E_C, (Mev)	90	80	75
σ_f, (cm^2)	~ 6×10^{-25}	~ 2×11^{-25}	~ 1×10^{-25}

From these numbers and use of the range energy relation for carbon ions in uranium it was established that every carbon particle of 90 Mev produces 1.7×10^{-5} fissions in passing through a thick target of uranium. Comparison of this figure with the yield of califorium nuclei leads to the conclusion that the fission processes in 3.8×10^3 times more probable than the process of neutron evaporation from the compound nucleus in the bombardment of a thick uranium target by 90 Mev carbon ions. This value for the ratio of probabilities of fission to those of californium isotope production is significantly different from the value (~ 10^5) obtained in published work.[5]

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[2] Fremlin, Golover, and Milsted, J. Ingor. and Nucl. Chem. **2**, 263 (1956).
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