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RADIATION PROPERTIES OF ^{244}Cm PRODUCED FOR ISOTOPIC POWER GENERATORS

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Savannah River Laboratory

Aiken, South Carolina

Printed in USA. Price $2.00
Available from the Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U. S. Department of Commerce, Springfield, Virginia

664271

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Isotopes — Industrial Technology
(TID-4500, 35th Ed.)

RADIATION PROPERTIES OF ^{244}Cm PRODUCED FOR ISOTOPIC POWER GENERATORS

Compiled by

D. H. Stoddard

Contributing Authors

T. R. Herold
H. P. Holcomb
R. C. Milham
R. F. Overman
C. S. Schlea
D. H. Stoddard

Approved by

C. H. Ice, Director
Separations Chemistry and Engineering Section

November 1964

E. I. DU PONT DE NEMOURS & COMPANY
SAVANNAH RIVER LABORATORY
AIKEN, SOUTH CAROLINA

CONTRACT AT(07-2)-1 WITH THE UNITED STATES ATOMIC ENERGY COMMISSION

ABSTRACT

The radiation properties of curium (~95 wt % ^{244}Cm) that would be produced in a large-scale program at the Savannah River Plant are similar to the properties reported in the literature for pure ^{244}Cm. The alpha, gamma, and neutron radiations associated with the ^{244}Cm product are presented for evaluation by users of ^{244}Cm as a heat source in isotopic power generators.

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INTRODUCTION

Curium-244 is a promising heat source for isotopic power generators. This isotope can be produced in large quantities at reasonable cost, and without excessively long lead times. A pilot production program for ^{244}Cm is underway at the Savannah River Plant.(1) The program not only pilots the large-scale production of curium, but will also provide three kilograms of ^{244}Cm for the development and demonstration of power generators fueled with this isotope.

This report presents the radiation properties of ^{244}Cm that would be produced in a large-scale program at the Savannah River Plant. The information is intended for evaluation by users of ^{244}Cm as a heat source in isotopic power generators. These radiation properties are based on:

- Measured radiation properties of a purified sample of ~95 wt % ^{244}Cm produced in a Savannah River reactor.
- Expected purification of the curium product in the chemical separations process being developed.
- Reported radiation properties of the nuclides in the curium product.

SUMMARY

When ^{244}Cm is produced by irradiating plutonium in a nuclear reactor, a mixture of curium isotopes is obtained. The radiation properties of the curium (~95 wt % ^{244}Cm) that would be produced in a large-scale program are similar to the properties reported in the literature for pure ^{244}Cm. The effective alpha half-life of the mixture will be practically the same as that of ^{244}Cm, since only 0.02 wt % of ^{242}Cm will be present in the ^{244}Cm product. The significant amounts of gamma radiation and neutrons associated with the ^{244}Cm product are not greatly different from those for pure ^{244}Cm because the isotopic composition of the product is favorable and also

because the chemical separations process can remove sufficient quantities of objectionable impurities such as ^{252}Cf.

The radiations from ^{244}Cm produced in a large-scale program include radiations from:

- Individual curium isotopes.
- Products of the spontaneous fission of curium isotopes.
- Radioactive contaminants that are not removed in chemical processing.
- Neutrons from α,n reactions with oxygen.

The total alpha, gamma, and neutron radiations are summarized in the following table.

Activity of ^{244}Cm Product

Alpha Activity: 2.88×10^{12} disintegrations/(sec)(gram)

Gamma Activity		Neutron Activity	
Energy, Mev	Abundance, photons/(sec)(gram)	Energy, Mev	Abundance, neutrons/(sec)(gram)
0 - 0.5	8.1×10^{8}	0 - 0.5	1.4×10^{6}
0.5 - 1.0	5.3×10^{7}	0.5 - 1.0	1.8×10^{6}
1.0 - 2.0	1.3×10^{7}	1.0 - 2.0	3.7×10^{6}
2.0 - 3.0	4.3×10^{6}	2.0 - 3.0	2.4×10^{6}
3.0 - 4.0	5.0×10^{5}	3.0 - 4.0	1.4×10^{6}
4.0 - 5.0	1.7×10^{5}	4.0 - 5.0	7.8×10^{5}
5.0 - 6.0	8.9×10^{4}	5.0 - 6.0	2.6×10^{5}
6.0 - 7.0	1.5×10^{4}	6.0 - 7.0	2.0×10^{5}
		7.0 - 8.0	6.1×10^{4}
		8.0 - 10	4.9×10^{4}
		10 - 13	1.0×10^{4}

DISCUSSION

GENERAL NUCLEAR PROPERTIES OF CURIUM ISOTOPES

The general nuclear properties of curium isotopes are presented in Table I.

TABLE I

General Nuclear Properties of Curium Isotopes

Isotope	Spontaneous Fission Half-Life	Neutrons per Fission of Pure Isotope	Alpha Decay Half-Life	Specific Activity of Pure Isotope, curies/gram	Specific Power of Pure Isotope, watts/gram
^{242}Cm	7.2×10^6 y[2]	2.61 ±0.09[4]	162.5 ±0.3 d[2]	3,320	120
^{243}Cm	-	-	35 y[2]	42	1.44
^{244}Cm	1.346 ±0.006 $\times 10^7$ y[3]	2.8 ±0.09[4]	18.1 y[3]	81	2.78
^{245}Cm	-	-	1.43 ±0.29 $\times 10^4$ y[2]	1.025×10^{-1}	5.8×10^{-3}
^{246}Cm	1.2×10^7 y[2]	3.0[5]	4.0 ±0.6 $\times 10^3$ y[2]	3.65×10^{-1}	7×10^{-3}
^{247}Cm	-	-	$>9 \times 10^7$ y[2]	1.62×10^{-5}	4.6×10^{-6}
^{248}Cm	4.6 ±0.5 $\times 10^6$ y[2]	3.4[5]	4.7 ±0.4 $\times 10^5$ y[2]	3.08×10^{-3}	1.03×10^{-4}

CURIUM PRODUCED IN TRANSPLUTONIUM PROGRAM

Several hundred grams of ^{244}Cm have been produced at Savannah River for the Atomic Energy Commission's Transplutonium Program. A sample of this material was purified from fission products and other actinides by solvent extraction, double carbonate precipitation, and ion exchange. The resulting curium was of very high purity as indicated by the concentrations of impurities in Table II and the isotopic content in Table III.

TABLE II

Spectrographic Analysis of Purified Curium from Transplutonium Program

Element	Concentration, ppm	Element	Concentration, ppm	Element	Concentration, ppm
Ca	60	Sn	<10	Sb	<5
Zn	50	Mg	5	Si	3
Ce	<50	Cs	<5	Bi	<3
La	<25	Cr	<5	Ti	<3
P	<25	Fe	<5	Li	<1
Zr	<25	Mo	<5	Mn	<1
Al	10	Nb	<5	Ag	<0.5
Na	10	Ni	<5	B	<0.5
Ba	<10	Pb	<5	Be	<0.01

TABLE III

Composition of Curium Products

Nuclide	Purified ^{244}Cm from Transplutonium Program Mass Abundance, wt %	^{244}Cm Product from Large-Scale Program[a] Mass Abundance, wt %
^{242}Cm	0.12 ±0.006	0.02
^{243}Cm	0.03 ±0.002	0.002
^{244}Cm	95.5	95.3
^{245}Cm	1.6 ±0.05	0.9
^{246}Cm	2.7 ±0.01	2.7
^{247}Cm	0.04 ±0.01	0.07
^{248}Cm	0.04 ±0.01	0.05
^{243}Am	0.0009	0.5
^{252}Cf	$<1 \times 10^{-8}$	$<4 \times 10^{-5}$

(a) One year after reactor irradiation, 97% of the ^{244}Cm product will be of this composition; 3% of the product will contain higher concentrations of ^{242}Cm and ^{243}Cm.

^{244}Cm PRODUCT OF LARGE-SCALE PRODUCTION PROGRAM

From the measured composition of the purified curium from the Transplutonium Program, the isotopic composition was calculated for curium produced in the irradiation scheme for a large-scale ^{244}Cm program. This calculated composition is listed in Table III.

The product of the large-scale program will be referred to as the "^{244}Cm product" in the remainder of this report.

ALPHA ACTIVITY OF THE ^{244}Cm PRODUCT

Alpha radiation is the major source of energy released by curium isotopes. The relative abundance and energies of the alpha particles emitted from the principal alpha-emitting curium isotopes are given in Table IV.

The alpha spectrum of purified curium from the Transplutonium Program is shown in Figure 1. The spectrum shows

TABLE IV

Alpha Radiations of Curium Isotopes

Isotope	Energy, Mev	Alpha Particles per Disintegration of Isotope[2]	Energy/Disintegration Per Energy Interval, Mev	Energy/Disintegration Total, Mev
^{242}Cm	6.110	0.737	4.5	
	6.066	0.263	1.6	
	5.965	3.5×10^{-4}	2.1×10^{-3}	
	5.811	6×10^{-5}	3×10^{-4}	
	5.605	3×10^{-7}	2×10^{-6}	
	5.515	1×10^{-6}	6×10^{-6}	
	5.200	3×10^{-7}	2×10^{-6}	
	5.120	4×10^{-8}	2×10^{-7}	
				6.1
^{243}Cm	6.061	1×10^{-2}	6×10^{-2}	
	6.054	5×10^{-2}	3×10^{-1}	
	6.005	9×10^{-3}	5×10^{-2}	
	5.987	6×10^{-2}	3×10^{-1}	
	5.900	1×10^{-3}	6×10^{-3}	
	5.872	5×10^{-3}	3×10^{-2}	
	5.780	0.73	4.2	
	5.736	0.115	0.66	
	5.680	1.6×10^{-2}	0.09	
				5.7
^{244}Cm	5.798	0.767	4.44	
	5.756	0.233	1.34	
	5.658	1.6×10^{-4}	9×10^{-4}	
	5.511	4×10^{-5}	2×10^{-4}	
				5.78

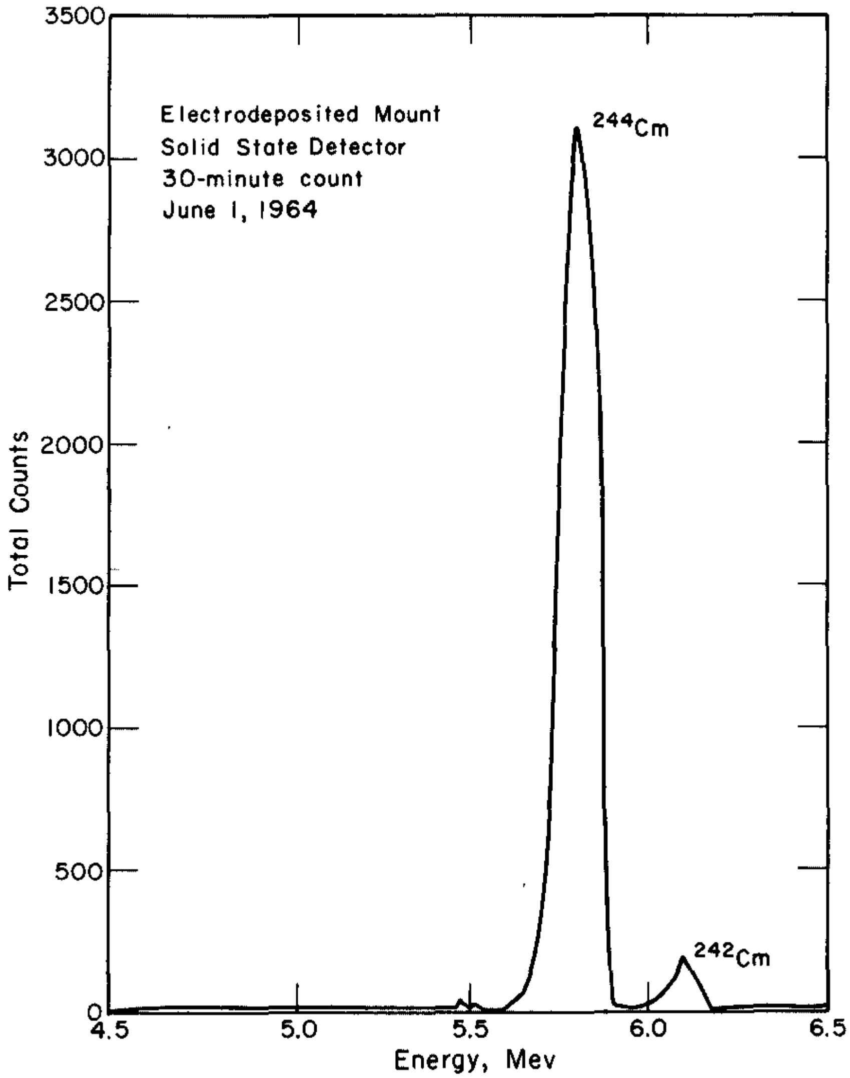

FIG. 1 ALPHA SPECTRUM OF PURIFIED CURIUM FROM TRANSPLUTONIUM PROGRAM

only the peaks from ^{242}Cm and ^{244}Cm and agrees with the spectrum calculated from the known isotopic content:

Isotope	Alpha Activity of Purified Cm from Transplutonium Program, % of total — From Measured Spectrum	Calculated from Isotopic Content
^{242}Cm	5	4.9
^{244}Cm	95	95.1

From the calculated isotopic content of the ^{244}Cm product, greater than 99% of the total alpha activity of the product will be from ^{244}Cm; therefore, the over-all alpha decay rate of the ^{244}Cm product will be practically the same as that of pure ^{244}Cm.

GAMMA ACTIVITY OF THE ^{244}Cm PRODUCT

The gamma activity of the ^{244}Cm product will consist of gamma rays from:

- Decay of curium isotopes and actinide impurities.
- Prompt spontaneous fission of curium isotopes and actinide impurities.
- Fission products continuously produced by the fission of curium isotopes and actinide impurities.
- Radioactive impurities (primarily fission products) that are not removed in the chemical separations process.

Gamma radiations from each of these sources are described in the following sections.

Gamma Rays from Decay of Actinides

Gamma rays reported for the decay of actinides in the ^{244}Cm product are listed in Table V.

From the mass abundances listed in Table III, only two groups of these gamma rays above 0.2 Mev contribute significantly to the total gamma spectrum of the purified curium

TABLE V

Gamma Rays from Decay of Actinides

Nuclide	Gamma Rays Energy, Mev	Gamma Rays Abundance, photons/(sec)(g of nuclide)
^{242}Cm (6)	0.044	4.8×10^{10}
	0.101	4.3×10^{9}
	0.157	2.8×10^{9}
	0.210	2.5×10^{7}
	0.562	2.2×10^{8}
	0.605	1.7×10^{8}
	0.890	1.1×10^{7}
	0.935	Negligible
	1.010	1.2×10^{7}
^{243}Cm (7)	0.106	Negligible
	0.2100	9.3×10^{10}
	0.2280	1.1×10^{11}
	0.2775	2.7×10^{11}
^{244}Cm (6)	0.043	6.3×10^{8}
	0.100	4.5×10^{7}
	0.150	3.9×10^{7}
	0.262	3.5×10^{6}
	0.570 } (9) 0.610 }	4.2×10^{6}
	0.825 (9)	2.0×10^{6}
^{252}Cf (6)	0.043	2.78×10^{9}
	0.100	2.0×10^{9}
^{243}Am-^{239}Np (8) (a)	0.074	5.9×10^{8}
	0.0447	4.1×10^{6}
	0.0494	9.5×10^{6}
	0.0572	7.5×10^{6}
	0.0615	4.0×10^{8}
	0.0678	1.1×10^{7}
	0.1062	2.14×10^{9}
	0.1818	3.4×10^{7}
	0.2099	2.5×10^{8}
	0.2265	1.1×10^{8}
	0.2284	5.4×10^{8}
	0.2546	1.5×10^{8}
	0.2731	5.4×10^{7}
	0.2778	9.0×10^{8}
	0.2856	8.2×10^{7}
	0.3161	2.7×10^{7}
	0.3346	1.4×10^{8}

(a) Daughter in equilibrium with parent. The 0.074-Mev gamma ray is from alpha decay of ^{243}Cm; the others are from beta decay of ^{239}Np.

from the Transplutonium Program. These are the 0.210-0.278 Mev gamma rays from ^{243}Cm and the 0.570-0.825 Mev gamma rays from ^{244}Cm. From the second and fourth columns of Table VI, the gamma rays from ^{243}Cm account for 16% of the total 0.0-0.5 Mev gamma radiation from fission and decay, and the gamma rays from ^{244}Cm account for 18% of the total 0.5-1.0 Mev gamma radiation.

TABLE VI

Significant Gamma Activity from Decay of Purified Curium from Transplutonium Program

	Gamma Activity from Decay, photons/(sec)(g of sample)		
Energy, Mev	Calculated from Decay Schemes and Isotopic Content	From Interpretation of Gamma Spectrum	Total Gamma Activity from Fission and Decay, photons/(sec)(g of sample)
0.2 - 0.5	1.4×10^8	1.1×10^8	8.9×10^8 (a)
0.5 - 1.0	6.2×10^6	4.0×10^6	3.5×10^7

(a) 0.0 - 0.5 Mev.

The contribution of gamma rays from decay calculated from published decay schemes and measured mass ratios was verified by the observed spectra shown in Figure 2. In interpreting the gamma spectra, the fission spectrum of ^{252}Cf was subtracted from the ^{244}Cm spectrum, and the intensities of the remaining photopeaks were corrected for detector efficiency, geometry, and Compton events.

In addition to the gamma rays from decay of curium isotopes, there would be gamma rays from decay of ^{252}Cf and ^{243}Am-^{239}Np in the ^{244}Cm product. The contributions of ^{252}Cf and ^{243}Am-^{239}Np to the total gamma rays from decay were calculated from the predicted concentrations of these isotopes in the ^{244}Cm product (Table III) and the data in Table V. Since ^{252}Cf has only low-energy decay gamma rays and would be present in extremely low concentration, it would not contribute a significant amount to the total. The decay gamma rays from the 0.5 wt % ^{243}Am (and the ^{239}Np daughter) predicted in the ^{244}Cm product would amount to about 2.8×10^7 photons/(second)(g ^{244}Cm product), with about 1.1×10^7 photons/(second)(g ^{244}Cm product) above 0.2 Mev.

Prompt Gamma Rays from Spontaneous Fission

The energy and abundance of prompt gamma rays from spontaneous fission were calculated by assuming the spontaneous fission gamma energy spectrum for ^{244}Cm to be the same as that reported for ^{235}U.[4] The validity of this assumption, which is in accord with theory,[5] was supported experimentally by measuring the total gamma spectra of ^{252}Cf and ^{244}Cm and by comparing literature data for ^{252}Cf[5] and ^{235}U.[4] The ^{252}Cf and ^{244}Cm spectra, shown in Figure 2, are quite similar in the high energy region (beyond 2 Mev)

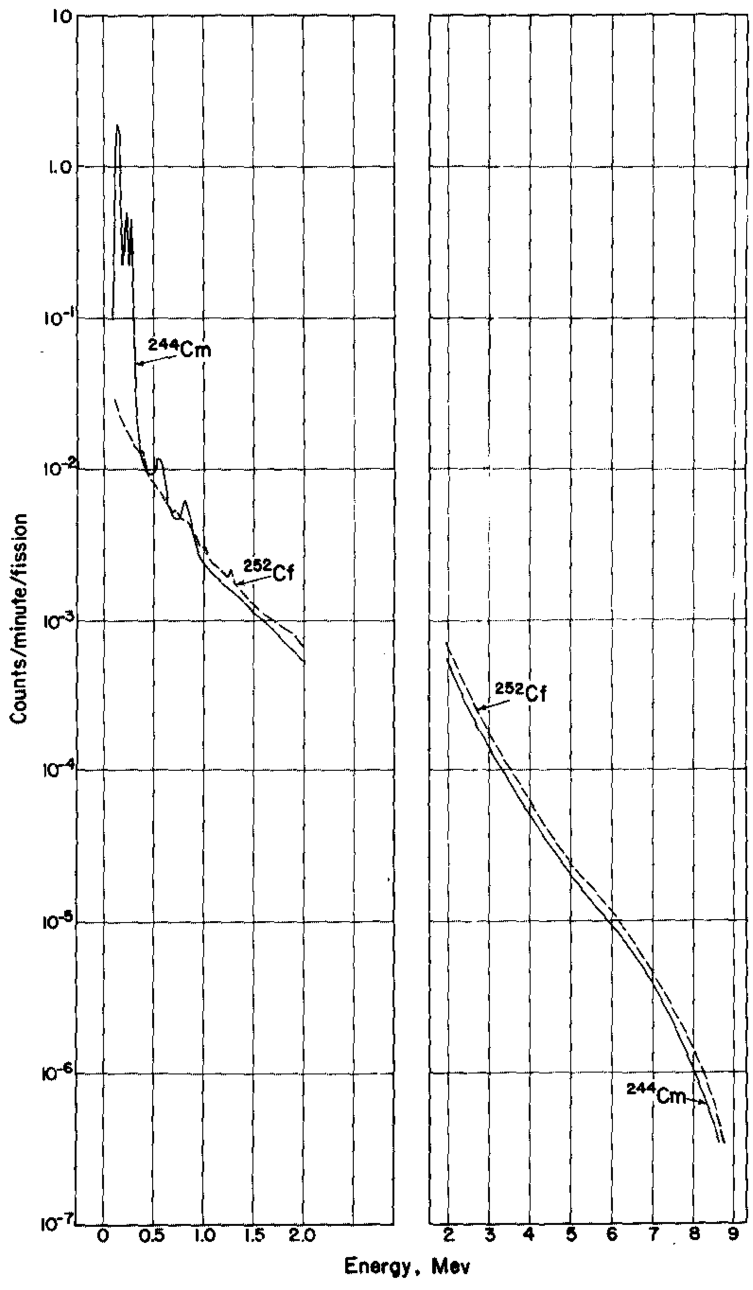

FIG. 2 TOTAL GAMMA SPECTRA OF ^{252}Cf AND PURIFIED CURIUM
0.1 to 9.0 Mev
3" x 3" NaI Detector

where the gamma contribution from short-lived fission products is relatively small. In this energy region the measured ratio of photons/fission for ^{252}Cf was 1.26 times that for ^{244}Cm, which is in line with the ratio of 1.35 calculated from literature data for ^{252}Cf and ^{235}U. The ^{244}Cm used in measuring the spectrum was the purified curium from the Transplutonium Program.

The spectra of prompt gamma rays from spontaneous fission of ^{244}Cm and ^{252}Cf were measured with a γ,n coincidence technique, also. With this technique, only 100-kev or greater gamma rays emitted within 180 nanoseconds of a spontaneous fission are recorded. The measurements are shown in Figure 3.

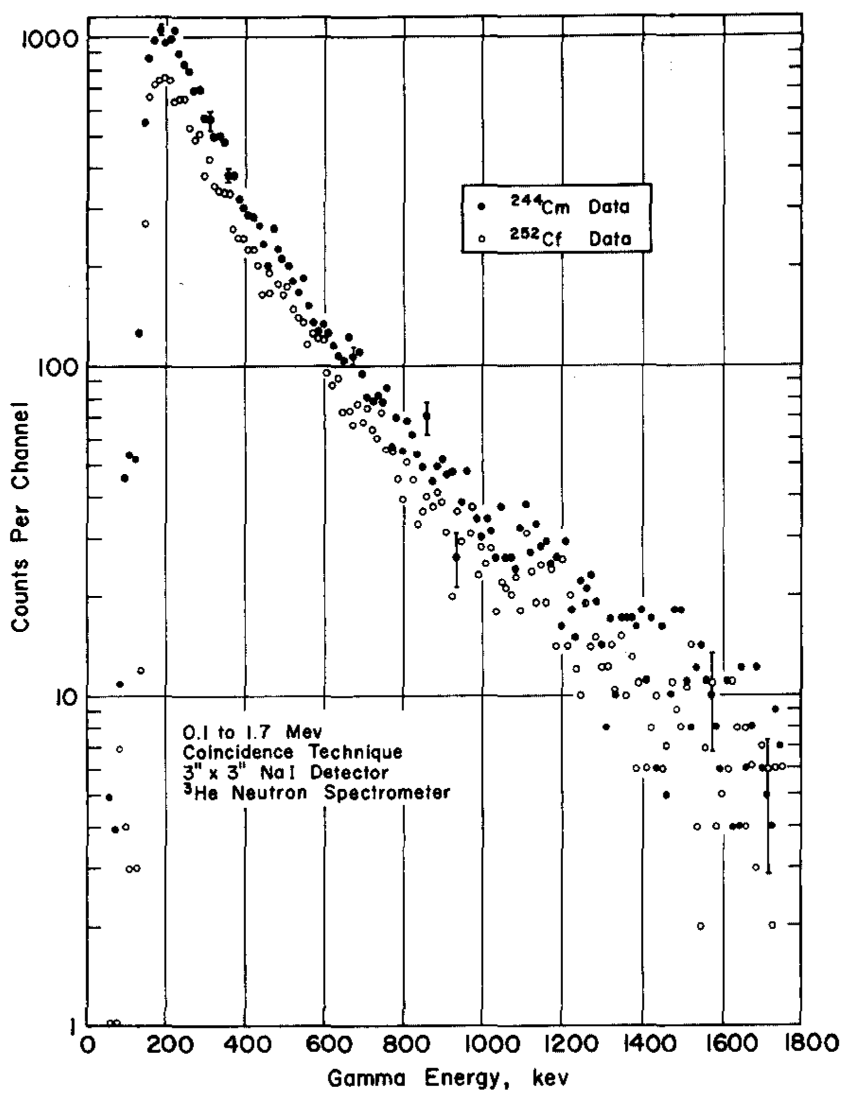

FIG. 3 FISSION GAMMA SPECTRA OF ^{252}Cf AND PURIFIED CURIUM

The energy and abundance of the prompt gamma rays calculated for ^{244}Cm from the literature data for ^{235}U are given in Table VII; literature data for ^{252}Cf are also included. In the ^{244}Cm product, prompt gamma rays from the spontaneous fission of curium isotopes other than ^{244}Cm will be less than 2.5% of those from ^{244}Cm. The prompt gamma rays from ^{252}Cf (<4 x 10^{-5} wt %) in the ^{244}Cm product will amount to 10% of the prompt gamma rays from ^{244}Cm. These are the only nuclides that will contribute significantly to the prompt gamma rays from spontaneous fission in the ^{244}Cm product.

TABLE VII

Prompt Gamma Rays from Spontaneous Fission of ^{244}Cm and ^{252}Cf

Energy, Mev	Abundance, photons/(sec)(g of nuclide) ^{244}Cm	Abundance, photons/(sec)(g of nuclide) ^{252}Cf (5)
0.0 - 0.5	1.2 x 10^{7}	3.3 x 10^{12}
0.5 - 1.0	7.4 x 10^{6}	1.7 x 10^{12}
1.0 - 1.5	3.3 x 10^{6}	7.7 x 10^{11}
1.5 - 2.0	2.1 x 10^{6}	4.2 x 10^{11}
2.0 - 2.5	1.1 x 10^{6}	2.2 x 10^{11}
2.5 - 3.0	5.8 x 10^{5}	1.1 x 10^{11}
3.0 - 3.5	2.4 x 10^{5}	5.6 x 10^{10}
3.5 - 4.0	2.5 x 10^{5}	3.0 x 10^{10}
4.0 - 4.5	9.3 x 10^{4}	1.7 x 10^{10}
4.5 - 5.0	7.4 x 10^{4}	8.2 x 10^{9}
5.0 - 5.5	6.6 x 10^{4}	4.9 x 10^{9}
5.5 - 6.0	2.7 x 10^{4}	1.8 x 10^{9}
6.0 - 6.5	1.6 x 10^{4}	1.0 x 10^{9}

Gamma Rays from Equilibrium Fission Products

The fission products formed from spontaneous fission approach equilibrium in the curium within a few hours after separation. Equilibrium fission product gamma activities were calculated by assuming that the gamma spectra of the fission products are the same as those of the fission products from ^{235}U. Table VIII lists the energy and abundance of these gamma rays from fission products of ^{244}Cm and ^{252}Cf.

TABLE VIII

Gamma Rays from Fission Products of Spontaneous Fission of ^{244}Cm and ^{252}Cf [4]

Energy, Mev	Abundance, photons/(sec)(g of nuclide) From Products of ^{244}Cm	From Products of ^{252}Cf
0.1 - 0.4	6.3×10^{6}	1.3×10^{12}
0.4 - 0.9	1.9×10^{7}	4.0×10^{12}
0.9 - 1.35	1.9×10^{6}	4.0×10^{11}
1.35 - 1.8	2.4×10^{6}	5.1×10^{11}
1.8 - 2.2	1.2×10^{6}	2.5×10^{11}
2.2 - 2.6	4.5×10^{5}	9.4×10^{10}
2.6 - 3.0	4.4×10^{4}	9.3×10^{9}

The contributions of ^{244}Cm and ^{252}Cf to the total gamma activity from equilibrium fission products in the ^{244}Cm product were calculated from the predicted isotopic composition (Table III) and the data in Table VIII. Curium-244 will contribute about 92% of the total; ^{252}Cf, about 8%.

Gamma Rays from Impurities

In addition to the equilibrium fission products from spontaneous fission, the ^{244}Cm product will contain small amounts of fission products formed in the irradiation process and not removed in the chemical separations process. From the predicted performance of the chemical process and the calculated quantities of fission products associated with the curium after irradiation, the gamma activity of the fission product impurities are those given in Table IX.

TABLE IX

Gamma Rays from Fission Product Impurities

Energy, Mev	Abundance, photons/(sec)(g ^{244}Cm Product)
0.0 - 0.5	6×10^{7}
0.5 - 1.0	2×10^{7}
1.0 - 2.0	3×10^{6}
2.0 - 3.0	1×10^{6}

Almost all of the gamma rays above 1 Mev are from ^{144}Pr and $^{152-154}$Eu, and those below 1 Mev are primarily from ^{95}Zr-^{95}Nb, ^{144}Ce, ^{106}Rh, and ^{103}Ru-^{103}Rh.

X-Rays

The X-ray spectrum of purified ^{244}Cm from the Transplutonium Program is shown in Figure 4. Because most of the X-rays detected are less than 40 kev in energy, X-rays are not included in the calculations of the total gamma radiation.

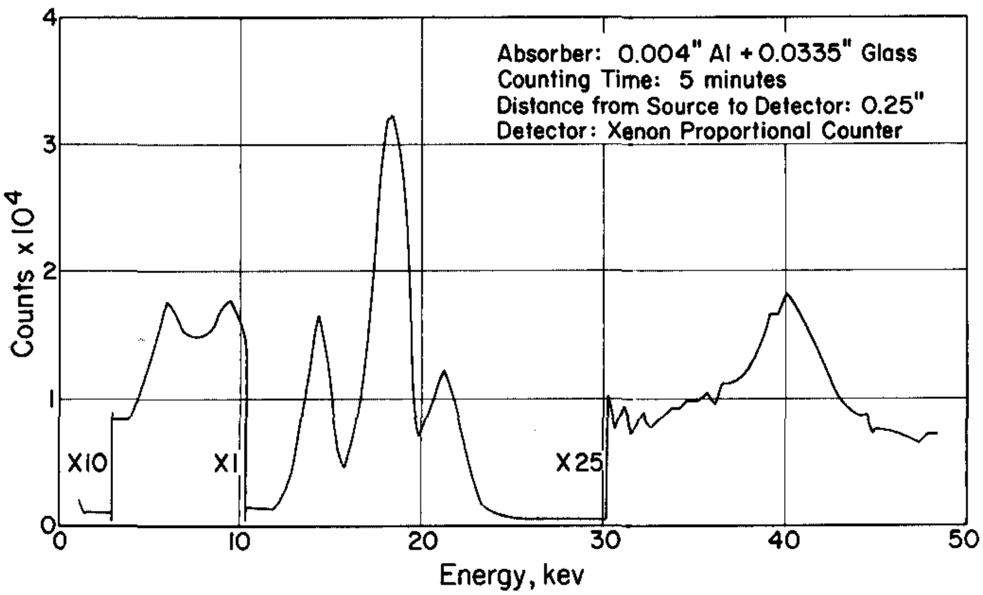

FIG. 4 X-RAY SPECTRUM OF 3.4 μg ^{244}Cm SAMPLE

Total Gamma Radiation

The total gamma activity of the ^{244}Cm product was obtained by combining the individual contributions listed in the preceding sections. The gamma energies and corresponding abundance are listed in Table X.

TABLE X

Significant Gamma Rays of ^{244}Cm Product[a]

Energy, Mev	Abundance, photons/(sec)(g ^{244}Cm product): From Decay of Nuclides				From Spontaneous Fissions		From Fission Products of		From Impurities	Total
	^{242}Cm	^{243}Cm	^{244}Cm	^{243}Am	^{244}Cm	^{252}Cf	^{244}Cm	^{252}Cf		
0.0-0.5	1.1×10^{7}	9.5×10^{6}	6.8×10^{8}	2.8×10^{7}	1.1×10^{7}	1.3×10^{6}	5.9×10^{6}	5.2×10^{5}	6×10^{7}	8.1×10^{8}
0.5-1.0	8×10^{4}	-	5.9×10^{6}	-	7×10^{6}	6.8×10^{5}	1.8×10^{7}	1.6×10^{6}	2×10^{7}	5.3×10^{7}
1.0-2.0	2.4×10^{3}	-	-	-	5.2×10^{6}	4.8×10^{5}	4.1×10^{6}	3.6×10^{5}	3×10^{6}	1.3×10^{7}
2.0-3.0	-	-	-	-	1.6×10^{6}	1.3×10^{5}	1.6×10^{6}	1.4×10^{3}	1×10^{6}	4.3×10^{6}
3.0-4.0	-	-	-	-	4.7×10^{5}	3.4×10^{4}	-	-	-	5.0×10^{5}
4.0-5.0	-	-	-	-	1.6×10^{5}	1.0×10^{4}	-	-	-	1.7×10^{5}
5.0-6.0	-	-	-	-	8.9×10^{4}	2.7×10^{3}	-	-	-	8.9×10^{4}
6.0-7.0	-	-	-	-	1.5×10^{4}	4.0×10^{2}	-	-	-	1.5×10^{4}

(a) Isotopic composition listed in Table III.

BETA ACTIVITY OF THE ^{244}Cm PRODUCT

The principal beta emitters in the ^{244}Cm product are short-lived fission products, fission product contaminants, and ^{249}Bk (estimated concentration: 2×10^{-5} wt %). Beta radiations will not contribute significantly to the specific power or to the shielding problems associated with the curium product.

NEUTRON ACTIVITY OF THE ^{244}Cm PRODUCT

The neutron radiation from the ^{244}Cm product will consist principally of neutrons from spontaneous fission of ^{244}Cm, with minor contributions from spontaneous fission of ^{242}Cm, ^{246}Cm, and ^{252}Cf. A second minor source of neutrons is the α,n neutrons from the reaction of alpha particles with light elements, for example, the reaction with oxygen in CmO_2.

α,n Neutron Spectra

The only appreciable source of α,n neutrons in a ^{244}Cm heat source will be the reaction with oxygen in CmO_2 or Cm_2O_3. If other curium compounds are used in the heat source, the values for the α,n neutrons must be changed accordingly.

The quantities[10] and spectra[11] of neutrons formed by the reaction of alpha particles with oxygen have been reported for polonium and plutonium isotopes. These data were extrapolated to the alpha energies of nuclides in the ^{244}Cm product.* From the resulting data in Table XI and the predicted composition of the ^{244}Cm product, the total neutrons produced by α,n reactions with oxygen in CmO_2 were calculated. The total was only 3% of the neutrons from spontaneous fission. Almost all of the α,n neutrons are produced by the alpha activity of ^{244}Cm.

Spontaneous Fission Neutron Spectra

The neutron spectrum of the purified ^{244}Cm from the Transplutonium Program was experimentally determined and compared with reported spectra of ^{235}U[12] and ^{252}Cf.[5] Since the spectra, shown in Figure 5, are quite similar, the spectra for ^{235}U or ^{252}Cf may be used to calculate the abundances in each energy interval for ^{244}Cm, ^{242}Cm, ^{246}Cm, and ^{252}Cf. Neutron energies and corresponding abundances for these nuclides are listed in Table XII. From these data and

* The total quantities of neutrons agree with those reported by Arnold.[13]

TABLE XI

Neutrons from α,n Reactions with Oxygen

Energy, Mev	Abundance, neutrons/(sec)(g of nuclide) α from ^{242}Cm	α from ^{244}Cm	α from ^{252}Cf
0.2	5.0×10^3	4.5×10^2	8.1×10^2
0.4	1.0×10^4	1.9×10^3	1.6×10^3
0.6	2.0×10^4	2.3×10^3	3.3×10^3
0.8	2.5×10^4	4.7×10^3	4.1×10^3
1.0	7.6×10^4	7.5×10^3	1.2×10^4
1.2	1.5×10^5	1.2×10^4	2.5×10^4
1.4	2.8×10^5	1.7×10^4	4.5×10^4
1.6	4.5×10^5	2.3×10^4	7.4×10^4
1.8	7.6×10^5	2.8×10^4	1.2×10^5
2.0	1.0×10^6	3.3×10^4	1.7×10^5
2.2	1.3×10^6	3.7×10^4	2.2×10^5
2.4	1.7×10^6	3.9×10^4	2.7×10^5
2.6	2.0×10^6	3.9×10^4	3.2×10^5
2.8	2.1×10^6	3.8×10^4	3.4×10^5
3.0	2.1×10^6	3.4×10^4	3.4×10^5
3.2	2.1×10^6	2.8×10^4	3.4×10^5
3.4	1.8×10^6	2.2×10^4	2.9×10^5
3.6	1.5×10^6	1.4×10^4	2.4×10^5
3.8	1.0×10^6	8.4×10^3	1.7×10^5
4.0	6.5×10^5	5.6×10^3	1.1×10^5
4.2	4.0×10^5	3.8×10^3	6.5×10^4
4.4	2.8×10^5	2.4×10^3	4.5×10^4
4.6	1.8×10^5	2.0×10^2	2.9×10^4
4.8	5.0×10^4		8.1×10^3

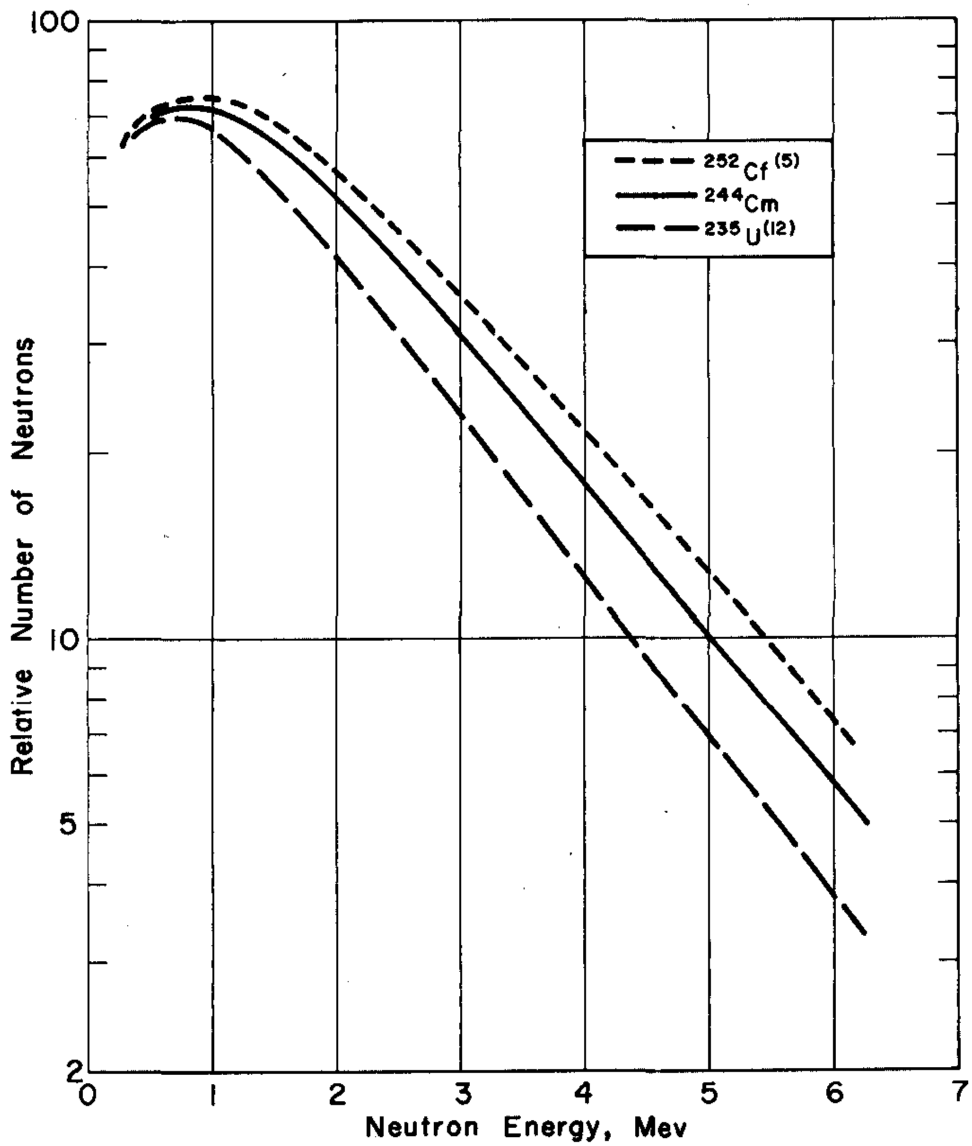

FIG. 5 SPONTANEOUS FISSION NEUTRON SPECTRA

TABLE XII

Spontaneous Fission Neutrons from ^{242}Cm, ^{244}Cm, ^{246}Cm, and ^{252}Cf

Energy, Mev	Abundance, neutrons/(sec)(g of nuclide)			
	^{242}Cm	^{244}Cm	^{246}Cm	^{252}Cf
0.3 - 0.4	7.7×10^5	4.2×10^5	5.2×10^5	9.4×10^{10}
0.4 - 0.6	1.6×10^6	8.7×10^5	1.1×10^6	1.9×10^{11}
0.6 - 0.8	1.6×10^6	8.9×10^5	1.1×10^6	2.0×10^{11}
0.8 - 1.0	1.4×10^6	7.7×10^5	9.5×10^5	1.7×10^{11}
1.0 - 1.2	1.4×10^6	7.9×10^5	9.7×10^5	1.8×10^{11}
1.2 - 1.4	1.4×10^6	7.8×10^5	9.6×10^5	1.7×10^{11}
1.4 - 1.6	1.2×10^6	6.8×10^5	8.3×10^5	1.5×10^{11}
1.6 - 1.8	1.1×10^6	6.1×10^5	7.5×10^5	1.4×10^{11}
1.8 - 2.0	1.0×10^6	5.5×10^5	6.7×10^5	1.2×10^{11}
2.0 - 2.2	9.1×10^5	5.0×10^5	6.2×10^5	1.1×10^{11}
2.2 - 2.4	8.4×10^5	4.6×10^5	5.7×10^5	1.0×10^{11}
2.4 - 2.6	8.0×10^5	4.4×10^5	5.5×10^5	1.0×10^{11}
2.6 - 2.8	6.5×10^5	3.6×10^5	4.4×10^5	8.0×10^{10}
2.8 - 3.0	5.5×10^5	3.0×10^5	3.7×10^5	6.8×10^{10}
3.0 - 3.2	5.0×10^5	2.8×10^5	3.4×10^5	6.2×10^{10}
3.2 - 3.4	5.0×10^5	2.7×10^5	3.4×10^5	6.1×10^{10}
3.4 - 3.6	4.7×10^5	2.6×10^5	3.2×10^5	5.9×10^{10}
3.6 - 3.8	3.7×10^5	2.1×10^5	2.5×10^5	4.6×10^{10}
3.8 - 4.0	4.1×10^5	2.2×10^5	2.8×10^5	5.0×10^{10}
4.0 - 4.4	5.2×10^5	2.9×10^5	3.5×10^5	6.4×10^{10}
4.4 - 4.8	4.4×10^5	2.4×10^5	2.9×10^5	5.4×10^{10}
4.8 - 5.2	3.2×10^5	1.8×10^5	2.2×10^5	3.9×10^{10}
5.2 - 5.6	2.5×10^5	1.4×10^5	1.7×10^5	3.1×10^{10}
5.6 - 6.0	1.9×10^5	1.1×10^5	1.2×10^5	2.3×10^{10}
6.0 - 6.4	1.5×10^5	8.2×10^4	1.0×10^5	1.8×10^{10}
6.4 - 6.8	1.1×10^5	5.9×10^4	7.2×10^4	1.3×10^{10}
6.8 - 7.2	7.5×10^4	4.1×10^4	5.1×10^4	9.3×10^9
7.2 - 7.6	5.6×10^4	3.1×10^4	3.8×10^4	6.9×10^9
7.6 - 8.0	4.7×10^4	2.5×10^4	3.2×10^4	5.8×10^9
8.0 - 8.8	5.0×10^4	2.8×10^4	3.4×10^4	6.2×10^9
8.8 - 9.6	1.5×10^4	8.2×10^3	1.0×10^4	1.8×10^9
9.6 - 10.4	1.6×10^4	8.6×10^3	1.1×10^4	1.9×10^9
10.4 - 11.2	1.0×10^4	5.7×10^3	7.0×10^3	1.3×10^9
11.2 - 12.8	7.1×10^3	3.9×10^3	4.8×10^3	8.8×10^8

the predicted isotopic composition (Table III), the neutron energies and abundances of the ^{244}Cm product were calculated. These data were combined with values for α,n neutrons to obtain the total neutron activity of the ^{244}Cm product listed in the Summary.

Total Neutrons

The neutron emission rate of purified curium from the Transplutonium Program was measured in a counting assembly of BF_3 tubes embedded in a paraffin moderator. The assembly was calibrated with a ^{252}Cf standard. The specific neutron activity of the purified curium was found to be 9.7×10^6 neutrons/(second)(g of sample), which agrees well with the specific neutron activity reported for ^{244}Cm, 1.09×10^7 neutrons/(second)(g ^{244}Cm) (see Table I).

REFERENCES

1. J. A. Smith. Curium-244 Production at Savannah River. USAEC Report DP-914, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, S. C. (1964) (Secret).

2. B. S. Dzhelepov and L. K. Peker. Decay Schemes of Radioactive Nuclei. Pergamon Press, New York (1961).

3. D. Metta, H. Diamond, R. F. Barnes, J. Milsted, J. Gray, Jr., D. J. Henderson, and C. M. Stevens. "Nuclear Constants of Nine Transplutonium Nuclides." 148th American Chemical Society Meeting, Chicago, 1964. Abstract of Papers, p. 8R (1964).

4. Reactor Physics Constants. USAEC Report ANL-5800, Argonne National Laboratory, Lemont, Illinois (1958).

5. E. K. Hyde. A Review of Nuclear Fission. Part One - Fission Phenomena at Low Energy. USAEC Report UCRL-9036, University of California, Lawrence Radiation Laboratory, Berkeley, California (1960).

6. 1960 Nuclear Data Tables. Part Four - Short Tables. National Academy of Sciences - National Research Council, Washington, D. C. (1961).

7. D. Strominger, J. M. Hollander, and G. T. Seaborg. "Table of Isotopes." Rev. Modern Phys. 30, 585-904 (1958).

8. C. F. Miller. Proposed Decay Schemes for Some Fission-Product and Other Radionuclides. USAEC Report USNRDL-TR-160, Naval Radiological Defense Laboratory, San Francisco, California (1957).

9. S. Bzornholm, M. Lederer, F. Asaro, and I. Perlman. "Alpha Decay to Vibrational States." Phys. Rev. 130, 2000-2010 (1963).

10. E. Segré and C. Wiegand. Thick-Target Excitation Functions for Alpha Particles. USAEC Report MDDC-185, Oak Ridge, Tenn. (1944)(Declassified July 30, 1946).

11. A. G. Khabakhpashev. "The Spectrum of Neutrons from a Po-α-O Source." Atomnaya Energiya 7, 71 (1959).