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Analysis of the Fission and Capture Cross Sections of the Curium Isotopes*

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Using a nuclear explosion as a neutron source, measurements were made of the fission cross sections of ^{244}Cm, ^{245}Cm, ^{246}Cm, ^{247}Cm, and ^{248}Cm between 20 eV and 3 MeV. Radiative-capture cross sections were measured at the same time for a sample of mixed Cm isotopes, consisting primarily of ^{244}Cm and ^{246}Cm. Resonance analysis was carried out for ^{244}Cm between 20 eV and 1 keV, for ^{246}Cm and ^{248}Cm between 20 and 400 eV, and for the odd isotopes between 20 and 60 eV. The results of the analysis show evidence of intermediate structure in the sub-barrier fission of ^{244}Cm.

I. INTRODUCTION

The neutron cross sections of curium isotopes are of interest for two reasons. The first reason has to do with fission systematics. The existence of pronounced structure in the sub-barrier fission of even-even targets of uranium and plutonium is well established, and is consistent with the double-humped fission barrier first proposed by Strutinsky.[1] More detailed calculations with this model[2-4] suggest a strong dependence of the shape of the barrier on proton number, such that one might expect the sub-barrier fission of even curium targets to show little if any intermediate structure. Secondly, these isotopes are an integral part of the production chain for ^{252}Cf, and if one attempts to optimize ^{252}Cf production in reactors by varying the neutron spectrum, one needs a detailed knowledge of the fission and capture cross sections of the isotopes in the chain.

Since sample material has been available for a short time, relatively little is known about the detailed neutron cross sections of the Cm isotopes. The earliest measurement was a total cross-section determination of ^{244}Cm and ^{246}Cm done by Coté, Barnes, and Diamond[5] on the fast chopper at the Argonne National Laboratory, using samples of 46 and 7 mg of Cm, which had different isotopic compositions. From the analysis of this measurement, Coté, Barnes, and Diamond were able to determine resonance parameters for 15 resonances in ^{244}Cm and for three which were attributed to ^{246}Cm.

More recently, total cross-section measurements have been carried out on the Materials Testing Reactor fast chopper by Berreth and Simpson.[6] Here, the samples used ranged up to several grams of material, which also had different isotopic content because of different irradiation histories. This permitted analysis of a number of low-lying resonances in ^{243}Cm and ^{245}Cm, as well as analysis of resonances in the even targets below 200 eV.

Fullwood[7] has reported fission cross-section measurements of ^{244}Cm from the Persimmon nuclear explosion. Fullwood noted that the data obtained were suggestive of intermediate structure, but since complementary capture or total cross sections were not available, no detailed analysis of the data was made.

The measurement on which the present analysis is based was carried out in 1969 using the nuclear explosion Physics 8 as the neutron source. In this measurement, fission cross sections of ^{244}Cm, ^{245}Cm, ^{246}Cm, ^{247}Cm, and ^{248}Cm were determined, as well as radiative-capture cross sections of a sample of mixed Cm isotopes consisting primarily of ^{244}Cm and ^{246}Cm. A report of the lower-resolution data obtained and of a preliminary analysis of these data was presented at the Helsinki conference on Nuclear Data for Reactors.[8] Additional high resolution data and listings of the data are contained in a Los Alamos report.[9] These data are also available through the National Neutron Cross Section Center at Brookhaven National Laboratory. The present paper reports the final analysis of the measurements.

II. EXPERIMENTAL PROCEDURE

The differences in techniques associated with explosion sources as opposed to conventional pulsed neutron sources (repetitively pulsed linacs and positive-ion machines) lie in the fact that the nuclear explosion gives only one neutron pulse. This pulse gives an intensity on target equivalent to about 10^{10} pulses of the best of the high-resolution electron linacs. This requires (1) a measurement of signal current vs neutron time of flight rather than of individual pulses, (2) a large dynamic range for recording signal levels, and (3) fast recording of data in a permanent fashion, so that the data can be reduced later.

The relating of a signal current to a cross section requires also that the detector response be a known function of neutron energy. Fission cross sections can be measured by detecting fission fragments, since the average kinetic energy release is, for all practical purposes, independent of the incident neutron energy. Capture cross sections are determined with Moxon-Rae detectors, for which the response is nominally proportional to the total γ-ray energy release, independent of the decay mode. The detector must also respond quickly and accurately in the high signal output range. Studies made by Silbert and Moat[10] indicated that the Si p-n junction detector gives a linear response to the magnitude of the signal levels encountered in a nuclear explosion experiment. Such detectors have been used successfully for a number of years for detecting currents of fission fragments in measurements made with nuclear explosion neutron beams, and have also been used in Moxon-Rae detectors for detecting γ radiation. In the Physics 8 event, Ellis *et al.*[11] determined the efficiency of the Moxon-Rae detectors absolutely, by allowing the detector to view as a sample a spinning ribbon of ^{197}Au. The gold foil was later removed and counted to determine the number of activated ^{198}Au nuclei produced as a function of neutron energy.

The dynamic range for recording of signal levels is obtained by use of an amplifier whose signal output is linear below 1 mV, and logarithmic over the next four decades.[12] The response of each amplifier was measured by feeding the amplifier an accurately known nine-step calibration signal, ranging from 0.5 mV to 1.5 V, shortly after the neutron pulse had passed.

Permanent recording of the signals was accomplished on the Physics 8 event in two different ways, photographically on moving film, and magnetically on a moving magnetic disk. The magnetic disk recording was done for a few signals, primarily as an experimental development project. The results have been reported by Furnish and Arlowe.[13] Photographic recording was used for all the signals from the curium samples. The output of each of the logarithmic amplifiers was fed to the vertical deflection plates of a high-speed oscilloscope, and the deflection was recorded on moving film, the film motion serving as the time base. Lower-resolution data were recorded with cameras which had film speeds of about 30 m/sec, while higher-resolution data were recorded with drum cameras with film speeds of about 250 m/sec. The resolution is determined primarily by the linewidth of the trace on the film, about 30 μm, giving about 0.1–0.2-μsec resolution for the high-resolution data. With a flight path of 250 m, this corresponds to somewhat less than 1 nsec/m for the nominal highest resolution.

This high resolution cannot be realized over the entire energy range, however, because of timing uncertainties introduced by the moderator. The moderated time-of-flight spectrum of a conventional neutron source such as an electron linac consists of a high-energy boiloff spectrum, a roughly $1/E$ part, resembling a slowing-down spectrum, and a thermal Maxwellian at the lowest energies. The moderated time-of-flight spectrum associated with a nuclear explosion source is similar, except that the thermal Maxwellian generally occurs at some 10's-of-eV neutron energy because of heating and recoil of the moderator placed near the nuclear explosive device. The time history of neutrons emitted from the moderator in this thermal Maxwellian appears to follow the same type of exponential decay as that observed by Fluharty *et al.*[14] for moderators in the laboratory. In the Physics 8 event, the decay constant was about 4.9 μsec, which determined the time resolution for energies below about 300 eV.

In the Physics 8 event, the curium measurements were only a small part of the total effort. Many foils of fissionable material were placed in the same neutron beam with about 21-cm separation, and each foil was viewed by two p-n junction Si solid-state detectors, at 55 and 90° to the beam. The fissionable material, ranging from a few μg to several mg, was deposited on stainless-steel backings, 3.5×10^{-3} mm thick. The beams were collimated several meters below the first sample, and trimmed to a circle of diameter 1.943 cm just below the stack of fission samples. In the stack containing the Cm samples, there were a number of other fissionable and monitor samples. The complete list of samples in this stack, in the order in which the beam passed through, is as follows: ^{243}Cm, ^{244}Cm, ^{246}Cm, ^{248}Cm, ^{238}U, Blank, ^{6}Li, ^{235}U, ^{245}Cm, ^{247}Cm, ^{242}Pu, ^{244}Pu, ^{237}Np, ^{243}Am, ^{10}B. After passing through this stack, located on the first floor of a 30-m-high tower, the beam was passed undisturbed to the sixth and seventh floors. On the sixth floor, a collimator reduced the size of the beam to a circle 9.53 mm in diameter. The beam was then passed through a ribbon of ^{197}Au and ^{238}U, spinning on a drum, to serve as an absolute calibration for Moxon-Rae capture detectors.[11] Next, the beam passed through thin foils of ^{235}U, ^{252}Cf, blank, ^{6}Li, and ^{236}U, and then through a Bi-^{243}Am sample, a ^{6}Li foil, the Cm capture sample, and another ^{6}Li foil. Higher on the seventh floor, the beam was polarized by transmission through a lanthanum-magnesium nitrate crystal, analyzed, and finally dumped into the air. This beam was one of five provided in the event for physics measurements.

Sample preparation and assay was a crucial part of the experiment. The target material used in most of the fission measurements was electromagnetically separated at Oak Ridge National Laboratory (ORNL). The ^{248}Cm sample consisted of material from ^{252}Cf decay. The Cm capture sample resulted from a high-flux irradiation at the Savannah River Plant, and consisted of material with a relatively high ^{246}Cm and ^{248}Cm content. The fission foils were prepared by electrodeposition from an organic solvent; the technique has been described by Kapplemann and Baybarz.[15] Target foils of ^{244}Cm and ^{246}Cm, and a backup foil of ^{248}Cm were prepared at the Savannah River Laboratory, and were assayed there by detection of the 44-keV ^{244}Cm γ ray. Target foils of ^{245}Cm, ^{247}Cm, and ^{248}Cm were prepared at the ORNL. All target foils were assayed at ORNL and at the Los Alamos Scientific Laboratory by low-geometry α counting. At Los Alamos, the energy deposited per fission was also determined by observing the pulse-height spectrum of fragments of spontaneous fission incident on a typical solid-state detector in the geometry used in the measurement. Slight corrections in the energy deposit were made both for the differences in detector window thickness and for the expected differences in energy release for spontaneous and neutron-induced fission, as deduced from the systematics discussed by Viola and Seaborg.[16]

The Cm capture sample was prepared at the Idaho Nuclear Corporation by mixing curium oxide and aluminum powder and pressing into a wafer. The technique used is very similar to that previously described by Berreth.[17]

III. DATA REDUCTION

The first step in processing the data is the digitizing of the analog signal recorded on photographic film. One of the major drawbacks in recording the signals photographically is the several months required for digitization. For the Physics 8 event, most of the data, including all the Cm data, were digitized by professional film readers at New Mexico State University. Reduction of the digitized data was done with the help of computer codes developed over the past several years by Seeger[18] at Los Alamos. This data reduction is done in three stages: Phase I data processing consists of converting the raw readings of oscilloscope deflection recordings (x-y readings) to a voltage signal (detector current through a standard resistor) vs neutron time of flight. In Phase II data processing, signals from flux monitors (detectors viewing ^{235}U and ^{6}Li samples) and background signals are combined to give cross sections as a function of neutron energy; these cross sections are then suitably averaged, since generally more than one detector and recording have been used. Phase III data processing is the stage at which the cross sections are analyzed and resonance parameters extracted.

All the Cm cross sections reported in this paper were determined relative to the cross section of ^{6}Li$(n, t)^{4}$He below 100 keV, and to the fission cross section of ^{235}U above 100 keV. The ^{235}U cross section used as a reference above 100 keV was the evaluated set of Davey.[19] The reference cross section of ^{6}Li used was that of Schwarz, Strömberg, and Bergström,[20] and appears to be perhaps 4% higher between 20 and 80 keV than a more recent determination by Uttley and Diment.[21] The Uttley and Diment determination was not available in tabular form at the time the Cm data were reduced.

A number of corrections were made to the data. All the fission samples contained a sizeable fraction of ^{244}Cm and at least trace amounts of the higher-mass isotopes, as shown by the isotopic analysis in Table I. The fission data for each isotope were corrected by subtracting the appropriate fraction of the contaminant cross section for the other isotopes. In virtually every case, the correction based on the isotopic analysis was sufficient to remove resonance structure due to the contaminant isotopes. The only exception was the ^{248}Cm sample, which required a 1.3% correction for ^{245}Cm, rather than the 0.13% correction implied by the isotopic analysis. The final cross sections thus ob-

TABLE I. Isotopic analysis of samples.

	^{240}Pu %	^{243}Am %	^{243}Cm %	^{244}Cm %	^{245}Cm %	^{246}Cm %	^{247}Cm %	^{248}Cm %
^{244}Cm fission (83.5 μg)	0.7	0.1	0.1	98.5	0.12	0.37	~0.1	~0.1
^{245}Cm fission (34.1 μg)	0.16	···	···	22.98	76.52	0.334	0.0025	0.0016
^{246}Cm fission (16.3 μg)	0.04	0.38	···	4.96	0.164	94.70	0.072	0.068
^{247}Cm fission (26.9 μg)	0.35	···	···	49.88	0.613	26.32	20.9	1.96
^{248}Cm fission (67.6 μg)	0.06	···	···	7.80	0.119	2.71	0.039	89.27
Mixed Cm capture (397 mg)	1.47	1.63	···	79.18	0.68	15.70	0.46	0.88

tained are fission cross sections for a pure isotopic sample, with the exception that fission contributions from the ^{240}Pu, ^{243}Am, and ^{243}Cm contaminants were ignored. It may be noted that the ^{244}Cm and ^{246}Cm corrections were particularly large for the ^{247}Cm sample above 1 MeV, where the even isotopes show large fission cross sections.

The capture cross section obtained with the sample of mixed isotopes required complete renormalization because only about half the sample was in the neutron beam. The sample was radiographed after the experiment, and the radiograph showed

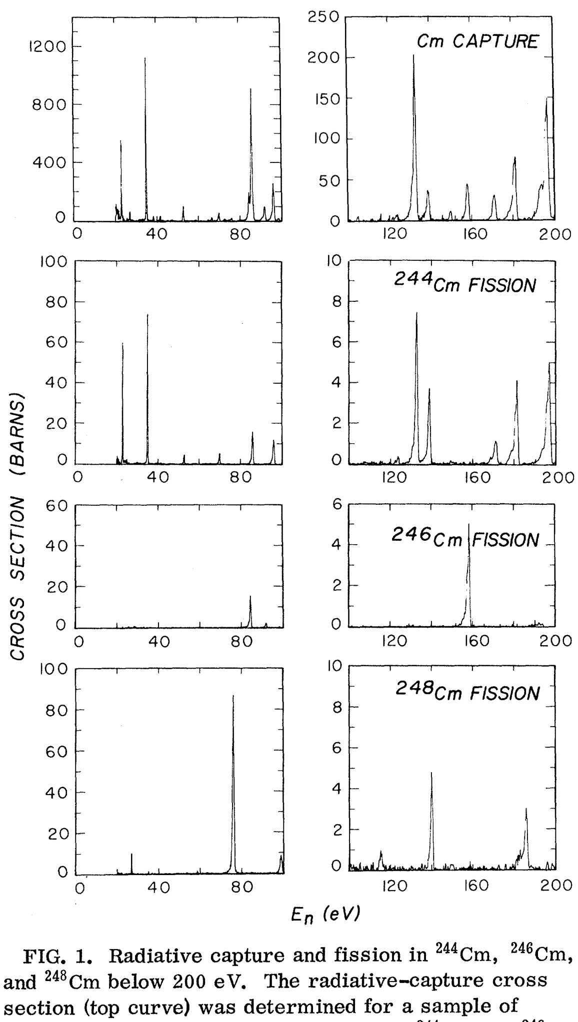

FIG. 1. Radiative capture and fission in ^{244}Cm, ^{246}Cm, and ^{248}Cm below 200 eV. The radiative-capture cross section (top curve) was determined for a sample of mixed Cm isotopes containing primarily ^{244}Cm and ^{246}Cm. The cross section was calculated using the sample thickness appropriate for ^{244}Cm; for ^{246}Cm and ^{248}Cm resonances, the cross sections shown should be multiplied by the appropriate relative isotopic abundances. Isotopic identification of the resonances was made using the fission cross sections for ^{244}Cm, ^{246}Cm, and ^{248}Cm shown in the lower three curves. The marked asymmetries evident in the resonances between 100–200 eV are attributed to moderator effects.

that the Cm wafer had shifted in the sample can, presumably in shipment. The data were renormalized as follows: The Moxon-Rae capture detector is sensitive to γ radiation from fission as well as to that from radiative capture, and the relative efficiencies of the detector to fission and capture radiation are known from previous measurements on ^{238}Pu by Silbert, Moat, and Young,[22] and from Physics 8 measurements on ^{239}Pu by Farrell *et al.*[23] The raw Cm γ-ray signals showed a large effect near 1 MeV which is due purely to prompt fission γ rays from the even isotopes above the fission threshold. Renormalization of the final capture cross section was done by requiring that this fission γ component should disappear when the fission contribution was subtracted to obtain the radiative capture cross section. Analysis of the resulting capture cross section yielded resonance parameters which are reasonably consistent with those obtained by Coté, Barnes, and Diamond,[5] by Berreth and Simpson[6] for ^{244}Cm, and with ^{240}Pu parameters determined by Asghar, Moxon, and Pattenden.[24]

An attempt was also made to determine the total cross section of ^{244}Cm, by placing matched ^{6}Li samples above and below the Cm capture sample. Since this sample did not completely cover the beam, a renormalization of these data was also carried out, using the capture results to determine the fraction of the beam which missed the sample. Analysis of the total cross sections gave resonance parameters which appeared to be systematically larger than those obtained from previous work on ^{244}Cm,[5,6] but which were generally within the rather sizeable errors introduced by the renormalization. While the total cross sections were not included in the final analysis, the transmission data did permit adequate sample self-shielding corrections to be made on the capture cross section.

Multiple scattering corrections to the resonance areas were calculated by an analytical program developed by Grench,[25] which has been shown to give excellent agreement for small corrections with a more exact Monte Carlo treatment. This program treats the resonances one at a time; for the Cm capture data, the resonances are widely enough spaced that ignoring resonance-resonance interaction is generally acceptable. For only one resonance, that at 86 eV, was the multiple scattering correction larger than 3%; here it was 6.2%. A correction expected to be $3 \pm 3\%$ was applied to the 84.4-eV ^{246}Cm resonance which lies on the low-energy shoulder of this large resonance and must contain some effect due to the higher energy scattered neutrons from the large ^{244}Cm resonance. Corrections smaller than 1% were ignored.

Fission backgrounds, determined to an accuracy of about 10%, were taken by measuring the signal

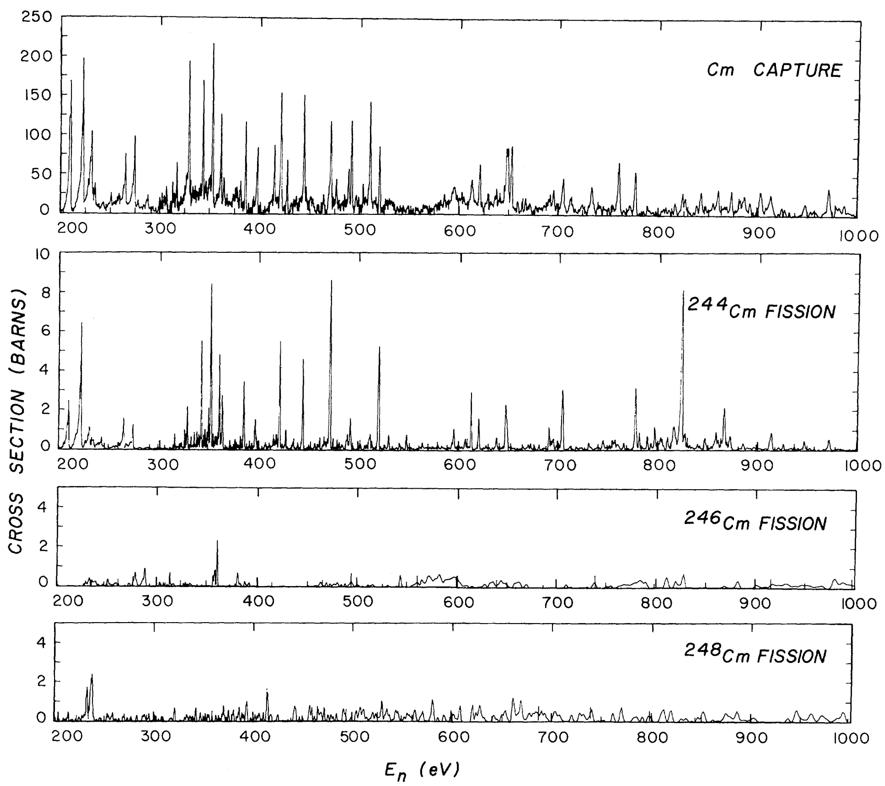

FIG. 2. Radiative capture and fission in ^{244}Cm, ^{246}Cm, and ^{248}Cm from 200 to 1000 eV. The cross sections were calculated using the sample thickness appropriate for ^{244}Cm; for ^{246}Cm resonances, the cross sections shown should be multiplied by the appropriate relative isotope abundances. All the resonance structure seen in the capture cross section could be attributed to ^{244}Cm or ^{246}Cm in this energy region.

from the blank stainless-steel backings. These backgrounds were generally quite low; they were important only for the even targets between 1 and 200 keV, where they amounted to about half the observed signal level for ^{244}Cm and ^{248}Cm, and to more than 90% of the observed signal level for ^{246}Cm. A more detailed discussion of fission backgrounds is given elsewhere.[9]

The background for the Cm capture sample was determined by detecting the signal from a canned wafer of bismuth, pressed with aluminum, which had been calculated to have the same effective macroscopic scattering cross section as the Cm sample while yielding no γ radiation. For the capture sample, the background level was equivalent to an effective cross section of 10–15 b over most of the energy region below 100 keV, and represents an effective upper limit of ~10 keV above which the capture cross section was not determined from the present measurements. No correction was made in the fission cross sections for the capture γ rays and conversion electrons detected by the fission-fragment detectors. The efficiency of these bare detectors for detecting capture events yielding only γ radiation is about 0.1% of the efficiency for detecting fission events. The detection of conversion electrons can enhance the apparent γ efficiency by a factor of 2 or more, depending on the details of the cascade and the conversion electron yield. Thus, all the resonances observed in capture can be expected to be observed in the fission measurement whether fission is actually taking place or not, with an apparent lower limit of the fission width of 0.1 to 0.2% of the capture width, or roughly 0.06 meV. In most cases, this is small compared to the probable errors assigned to the fission widths.

Low- and high-resolution recordings of the signals were averaged together below 300 eV, where the experimental resolution is determined by the moderator, and between 1 and 100 keV where the resolution function becomes larger than the resonance spacing. High-resolution recordings were used exclusively between 300 and 1000 eV for the ^{244}Cm, ^{245}Cm, ^{247}Cm, and capture samples, and above 100 keV for all samples. The resolution was sufficient for detailed resonance analysis to be carried out below 1000 eV for ^{244}Cm, below about 400 eV for ^{246}Cm and ^{248}Cm, and below 60 eV for the odd targets, where the level spacing is a factor

TABLE II. Resonance parameters for ^{244}Cm + n with Γ_γ = 37 meV assumed.

E_0 (eV)	$\frac{\pi}{2}\sigma_0\Gamma_\gamma$ (b eV)	$\frac{\pi}{2}\sigma_0\Gamma_f$ (b eV)	Γ_n (meV)	Γ_f (meV)	E_0 (eV)	$\frac{\pi}{2}\sigma_0\Gamma_\gamma$ (b eV)	$\frac{\pi}{2}\sigma_0\Gamma_f$ (b eV)	Γ_n (meV)	Γ_f (meV)
22.85	140 ± 10	14.0 ± 0.6	0.88 ± 0.09	3.7 ± 0.3	512.4	290 ± 14	1.6 ± 0.3	Large	0.20 ± 0.04
34.99	350 ± 9	23.7 ± 0.3	3.5 ± 0.3	2.51 ± 0.07	520.5	116 ± 7	8.0 ± 0.6	26 ± 4	2.55 ± 0.26
52.78	41 ± 5	1.9 ± 0.1	0.56 ± 0.08	1.7 ± 0.2	596.4 [a]	79 ± 39	2.1 ± 0.5	17 ± 12	1.0 ± 0.5
67.99	36 ± 3	2.9 ± 0.1	0.67 ± 0.07	3.0 ± 0.3	612.4	109 ± 45	3.0 ± 0.5	30 ± 22	1.0 ± 0.5
85.96	710 ± 20	12.5 ± 0.2	24.5 ± 2.3	0.65 ± 0.02	620.0	103 ± 23	2.2 ± 0.3	27 ± 10	0.8 ± 0.2
96.12	252 ± 6	10.5 ± 0.2	7.3 ± 0.6	1.54 ± 0.05	627.8	36 ± 21	0.2 ± 0.2	7 ± 4	<0.5
132.8	320 ± 11	10.2 ± 0.2	15.5 ± 2	1.17 ± 0.04	637.9 [a]	49 ± 21	0.9 ± 0.3	10 ± 5	0.7 ± 0.4
139.1	65 ± 6	5.0 ± 0.2	2.5 ± 0.3	2.8 ± 0.3	646.9 [a]	321 ± 31	5.9 ± 0.6	Large	0.68 ± 0.10
171.2	70 ± 8	2.4 ± 0.1	3.3 ± 0.5	1.3 ± 0.2	652.4	160 ± 16	0.2 ± 0.2	81 ± 27	<0.1
181.6	170 ± 9	9.7 ± 0.3	10 ± 0.9	2.1 ± 0.1	691.3	57 ± 17	1.2 ± 0.3	13 ± 5	0.8 ± 0.3
197.0	410 ± 17	11.1 ± 0.5	43 ± 5	1.00 ± 0.06	695.3	64 ± 16	1.2 ± 0.3	16 ± 5	0.7 ± 0.3
209.8	380 ± 17	5.3 ± 0.4	42 ± 5	0.52 ± 0.04	704.5	135 ± 22	5.5 ± 0.7	64 ± 28	1.5 ± 0.3
220.1	398 ± 48	13.6 ± 0.6	54 ± 16	1.25 ± 0.16	712.8	75 ± 16	0.1 ± 0.1	20 ± 7	<0.2
230.5	289 ± 41	3.1 ± 0.3	30 ± 7	0.40 ± 0.07	731.6 [a]	128 ± 15	0.6 ± 0.3	60 ± 19	0.17 ± 0.09
234.9	60 ± 17	1.5 ± 0.3	3.8 ± 1.2	0.9 ± 0.3	746.0 [b]	18 ± 9	0.8 ± 0.3	4 ± 2	1.6 ± 1.0
242.7	20 ± 19	2.1 ± 0.3	1.3 ± 1.2	>2.2	759.7 [a]	193 ± 14	0.9 ± 0.5	Large	0.17 ± 0.10
264.9	124 ± 48	3.1 ± 0.4	10 ± 5	0.9 ± 0.4	778.6	127 ± 9	6.0 ± 0.7	72 ± 15	1.7 ± 0.2
274.1	164 ± 50	2.8 ± 0.4	16 ± 7	0.6 ± 0.2	790.1 [b]	17 ± 8	0.8 ± 0.3	4 ± 2	1.7 ± 1.0
316.8	62 ± 6	0.5 ± 0.1	5.5 ± 0.7	0.3 ± 0.07	797.5	7 ± 7	1.8 ± 0.5	2 ± 2	>3.7
329.5	294 ± 21	2.3 ± 0.2	6.6 ± 1.4	0.29 ± 0.03	802.5 [a]	29 ± 9	2.4 ± 0.6	7 ± 2	3.1 ± 1.2
343.6	177 ± 22	5.6 ± 0.4	26 ± 5	1.16 ± 0.16	815.8	41 ± 7	3.3 ± 0.7	11 ± 2	3.0 ± 0.8
353.1	309 ± 19	10.8 ± 0.6	101 ± 23	1.28 ± 0.11	823.0	69 ± 13	17.4 ± 1.5	28 ± 7	9.3 ± 1.9
361.7	196 ± 25	5.5 ± 0.4	34 ± 8	1.03 ± 0.16	846.3	24 ± 14	1.1 ± 0.4	6 ± 4	1.7 ± 1.2
364.4	85 ± 17	4.8 ± 0.3	10 ± 2	2.1 ± 0.4	857.9	82 ± 19	3.2 ± 0.5	33 ± 14	1.4 ± 0.4
386.2	158 ± 8	4.8 ± 0.3	26 ± 3	1.11 ± 0.09	865.6	47 ± 22	5.2 ± 0.7	15 ± 9	4.1 ± 2.0
397.6 [a]	145 ± 8	2.6 ± 0.3	23 ± 3	0.66 ± 0.08	872.0	66 ± 16	1.8 ± 0.6	23 ± 9	1.0 ± 0.4
415.0	122 ± 9	0.9 ± 0.2	19 ± 2	0.27 ± 0.06	884.9	107 ± 19	0.7 ± 0.4	62 ± 29	0.2 ± 0.1
420.6 [a]	254 ± 11	6.2 ± 0.5	93 ± 16	0.89 ± 0.08	899.7	131 ± 14	0.5 ± 0.3	128 ± 62	0.14 ± 0.09
426.9	94 ± 7	0.9 ± 0.3	13 ± 2	0.35 ± 0.12	914.0	146 ± 20	2.3 ± 0.7	Large	0.6 ± 0.2
443.4	236 ± 15	5.3 ± 0.6	86 ± 19	0.82 ± 0.11	926.3	56 ± 13	0.4 ± 0.4	19 ± 7	<0.5
470.9	260 ± 17	13.0 ± 0.7	167 ± 58	1.84 ± 0.16	946.9	76 ± 13	0.9 ± 0.6	34 ± 11	0.4 ± 0.3
488.9	88 ± 7	1.2 ± 0.3	15 ± 2	0.50 ± 0.13	971.5	139 ± 14	1.3 ± 0.4	Large	0.35 ± 0.11
491.9	180 ± 7	2.3 ± 0.5	54 ± 6	0.47 ± 0.10					

[a] Resonances marked with an "a" are probably unresolved doublets, which were analyzed as single resonances. The neutron widths are thus upper limits, and the fission widths are a weighted average, the weighting factors being unknown.

[b] Fission resonances at 746 and 790 eV are probably attributable to the 0.7% ^{240}Pu contaminant in the sample.

of 10 lower.

IV. ANALYSIS AND RESULTS

A. Capture and Fission in Even Cm Targets in Resonance Region

Measurement of the fission cross section usually permitted isotopic identification of the capture resonances observed. Figure 1 shows radiative capture and fission in ^{244}Cm, ^{246}Cm, and ^{248}Cm below 200 eV. All the strong resonance peaks in capture could be attributed to ^{244}Cm or ^{246}Cm; weaker ones could be identified as belonging to ^{248}Cm or ^{240}Pu, present from ^{244}Cm decay. Resonances seen in the capture data between 200 and 1000 eV, shown in Fig. 2, were all assigned to ^{244}Cm or ^{246}Cm. Resonance parameters obtained from single-level area analysis of these data are listed in Tables II–IV. Although it was assumed that all these resonances are *s* wave, the possibility that some of the weaker ones may be *p*-wave resonances should not be overlooked. In the analysis of resonances in the even-even Cm targets, neutron widths were calculated from the capture and fission areas under the assumption that the radiative capture width is constant and equal to 37 meV, following Coté, Barnes, and Diamond.[5] For ^{244}Cm, an attempt was made to determine the average capture width for those resonances for which Coté, Barnes, and Diamond determined neutron widths; the resulting value was 50 ± 13 meV. An attempt was also made to utilize the total cross section of ^{244}Cm obtained in the present measurement to determine Γ_n; here the results gave $\langle \Gamma_\gamma \rangle$ = 32 ± 9 meV. Both of these values are

TABLE III. Resonance parameters for ^{246}Cm + n with $\Gamma_\gamma = 37$ meV assumed.

E_0 (eV)	$\frac{\pi}{2}\sigma_0\Gamma_\gamma$ (b eV)	$\frac{\pi}{2}\sigma_0\Gamma_f$ (b eV)	Γ_n (meV)	Γ_f (meV)
84.43	661 ± 100	12.5 ± 0.4	22 ± 5	0.70 ± 0.10
91.84	560 ± 30	2.6 ± 0.4	19 ± 2	0.17 ± 0.03
158.4	414 ± 40	8.2 ± 0.8	29 ± 5	0.73 ± 0.11
250.7	116 ± 60	1.2 ± 0.5	9 ± 6	0.38 ± 0.3
278.3	80 ± 60	2.9 ± 0.9	7 ± 6	1.3 ± 1.2
288.2	323 ± 80	2.7 ± 0.9	59 ± 38	0.31 ± 0.14
313.4	197 ± 35	0.8 ± 0.3	25 ± 8	0.15 ± 0.10
361.0 [a]	···	3.5 ± 0.7	···	···
381.1	303 ± 35	1.5 ± 0.6	118 ± 57	0.18 ± 0.09

[a] The resonance at 361 eV is probably an unresolved doublet.

consistent, within their errors, with the 37.7 ± 5.3 meV which is the weighted average of the three values given by Coté, Barnes, and Diamond.

It should be noted that some of the resonances in ^{244}Cm and ^{248}Cm are not consistent with the assumption that the radiative width is as small as 37 meV. A few of these are probably doublets, analyzed as single resonances. The others imply $\Gamma_\gamma > 37$ meV and/or a neutron width which is so large as to be indeterminate by the present analysis. All such cases are designated in Tables II and IV as having "large" neutron widths. The neutron width distribution was studied for resonances in (^{244}Cm + n) below 390 eV, where all resonances observed appear to be clearly resolved. If it is assumed that the neutron widths follow a Porter-Thomas distribution (a χ^2 distribution with one degree of freedom), then the observed neutron-width distribution indicates that ~20% of the levels were missed because their neutron widths are too small for them to have been observed.

The fission widths in (^{244}Cm + n) fit almost perfectly a χ^2 distribution with 2 degrees of freedom.

TABLE IV. Resonance parameters for ^{248}Cm + n with $\Gamma_\gamma = 37$ meV assumed.

E_0 (eV)	$\frac{\pi}{2}\sigma_0\Gamma_\gamma$ (b eV)	$\frac{\pi}{2}\sigma_0\Gamma_f$ (b eV)	Γ_n (meV)	Γ_f (meV)
26.84	2270 ± 160	5.1 ± 0.4	25 ± 3	0.08 ± 0.01
76.08	1830 ± 200	162.0 ± 10.0	Large	3.3 ± 0.4
98.79	1640 ± 90	21.0 ± 1.3	Large	0.47 ± 0.04
140.0	···	5.9 ± 0.4	···	···
186.0	···	7.1 ± 0.5	···	···
232.5	···	2.3 ± 1.1	···	···
237.0	···	8.8 ± 1.1	···	···
415.2	···	2.8 ± 0.8	···	···

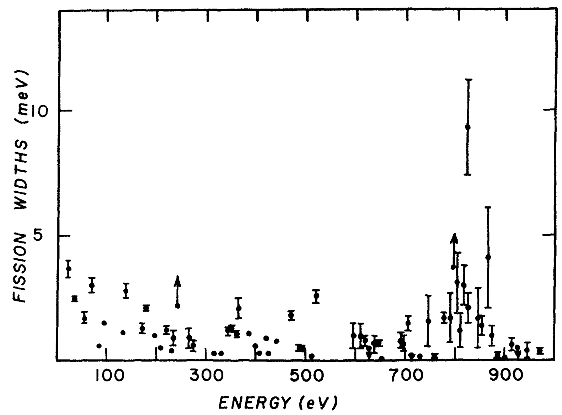

FIG. 3. Fission widths for (^{244}Cm + n), calculated from the resonances areas under the assumption that the radiative capture width has the value of 37 meV.

In this study, all the levels were considered, since if the neutron and fission widths are uncorrelated, the missed levels do not affect the distribution.

A plot of the fission widths of ^{244}Cm as a function of neutron energy gives some evidence for intermediate structure in the region of 820 eV, as shown in Fig. 3. A search for possible anomalies of this sort at higher energies, where individual resonances are not resolved, was made by calculating the average fission-to-capture ratio below 5 keV. The results of this calculation are shown in Fig. 4. It can be seen that several additional regions seem to exist where the average fission cross section is enhanced relative to capture. Since ^{244}Cm decays to ^{240}Pu with a relatively short half-life (18 yr), a possible explanation for this structure is that it may be due to an unexpected contaminant of ^{240}Pu. Subthreshold fission of ^{240}Pu shows enhancement near 800, 1400, 1900, and 2700 eV, as reported by Migneco and Theobald.[26] However,

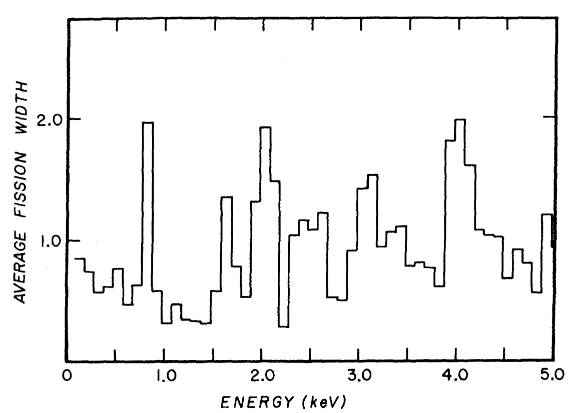

FIG. 4. The average fission width for (^{244}Cm + n) below 5 keV. The average width has been calculated from the fission-to-capture ratio, under the assumption that the capture width is 37 meV.

by comparing the detailed fission resonance structure in ^{240}Pu with that shown here, one can rule out ^{240}Pu as a significant cause of the observed effect. Resonances at 746, 790, and 809 possibly do correspond to the strongest three subthreshold fission resonances in ^{240}Pu, since their fission areas would be at about the 0.7% level for ^{240}Pu contamination. For the other ^{244}Cm resonance energies, there is no correlation with fission structure in ^{240}Pu. In particular, the areas of the peaks in Fig. 4 cannot be attributed to ^{240}Pu.

Considering just those ^{244}Cm resonances lying in an energy interval of 100 eV about 820 eV, one notes that only 2 of 12 have a fission width less than the average. If one assumes that the distribution of fission widths is a χ^2 distribution with 1 degree of freedom, one would expect in any arbitrary energy interval to find roughly 67% of the resonance widths below the average. Applying a χ^2 test to these fission widths, one finds that the χ^2 for 6 degrees of freedom is 15, or the probability that these resonances belong to the assumed Porter-Thomas distribution is about 1%. However, one can go through the same exercise for a χ^2 distribution with 2 degrees of freedom, which gives a much better fit to the data. Here, one finds χ^2 of 13 for 6 degrees of freedom, or a probability of 2% that a random sample of resonances belonging to the distribution would give a larger χ^2. One can also consider just the level at 823 eV, which has a fission width nearly 7 times the average. This is far out on the wing of a Porter-Thomas distribution ($P = 0.86\%$), and is even less likely ($P = 0.10\%$) for a χ^2 distribution with 2 degrees of freedom. The evidence is strong that the structure in fission is due to something other than the expected Porter-Thomas fluctuations, but it is not conclusive.

At higher energies, the individual resonances are not resolved, and statistically the average fission width should follow a χ^2 distribution with the number of degrees of freedom roughly equal to the number of resonances in the averaging interval. The average fission widths shown in Fig. 4 are distri-

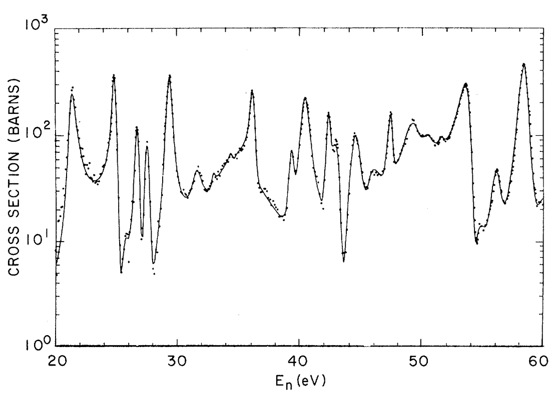

FIG. 5. The fission cross section of ^{245}Cm from 20 to 60 eV. The points represent the digitized experimental measurement; the solid curve is a least-squares multilevel fit to the data which gave the parameters in Table V.

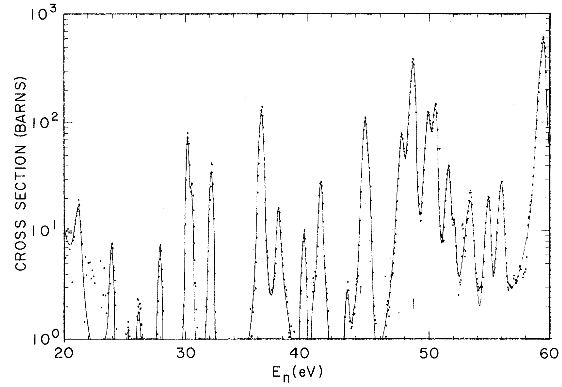

Fig. 6 The fission cross section of ^{247}Cm from 20 to 60 eV. The points represent the digitized experimental measurement; the solid curve is a least-squares multilevel fit to the data which gave the parameters in Table VI.

TABLE V. Resonance parameters for resonances in ($^{245}Cm+n$) between 20 and 60 eV. Phase angles refer to the fission-width-vector orientation in a two-fission-channel, single-spin-state analysis.

E_0 (eV)	$2g\Gamma_n{}^0$ (meV)	Γ_γ (meV)	Γ_f (meV)	θ (deg)
21.36	0.457	(40)	485	−16
24.90	0.521	(40)	226	99
25.84	0.007	(40)	549	89
26.83	0.147	(40)	131	160
27.63	0.114	(40)	165	90
29.42	0.638	(40)	328	−171
31.71	0.088	(40)	691	−69 [a]
32.99	0.064	(40)	4	−61
34.59	0.039	(40)	61	113
35.31	1.276	(40)	4195	54
36.32	0.256	(40)	189	177
39.45	0.104	(40)	102	−126 [a]
40.44	0.705	(40)	585	128
42.45	0.824	(40)	10	56
43.10	0.264	(40)	537	−55
44.57	0.391	(40)	694	−67
45.74	0.087	(40)	901	−9
47.51	0.516	(40)	28	28
49.20	0.718	(40)	1399	58
50.48	0.252	(40)	751	92
51.64	0.087	(40)	207	106
53.63	1.687	(40)	896	−173
54.63	0.045	(40)	1057	174
56.32	0.186	(40)	505	54
58.54	1.811	(40)	393	162
59.99	0.079	(40)	518	−39

[a]Best fits were obtained by placing those resonances marked with an a in a different spin group.

buted as a χ^2 distribution with $\nu \geq 8$, with a probability of ~2% that the highest peaks are part of the distribution. If the structure shown in Fig. 4 is attributed instead to intermediate structure, then there appear to be 5 ± 2 groups below 5 keV, giving a D_{II} spacing of $1000\pm^{600}_{300}$ eV.

B. Capture and Fission in Odd Cm Targets in Resonance Region

Because of the much closer spacing of resonances, analysis of the fission cross sections of ^{245}Cm and ^{247}Cm was possible only below 60 eV. The results of the analysis are shown by the solid curves in Figs. 5 and 6. There is a qualitative difference in the appearance of the cross sections of ^{245}Cm and ^{247}Cm. The structure in (^{245}Cm + n) shows marked interference effects among rather wide resonances, while the structure in (^{247}Cm + n) is narrower and shows only a few asymmetries in shape. Both sets of data were analyzed by the R-matrix least-squares search routine developed by Auchampaugh.[27] Multilevel parameters are listed in Tables V and VI, and average parameters for all five targets studied are listed in Table VII.

Only one resonance was observed in the raw capture data which could be attributed to (^{245}Cm + n), that at 115 eV. This one disappeared when the fission component was subtracted, leaving no net area due to radiative capture alone. No resonances in ^{247}Cm were observed in the capture data. Nevertheless, the analysis of the fission data can be used to give information on the radiative capture cross sections of ^{245}Cm and ^{247}Cm. Since the fission widths are generally much larger than the capture widths, the calculated capture cross section is proportional to the value assumed for the capture width.

In order to check the validity of this argument, the ratios of the resonance capture and absorption integrals were calculated from resonance parameters, for the energy region between 20 and 60 eV. The resulting ratios are 0.15 ± 0.02 and 0.49 ± 0.10 for ^{245}Cm and ^{247}Cm, respectively. These can be compared to recommended values[28] of 0.12 and

TABLE VI. Resonance parameters for resonances in (^{247}Cm + n) between 20 and 60 eV. Phase angles refer to the fission-width-vector orientation in a two-fission-channel, single-spin-state analysis.

E_0 (eV)	$2g\Gamma_n{}^0$ (meV)	Γ_γ (meV)	Γ_f (meV)	θ (deg)
21.30	0.027	(40)	404	−61
24.03	0.009	(40)	134	−153
25.35	0.002	(40)	26	−103
26.19	0.003	(40)	220	−129
28.04	0.011	(40)	53	35
30.25	0.627	(40)	4	−94
30.62	0.034	(40)	52	−30
32.23	0.089	(40)	26	−92
36.36	0.270	(40)	61	−38
37.74	0.004	(40)	555	−153
37.76	0.217	(40)	13	−178
39.52	0.001	(40)	705	−163
39.95	0.015	(40)	167	19
40.61	0.005	(40)	48	−134
41.25	0.103	(40)	20	105
41.76	0.008	(40)	546	−11
43.39	0.029	(40)	4	117
44.87	0.313	(40)	32	11
45.21	0.086	(40)	60	−119
47.92	0.169	(40)	164	−75
48.85	0.973	(40)	82	25
50.08	0.334	(40)	55	−127
50.69	0.447	(40)	52	22
51.78	0.231	(40)	14	−154
52.19	0.175	(40)	4	−48
53.63	0.062	(40)	324	121
55.10	0.072	(40)	38	88
56.18	0.088	(40)	69	63
59.66	2.037	(40)	114	−68

0.39 for the ratios of the complete capture and absorption resonance integrals of ^{245}Cm and ^{247}Cm, respectively, and to 0.15 and 0.36 for the ratios obtained with thermal reactor neutrons. The present value of 0.49 ± 0.10 for ^{247}Cm can be questioned because the fit to the fission data is quite insensitive to the actual value of Γ_f whenever it is much smaller than Γ_γ. However, the ratio of the capture and absorption resonance integrals is also surprisingly insensitive to these: if all the Γ_f parameters hav-

TABLE VII. Average parameters for curium isotopes, as determined from resolved resonances. The value of $\langle\Gamma_f\rangle$ at 100 eV from the fit to the threshold is included for comparison.

Target	D (observed) (eV)	$\langle\Gamma_n{}^0\rangle$ (observed) (meV)	$\langle\Gamma_n{}^0\rangle / D$ ($\times10^{-4}$)	$\langle\Gamma_f\rangle$ (meV)	$\langle\Gamma_f\rangle$ from threshold (meV)
^{244}Cm	13.7	1.64	1.2	1.35	1.0
^{245}Cm	4.6	0.437	1.0	600	···
^{246}Cm	38	2.3	0.6	0.48	2.4
^{247}Cm	4.1	0.222	0.5	140	···
^{248}Cm	35	···	···	1.3	1.9

ing values below 40 meV are doubled, keeping the product $\Gamma_n\Gamma_f$ constant, the calculated ratio of the capture-to-absorption resonance integrals is still 0.41. The assigned error includes this uncertainty as well as an assumed error of 10% in the value chosen for Γ_γ.

The analyses of both the ^{245}Cm and ^{247}Cm fission cross sections were carried out under the assumption that resonances could interfere in two channels in a single-spin state. This, of course, is not correct in principle, but it is the simplest procedure in practice, because it allows the search routine to have maximum freedom. The differences in the parameters between this approach and the more nearly correct one (to be used if all resonance spins are known) are small.

The target ^{245}Cm, with a ground-state spin of $\frac{7}{2}^+$, resembles $\frac{5}{2}^+$ ^{233}U and ^{241}Pu. As might be expected, $\frac{9}{2}^-$ ^{247}Cm more nearly follows $\frac{7}{2}^-$ ^{235}U. For (^{241}Pu + n), a multilevel analysis of the fission cross section by Moore *et al.*[29] suggested that the widths of the resonances are strongly spin dependent. This was verified by a measurement of the scattering cross section of ^{241}Pu by Sauter and Bowman,[30] from which the resonance spins were determined. Multilevel analysis of the ^{235}U fission cross section by Cramer[31] also suggested that the resonance spins could be determined in this way, although direct evidence has not supported the assignments which were made.

Even though it has been pointed out by Auchampaugh[32] that in general the phase relationships of the fission vectors are not uniquely given in the R-matrix approach, some indication of the resonance spins does appear to be possible in favorable cases. A study of the fission-vector phase relationships

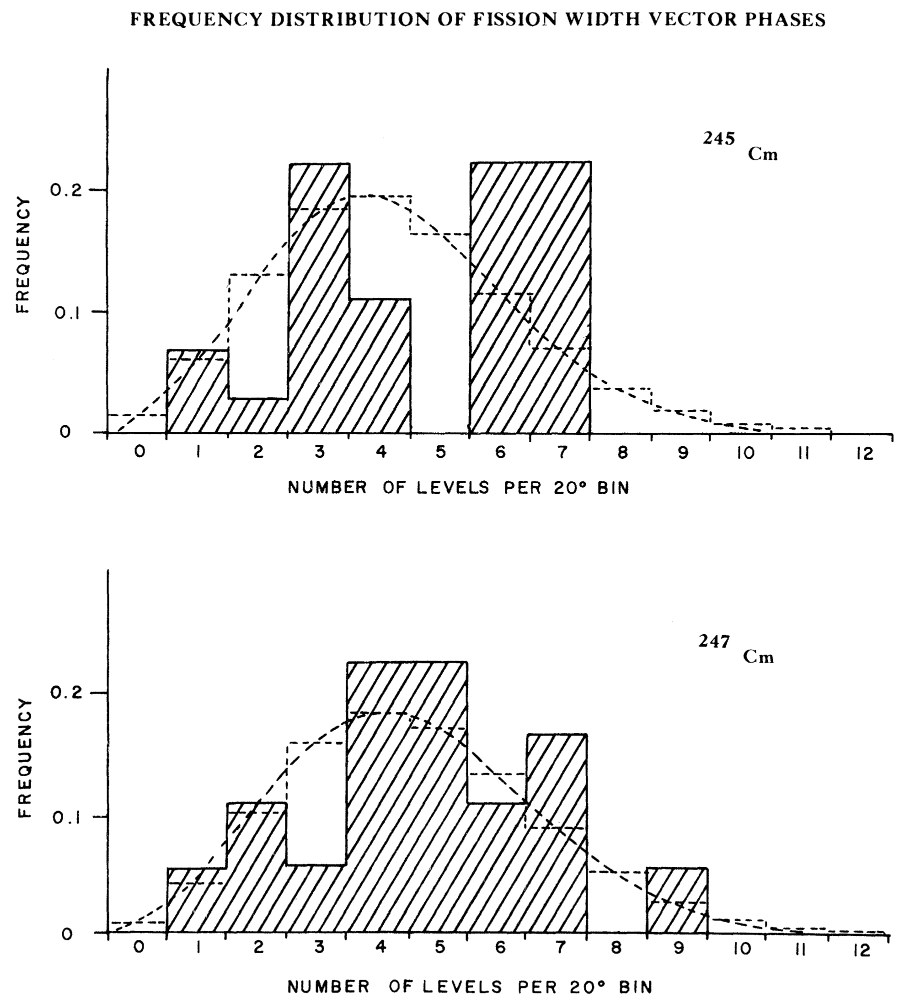

FIG. 7. Distribution of the fission-vector phase relationships from a two-fission-channel, single-spin-state analysis. The dashed curves show a Poisson distribution, which would be expected if the vectors were randomly oriented in the assumed channel space.

was carried out for ^{245}Cm and ^{247}Cm, in order to discover if a spin dependence of the resonance fission width is indicated for these isotopes. Figure 7 shows the distribution of the phase angles for ^{245}Cm and ^{247}Cm. For ^{247}Cm, the distribution is compatible with a Poisson distribution, which is to be expected if the fission vectors are randomly oriented. The distribution for ^{245}Cm is probably not a Poisson distribution ($P = 0.02$), although there is not a clean separation of the phases into two groups.

C. Fission Cross Sections of Cm Isotopes Above Resonance Region

Figure 8 shows the fission cross section of the five targets studied below 3 MeV. Fission thresholds for ^{244}Cm, ^{246}Cm, and ^{248}Cm appear at 740, 930, and 890 keV, respectively. The fission cross sections above 1 MeV do not seem to show the systematic trend downward with increasing mass, as suggested by Smith, Smith, and Henkel.[33] However, the values of the Cm cross sections are within 30% of those predicted by Smith, Smith, and Henkel, with the exception of ^{247}Cm. Here, the data may be in error because of the very large corrections for ^{244}Cm and ^{246}Cm in the sample. The ^{244}Cm fission cross section above threshold is about 10% higher, on the average, than the data obtained by Barton and Koontz,[34] and agrees well within the errors with previous measurements reported by Fullwood.[7]

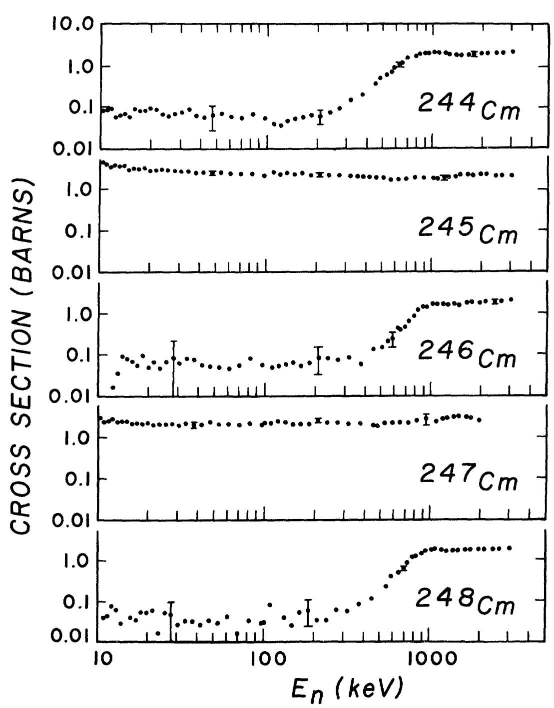

FIG. 8. Fission cross sections of ^{244}Cm, ^{245}Cm, ^{246}Cm, ^{247}Cm, and ^{248}Cm from 10 keV to 3 MeV.

The level of the fission cross section for the even targets near threshold can be used to derive some information on the properties of the barrier. If it is assumed that the outer barrier is much lower than the inner one, then fission of the Class I levels is due to tunneling through only the inner barrier. Assuming a Hill-Wheeler potential for this barrier gives

$$\langle \Gamma_f \rangle = \frac{D}{2\pi} \frac{1}{1 + e^{2\pi(E_T - E)/\hbar\omega}} .$$

The fission cross section was calculated from the total by the expression

$$\sigma_f = \sigma_T \Gamma_f / \Gamma = \sigma_T \Gamma_f / (\Gamma_n + \Gamma_{n'} + \Gamma_\gamma + \Gamma_f) ,$$

where consideration was taken of elastic scattering widths up to d-wave, inelastic scattering, and radiative capture as well as fission, and where the total cross section above 10 keV was assumed to have the shape and magnitude of that for ^{239}Pu. Fitting this expression to the fission cross section for ^{244}Cm, ^{246}Cm, and ^{248}Cm in the region below the barrier leads to values of $\hbar\omega = 0.61$, 0.75, and 0.70 MeV, respectively, for these three targets.

V. ACKNOWLEDGMENTS

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