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Total Neutron Cross Section of Cm^{244}†

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The total neutron cross section of Cm^{244} has been studied from 0.01 to about 900 eV with the Argonne fast chopper. Resonance parameters are given for many of the approximately 20 resonances observed below 500 eV. Three resonances have been assigned to Cm^{246}, but none to Cm^{245} although this isotope was about as abundant as the Cm^{246} in one of the samples studied. The value of the strength functions of Cm^{244} and Cm^{246}, when combined with other measured values, suggests that this quantity has a maximum near $A=239$.

INTRODUCTION

As part of a continuing program to measure the total neutron cross sections of the transplutonium nuclides (in order to extend the base for the study of nuclear systematics in this mass region) the transmissions of two samples of curium have been measured as a function of neutron energy with the Argonne fast chopper.[1] A first study with a small sample does not ordinarily provide a result that can be interpreted in terms of nuclear models or resonance theory. Hence, to make this type of measurement useful to nuclear physics, it must be part of a series of such measurements. This particular measurement, when combined with all of the other measurements that result in a value of the s-wave strength function $\bar{\Gamma}_n^0/D$ in this mass region, appears to define a peak in the strength function near $A=239$.

EXPERIMENTAL DETAILS

All of the measurements described in this paper were made with Rotor No. III[2] of the Argonne fast chopper; flight paths of 25 and 60 m were used and the data were stored in a 1024-channel time analyzer.[3] The best time-of-flight resolution was about 35 nsec/m with the 60-m flight path.

Two samples of curium were used in the study. Most of the measurements were made with a sample of about 46 mg of curium contained in a capsule like that used for similar measurements[4] on Th^{229}. The sample holder is shown in Fig. 1. The major difference between this capsule and that used for the Th^{229} is that the height of the sample, and consequently the height of the beam that can be used, is twice as large for the curium as for the thorium. The capsule as shown was mounted in a special collimator, placed between the reactor and the chopper, that restricted the neutron beam to a cross section of 0.240×0.025 in. The sample holder could be rotated so that almost any thickness between those corresponding to the thickest (0.250 in.) and the thinnest (0.030 in.) dimensions could be used. For even the thinnest value, sample No. I (46 mg) was not thin enough to allow a reasonably precise value of the radiation width Γ_γ to be obtained from the data, so that a thinner sample No. II was made. The physical dimensions were kept the same, and approximately 7 mg of curium were mixed with enough aluminum powder to fill the cavity. One other important difference between

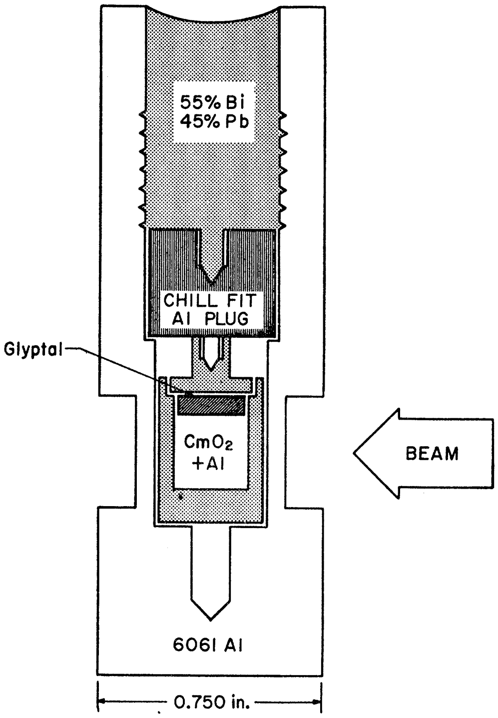

FIG. 1. The capsule in which the curium was contained. A rectangular slit in the cylindrical inner capsule is filled with Al and CmO_2, compacted to within $\frac{1}{16}$ in. from the surface. A rectangular follower is added, and a cap is sealed in place with Glyptal. The inner capsule is keyed into its outer container and an oversized plug is forced to fit into place by chilling with liquid nitrogen. A lead bismuth mixture that does not contract upon solidification completes the seal. Such an encapsulation was adequate for complete containment of the 2-Ci source used here, and has further been shown to be adequate to contain the emanation from 0.03 Ci of Th^{228}.

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† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] L. M. Bollinger, R. E. Coté, and G. E. Thomas, *Proceedings of the Second International Conference on Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 14, p. 239.

[2] L. M. Bollinger, R. E. Coté, and G. E. Thomas, Argonne National Laboratory Report ANL-6169, 1960, p. 1 (unpublished).

[3] R. W. Schumann, Rev. Sci. Instr. 28, 489 (1957).

[4] R. E. Coté, H. Diamond, and J. E. Gindler, Bull. Am. Phys. Soc. 6, 417 (1961).

TABLE I. The isotopic composition of the samples of curium used for the measurements.

Samples	Cm^{242}	Cm^{244}	Cm^{245}	Cm^{246}	Cm^{247}	Cm^{248}
I		96.50±0.03	1.60 ±0.02	1.87±0.02	0.0220±0.0008	≤0.0044 ±0.0002
II	0.0019[a]	75.9 ±0.2	0.838±0.016	21.48±0.2	0.648 ±0.014	1.059±0.02

[a] From activity.

sample No. I and sample No. II was in the isotopic composition (Table I) of the curium used for the two samples. It was hoped that halving the abundance of Cm^{245} would allow the identification of some resonances in this important isotope. Although this hope was not realized the change in the abundance of the Cm^{246} from 1.87 to 21.48% made it possible to identify three resonances in this isotope.

The amounts of curium loaded into the capsules were measured by standard radiochemical techniques; in addition, the thicknesses of the samples as seen by the neutron beam were determined by measurements of the well known resonance in Pu^{240} at 1.054 eV, for which σ_0 and Γ were taken to be 1.60×10^5 b and 36.36×10^{-3} eV, respectively.[5] The α decay from Cm^{244} to Pu^{240} has a half-life of 18.11±0.07 yr.[6] Thus, since all of the plutonium had been removed just before encapsulation, the growth of the Pu^{240} (inferred from the size of the 1.054-eV resonance) could be used to reveal the amount of Cm^{244} present at the time of preparation. From the amount of Cm^{244} present at that time, the volume of the cavity, and the half-lives of the various isotopes, the total amount of curium could be determined and the amounts of any isotopes at the time of any of the transmission measurements could be obtained. For the ¼-in. directions in the two samples, the sample thicknesses at the time of encapsulation were $(2.24\pm0.05)\times10^{-3}$ and $(2.64\pm0.15)\times10^{-4}$ atoms Cm^{244}/b, corresponding to total amounts of curium of 45.6 and 6.8 mg, respectively. The maximum thickness of Cm^{246} in sample No. II was $(7.4\pm0.37)\times10^{-5}$ atoms/b. No reasonably precise value of the 0.030-in. thickness of sample No. II could be obtained from a measurement of the area of the Pu^{240} resonance, so that the value for this thickness was obtained by multiplying the ¼-in. value by the ratio of the cavity dimensions.

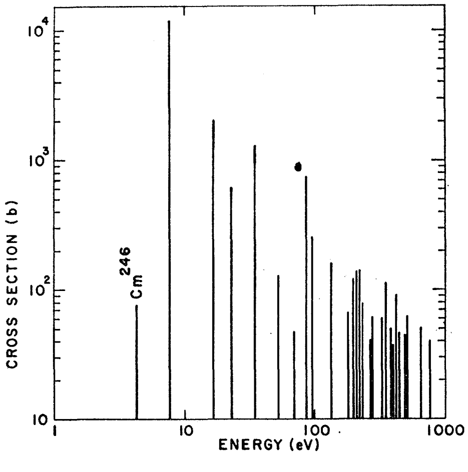

FIG. 2. The resonance spectrum of Cm^{244} as revealed by the transmission of sample No. I.

SUMMARY

The resonance spectrum is shown in Fig. 2 in which the heights of the lines indicate the measured peak heights obtained from the measurements with sample No. I. Most of the peak values were measured with the 0.030-in. thickness. The resonance parameters, as determined from all sample thicknesses are listed in Table II. From a consideration of the resonances

TABLE II. The resonance parameters of Cm^{244} and Cm^{246}.

E_0 (eV)	Γ_n (10^{-3} eV)	σ_0 (b)	Γ_γ (10^{-3} eV)	Γ (10^{-3} eV)
		Cm^{244}		
7.73	10.3 ±0.5	73000±8500	37.2±3.3	47.5±2.5
16.9	2.0 ±0.05	8000± 800	37.0±3.0	39.0±3.0
22.9	0.97±0.05			
35.0	4.03±0.20	6300±1320	43.5±8.0	47.5±8.0
52.8	0.70±0.05			
69.9	0.48±0.06			
86.0	20.0 ±1.3			
96.0	6.2 ±3.1			
133	15.1 ±1.8			
182	8.8 ±2.4			
197	22.0 ±2.7			
211	42.7 ±3.8			
222	39 ±4			
231	18.3 ±3.0			
273	43 ±14			
360				
419				
445				
516				
650				
768				
		Cm^{246}		
4.33	0.39±0.01	6700±900	35±5	35.4±5.0
(19.66)[a]				
26.9	1.6 ±0.7			
(36.2)[a]				
84.5	~35			

[a] There is a possibility that these energies correspond to resonances in Cm^{247} or Cm^{248}.

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[5] *Neutron Cross Sections*, compiled by D. J. Hughes and R. B. Schwartz, Brookhaven National Laboratory Report BNL-325, 2nd ed. (U. S. Government Printing Office, Washington, D. C., 1960), Suppl. No. 1.

[6] William Bentley (private communication, 1963).

below 100 eV, the average level spacing is found to be $12.6_{-3.3}^{+6}$ eV for Cm^{244}.

It was possible to measure Γ_γ for three of the resonances of Cm^{244}; a weighted mean of these values is $\Gamma_\gamma = (37.5\pm2.1)\times10^{-3}$ eV. The parameters for the remainder of the resonances have been derived from the data under the assumption that $\Gamma_\gamma = 37\times10^{-3}$ eV. Three resonances have been assigned to Cm^{246} and there are indications in the data that suggest resonances at 19.7 and 36.2 eV in this isotope, although there is a small possibility that these resonances may be in Cm^{247} or Cm^{248}. From a shape analysis of the resonance at 4.33 eV it was possible to estimate that $\Gamma_\gamma = (35\pm5)\times10^{-3}$ eV for Cm^{246}. It may be noted here that the value of the radiation width listed above for Cm^{244} is consistent with the values of 31×10^{-3} eV computed from the semiempirical formula of Cameron[7] and 40×10^{-3} eV from that of Stolovy and Harvey.[8] There is also reasonable agreement between the measured value of $(35\pm5)\times10^{-3}$ eV for Cm^{246} and the corresponding semiempirical values of 25 and 31×10^{-3} eV. Since the binding energy of $Cm^{246}+n$ is not known, and therefore an estimate must be used, this agreement may be considered to be quite satisfactory.

None of the resonances observed could be assigned to Cm^{245}, although its abundance was 1.6% of sample No. I. Cm^{245} is important in the production of transplutonic elements because of its very large fission cross section of 1900 b for thermal neutrons. It was hoped that the origin of this large cross section could be found in terms of the resonance structure of Cm^{245}. However, the study of the transmission of sample No. I for neutron energies as low as 0.01 eV failed to reveal any resonances that could cause such a large cross section. It is, therefore, almost certain that a strong bound level is the chief contributor to the cross section of Cm^{245} for thermal neutrons.

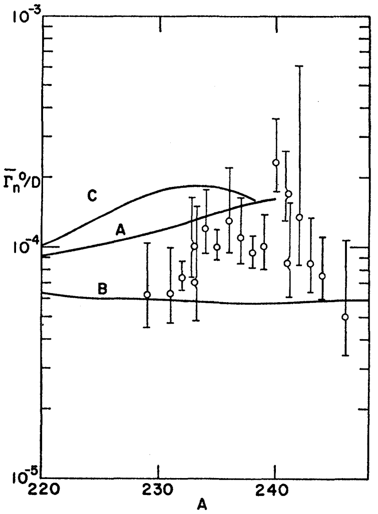

FIG. 3. The strength function $\bar{\Gamma}_n^0/D$ for the nuclides with nucleon numbers A between 220 and 248. The curves are all from Chase, Wilets, and Edmonds (Ref. 9). Curve A is based on a spheroidal potential that provides the best fit to the data near $A=160$. Curve B is based on a spherical potential. Curve C corresponds to the same set of parameters as curve A except for the quadrupole deformation which is 33% larger for C. The values of $\bar{\Gamma}_n^0/D$ are from the results of the many workers listed in Table III.

TABLE III. Values of the s-wave neutron strength function. The values are those of the authors listed, but the errors were derived by the present authors to allow a more unbiased evaluation of the data. The errors represent 80% confidence limits for the measured values of statistical quantities that obey χ^2 distributions for which the number of degrees of freedom is equal to the number of resonances included in the determination of the value of $\bar{\Gamma}_n^0/D$.[a]

Nuclide	$10^4\times\bar{\Gamma}_n^0/D$	Reference
Th^{229}	$0.62_{-0.17}^{+0.42}$	c
Pa^{231}	$0.63_{-0.16}^{+0.36}$	d
Th^{232}	$0.74_{-0.09}^{+0.13}$	e
Pa^{233}	$0.7_{-0.22}^{+0.79}$	f
U^{233}	$1.0_{-0.26}^{+0.62}$	g
U^{234}	$1.2_{-0.26}^{+0.56}$	h
U^{235}	$1.0_{-0.12}^{+0.18}$	i
U^{236}	$1.3_{-0.36}^{+0.9}$	h
Np^{237}	$1.1_{-0.25}^{+0.53}$	j
U^{238}	$0.94_{-0.13}^{+0.18}$	k
Pu^{239}	$1.0_{-0.20}^{+0.38}$	l
Pu^{240}	$2.3_{-0.57}^{+1.3}$	m
Pu^{241}	$0.85_{-0.24}^{+0.70}$	n
Am^{241}	$1.7_{-0.4}^{+0.9}$	o
Pu^{242}	$1.3_{-0.5}^{+4.75}$ [b]	p
Am^{243}	$0.84_{-0.21}^{+0.49}$	p

[a] R. T. Carpenter, Argonne National Laboratory Report ANL-6589, 1962 (unpublished).
[b] There is a numerical error in the reference cited. This value should be considered as the correct one.
[c] R. E. Coté, H. Diamond, and J. E. Gindler, Bull. Am. Phys. Soc. **6**, 417 (1961).
[d] F. B. Simpson, W. H. Burgus, J. E. Evans and W. H. Kirby, Nucl. Sci. Eng. **12**, 243 (1962).
[e] C. A. Uttley and R. H. Jones in *Neutron Time-of-Flight Methods*, edited by J. Spaepen (EURATOM, Brussels, 1961), p. 23.
[f] F. B. Simpson and R. P. Schuman in *Neutron Time-of-Flight Methods*, edited by J. Spaepen (EURATOM, Brussels, 1961), p. 85.
[g] R. G. Fluharty, M. S. Moore, and J. E. Evans, *Proceedings of the Second International Conference on Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 15, p. 239.
[h] V. E. Pilcher, D. J. Hughes, and J. A. Harvey, Bull. Am. Phys. Soc. **1**, 187 (1956).
[i] W. W. Havens, Jr., and E. Melkonian, *Proceedings of the Second International Conference on Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 15, p. 99.
[j] G. G. Slaughter, J. A. Harvey, R. C. Block, and G. J. Jenkins, Bull. Am. Phys. Soc. **3**, 364 (1958).
[k] J. Rosen, W. W. Havens, Jr., J. Rainwater, and S. Desjardins, Bull. Am. Phys. Soc. **4**, 33 (1959).
[l] L. M. Bollinger, R. E. Cote, and G. E. Thomas, *Proceedings of the Second International Conference on Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 15, p. 127.
[m] O. D. Simpson and R. G. Fluharty, Bull. Am. Phys. Soc. **2**, 219 (1957).
[n] O. D. Simpson and R. P. Schuman, Nucl. Sci. Eng. **11**, 111 (1961).
[o] J. A. Harvey, R. C. Block, and G. G. Slaughter, Bull. Am. Phys. Soc. **4**, 34 (1959).
[p] R. E. Coté, L. M. Bollinger, R. F. Barnes, and H. Diamond, Phys. Rev. **114**, 505 (1959).

The most important quantities that can be obtained from the results of the present measurements are values of the s-wave strength $\bar{\Gamma}_n^0/D$ for the different isotopes. These are $0.76_{-0.17}^{+0.35}\times10^{-4}$ for Cm^{244} and $0.5_{-0.16}^{+0.57}\times10^{-4}$ for Cm^{246}. These results, along with the values of the strength function for all nuclides above $A=220$ are shown in Fig. 3 and listed in Table III. Most presentations of these data in the past have not included any

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[7] A. G. W. Cameron, Can. J. Phys. **35**, 666 (1957).
[8] A. Stolovy and J. A. Harvey, Phys. Rev. **108**, 353 (1957).

points beyond $A=241$. The four values for the nuclides above 241, of which the present results represent half, appear to show that a peak has been reached and that the nuclides Pu^{242}, Am^{243}, Cm^{244}, and Cm^{246} lie on the high-mass side of this peak.

A maximum in the strength function in the region around $A=235$ has been discussed by several authors[9,10] after it was pointed out[11] that the values of $\bar{\Gamma}_n{}^0/D$ in this region are high compared with values located symmetrically on the low side of the "maximum" at $A=160$. The calculations of Chase, Wilets, and Edmonds[9] and of McVoy[10] show that a peak in $\bar{\Gamma}_n{}^0/D$ is indeed predicted for nuclides in this mass region when quadrupole deformations, consistent with measured $E2$ transition probabilities, are included. In addition, McVoy has shown that the effect of a reasonable amount of octupole deformation is to shift the position of this peak to lower nucleon numbers. The curves shown in Fig. 3 are all from the work of Chase, Wilets, and Edmonds. They show that: (1) the parameters that fit the more extensive data for the region near $A=160$ do not produce a satisfactory fit to the results for higher mass (curve A) and (2) the values of $\bar{\Gamma}_n{}^0/D$ computed on the basis of a spherical potential (curve B) do not fit the data. The third curve (C), based on the same parameters as A except for a 33% greater quadrupole deformation, indicates the degree to which the maximum can be shifted by changes in the amount of quadrupole deformation included. A reasonable amount of octupole deformation can produce a shift of the same order. Thus, although the data can be described by the same model as that used to describe the maxima at lower mass numbers, some adjustment of the parameters is required.

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[9] D. M. Chase, L. Wilets, and A. R. Edmonds, Phys. Rev. **110**, 1080 (1958).

[10] K. W. McVoy, Phys. Rev. **118**, 1323 (1960).

[11] R. B. Schwartz, V. E. Pilcher, D. J. Hughes, and R. T. Zimmerman, Bull. Am. Phys. Soc. **1**, 347 (1956).