## Brief Reports

*Brief Reports are short papers which report on completed research or are addenda to papers previously published in the* **Physical Review**. *A Brief Report may be no longer than 3½ printed pages and must be accompanied by an abstract.*

# Yields of fission products produced by thermal-neutron fission of $^{243}$Cm

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On the basis of measured yields for 72 gamma rays and known nuclear data, cumulative fission-product yields were deduced for 69 fission products having half-lives between 36 seconds and 65 days representing 41 mass chains created during thermal-neutron fission of $^{243}$Cm.

As part of an ongoing program[1-3] we have measured yields for thermal-neutron fission of the rare isotope $^{243}$Cm. The sample used contained ~75 ng of curium isotopically enriched to >99% in the $^{243}$Cm isotope by a special isotope separator.[4] Sample preparation and irradiation by thermal neutrons, gamma-ray detection, data accumulation, and data reduction followed the same procedures as detailed previously.[2,5] The only substantive differences were (a) use of the Oak Ridge High Flux Isotope Reactor in addition to the Oak Ridge Research Reactor as the neutron source, (b) more recent[6-15] nuclear data characterizing decay of several of the fission products, and (c) corrections to the experimental yields due to fissions of $^{239}$Pu in the sample at the time of the experiment.[16]

Five irradiations of different durations were used. The numbers of fissions, $n_f$, created during each irradiation were deduced with an overall uncertainty of ±7.2% from

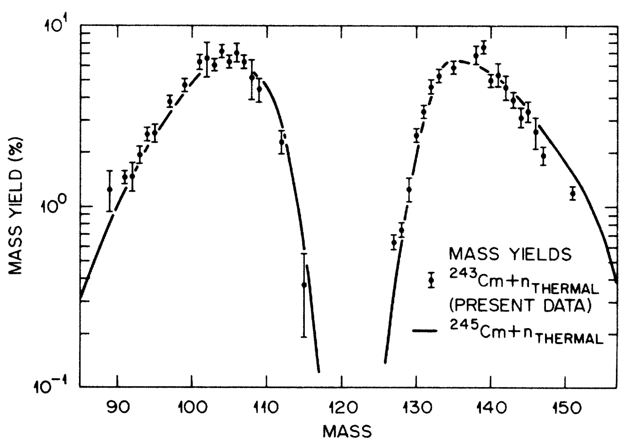


FIG. 1. Mass-yield distribution for $n_{\text{thermal}}+{}^{243}$Cm derived from the present measurements. Also shown is a smoothed curve representing the $n_{\text{thermal}}+{}^{245}$Cm mass distribution.

the sample mass, from measured[4] thermal fission cross section and resonant integral values, and from the known thermal-neutron fluence.

Deduced cumulative fission-product yields (CFY) for the sample, including total absolute uncertainties, are collected in Table I. These CFY were corrected for the contributions from fission of the $^{239}$Pu in the sample; the penultimate column of the table gives the $^{239}$Pu CFY from the current U.S. ENDF/B evaluation[17] used for these corrections. The $^{239}$Pu in the sample accounted for 12% of the fission events. The final column of Table I gives the deduced CFY for thermal-neutron fission of $^{243}$Cm.

Deduction of total-mass (i.e., chain) yields (MY) from individual CFY requires knowledge of fractional cumulative yields (FCY). We adopted the FCY vs $(Z-Z_{\text{UCD}})$ relationships deduced[2] for $^{245}$Cm, but, however, computing $Z_{\text{UCD}}$ values[18] for $^{243}$Cm as the independent variable to determine the FCY for each fission product in Table I. Mass yields were deduced for 38 masses, and they are exhibited in Fig. 1 compared with a curve representing MY for $^{245}$Cm obtained from the evaluation.[17] The comparison shown in the figure indicates that the absolute normalization of the $^{243}$Cm data appears to be accurate to within ±7.2% uncertainty associated with $n_f$. One may also observe that the mass distribution for $^{243}$Cm is quite similar to that for $^{245}$Cm. Indeed, evaluated[17] mass distributions (for thermal-neutron fission) of the pairs $^{233}$U-$^{235}$U, $^{239}$Pu-$^{241}$Pu, and $^{249}$Cf-$^{251}$Cf are also quite similar, much more so than distributions for fissioning systems of different total $Z$.

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TABLE I. Deduced cumulative fission-product yields for thermal-neutron fission of $^{243}$Cm.

| Fission product | $E_\gamma$ (keV) | Gamma-ray branching ratio (%)[a] | Cumulative fission-product yield (%) Sample | $^{239}$Pu[b] | $^{243}$Cm |
|---|---|---|---|---|---|
| $^{89}$Rb | 1031.9 | 58.0±5.0 | 1.29±0.17 | 1.60±0.27 | 1.24±0.32 |
| $^{91}$Sr | 1024.3 | 33.5±0.7 | 1.57±0.12 | 2.49±0.05 | 1.45±0.14 |
| $^{91}$Y$^{m}$ | 555.6 | 95.1±0.1 | 0.91±0.07 | 1.43±0.05 | 0.84±0.08 |
| $^{92}$Sr | 1383.9 | 90.0±9.9 | 1.63±0.23 | 2.98±0.12 | 1.45±0.26 |
| $^{93}$Sr | 590.2 | 67.4±1.2[c] | 1.98±0.18 | 3.64±0.22 | 1.76±0.20 |
| $^{94}$Sr | 1428.1 | 95.4±0.4 | 2.04±0.19 | 3.26±0.20 | 1.88±0.22 |
| $^{94}$Y | 918.2 | 49.0±5.0[d] | 2.57±0.35 | 4.33±0.17 | 2.34±0.39 |
| $^{95}$Zr | 756.7 | 54.6±0.5 | 2.61±0.19 | 4.88±0.10 | 2.31±0.22 |
| $^{95}$Nb | 765.8 | 99.8±0.1 | 3.05±0.22 | 4.88±0.10 | 2.81±0.25 |
| $^{97}$Zr | 743.4[e] | 92.8±0.3[e] | 3.94±0.28 | 5.26±0.15 | 3.77±0.32 |
| $^{97}$Nb | 657.9 | 98.3±0.1 | 3.91±0.28 | 5.34±0.11 | 3.70±0.32 |
| $^{98}$Nb$^{m}$ | 787.2 | 93.2±0.2[f] | 0.33±0.03 | 0.03±0.02 | 0.37±0.04 |
| $^{99}$Tc$^{m}$ | 140.5 | 87.2±0.7[g] | 5.20±0.65 | 5.43±0.11 | 5.17±0.74 |
| $^{99}$Mo | 140.5 | 90.7±0.6 | 4.81±0.35 | 6.20±0.13 | 4.64±0.40 |
| $^{101}$Mo | 192.1 | 19.2±1.1[c] | 5.81±0.73 | 5.99±0.18 | 5.79±0.83 |
| $^{101}$Tc | 306.9 | 88.0±4.4[h] | 6.47±0.64 | 6.00±0.17 | 6.53±0.72 |
| $^{102}$Tc$^{m}$ | 475.1 | 85.0±2.0[f] | 0.07±0.04 | 0.32±0.02[i] | 0.04±0.04 |
| $^{102}$Tc | 475.1 | 6.3±1.0 | 6.52±1.23 | 6.05±0.49[i] | 6.58±1.39[j] |
| $^{103}$Tc | 136.0 | 16.3±2.9[k] | 5.58±1.14 | 6.95±0.28 | 5.40±1.29 |
| $^{103}$Ru | 497.1 | 90.9±0.7 | 6.18±0.45 | 6.95±0.14 | 6.08±0.51 |
| $^{104}$Tc | 358.0 | 89.0±5.0 | 6.90±0.52 | 6.01±0.36 | 7.02±0.59 |
| $^{105}$Tc | 143.3 | 15.7±1.0[l] | 5.54±0.42 | 5.54±0.61 | 5.54±0.47 |
| $^{105}$Ru | 724.3 | 48.0±1.0 | 6.31±0.53 | 5.59±0.16 | 6.41±0.60 |
| $^{105}$Ru | 469.4 | 1.80±0.07 | 6.07±0.55 | 5.59±0.16 | 6.13±0.62 |
| $^{105}$Rh | 318.9 | 19.2±0.2 | 6.41±0.47 | 5.59±0.11 | 6.52±0.54 |
| $^{106}$Tc | 270.1 | 56.0±3.0 | 4.93±0.52 | 3.58±0.39 | 5.10±0.59 |
| $^{107}$Ru | 194.0 | 14.3±3.4[f] | 5.73±1.52 | 3.25±0.78 | 6.06±1.72 |
| $^{107}$Rh | 302.9 | 65.9±4.6 | 5.87±1.08 | 3.26±0.36 | 6.22±1.22 |
| $^{108}$Ru | 165.0 | 28.0±7.0 | 3.93±1.03 | 2.03±0.33 | 4.18±1.18 |
| $^{109}$Rh | 326.5 | 62.0±7.0 | 4.03±0.58 | 1.69±0.19 | 4.34±0.66 |
| $^{112}$Ag | 617.4 | 42.0±5.0 | 1.89±0.28 | 0.12±0.05 | 2.12±0.31[m] |
| $^{115}$In$^{m}$ | 336.2 | 45.9±0.1 | 0.32±0.15 | 0.06±0.01 | 0.35±0.17 |
| $^{127}$Sb | 685.7 | 36.6±0.5 | 0.62±0.05 | 0.50±0.04 | 0.64±0.06 |
| $^{128}$Sn | 482.2 | 62.3±6.2 | 0.36±0.07 | 0.57±0.05 | 0.34±0.08 |
| $^{128}$Sb$^{m}$ | 754.0 | 99.8±0.2 | 0.58±0.07 | 0.63±0.04 | 0.58±0.08 |
| $^{128}$Sb | 754.0 | 99.8±0.2 | 0.19±0.02 | 0.06±0.04 | 0.21±0.02 |
| $^{129}$Sb | 812.8 | 45.0±4.5 | 1.15±0.15 | 1.35±0.08 | 1.13±0.17 |
| $^{130}$Sn | 779.8 | 59.1±3.9[n] | 0.34±0.08 | 0.91±0.07 | 0.26±0.09 |
| $^{130}$Sb$^{m}$[o] | 793.4 | 86.0±5.0[f] | 1.08±0.13 | 1.28±0.10 | 1.05±0.15 |
| $^{130}$Sb$^{m}$ | 839.5 | 99.8±0.1 | 0.93±0.09 | 1.28±0.10 | 0.89±0.10 |
| $^{130}$Sb[o] | 330.9 | 77.8±3.9[f] | 0.90±0.10 | 0.50±0.02 | 0.95±0.11 |
| $^{130}$Sb | 793.4 | 99.8±0.1[f] | 0.84±0.08 | 0.50±0.02 | 0.89±0.09 |
| $^{130}$Sb | 839.4 | 99.8±0.1 | 0.84±0.08 | 0.50±0.02 | 0.89±0.09 |
| $^{131}$Sb | 943.6 | 44.0±4.4[p] | 1.70±0.23 | 2.53±0.15 | 1.59±0.26 |
| $^{131}$Te$^{m}$ | 852.2 | 21.3±0.9 | 1.16±0.10 | 1.04±0.04 | 1.17±0.11 |
| $^{131}$Te | 149.8 | 68.9±0.9[c] | 2.28±0.26 | 2.99±0.08 | 2.19±0.30 |
| $^{131}$I | 364.5 | 82.5±0.4 | 3.41±0.25 | 3.87±0.04 | 3.35±0.28 |
| $^{132}$Sb$^{m}$ | 973.9 | 99.9±0.1 | 1.00±0.11 | 2.91±0.23 | 0.74±0.12 |
| $^{132}$Sb | 973.9 | 99.9±0.1 | | | |
| $^{132}$Te | 228.3 | 88.2±0.2 | 4.57±0.36 | 5.16±0.10 | 4.50±0.41 |
| $^{132}$I | 667.8 | 98.7±0.1 | 4.47±0.34 | 5.42±0.08 | 4.34±0.38 |
| $^{133}$I | 529.9 | 87.3±0.2 | 5.38±0.39 | 6.97±0.14 | 5.17±0.44 |
| $^{134}$I$^{m}$ | 271.9 | 79.0±3.0 | 1.82±0.17 | 1.16±0.37 | 1.91±0.19 |
| $^{135}$I | 1131.5 | 22.8±0.5 | 4.13±0.35 | 6.41±0.18 | 3.83±0.40 |
| $^{135}$I | 1260.4 | 29.0±0.4 | 4.20±0.35 | 6.41±0.18 | 3.90±0.40 |
| $^{135}$Xe$^{m}$ | 526.6 | 81.0±1.0 | 0.84±0.07 | 1.71±0.55 | 0.72±0.06 |
| $^{135}$Xe | 249.9 | 89.9±0.3[c] | 6.14±0.68 | 7.60±0.11 | 5.95±0.76 |
| $^{136}$I$^{m}$ | 381.4 | 99.8±5.5 | 0.90±0.10 | 1.67±0.13 | 0.80±0.11 |

TABLE I. (*Continued*).

| Fission product | $E_\gamma$ (keV) | Gamma-ray branching ratio (%)[a] | Cumulative fission-product yield (%) Sample | $^{239}$Pu[b] | $^{243}$Cm |
|---|---|---|---|---|---|
| $^{136}I^m$ | 1313.0 | 99.9±0.1[f] | 0.93±0.21 | 1.67±0.13 | 0.83±0.24 |
| $^{136}I$ | 1313.0 | 68.0±1.0 | 0.80±0.19 | 1.74±0.42 | 0.68±0.21 |
| $^{136}Cs$ | 818.5 | 99.7±0.1[c] | 0.39±0.04 | 0.09±0.01 | 0.43±0.05 |
| $^{136}Cs$ | 1048.1 | 79.8±0.9 | 0.44±0.04 | 0.09±0.01 | 0.48±0.05 |
| $^{138}Xe$ | 258.4 | 31.5±1.3 | 3.54±0.42 | 5.17±0.07 | 3.32±0.47 |
| $^{138}Xe$ | 1748.3 | 16.7±0.7 | 3.75±0.36 | 5.17±0.07 | 3.56±0.41 |
| $^{139}Xe$ | 218.8 | 50.0±6.0 | 2.09±0.32 | 3.01±0.09 | 1.97±0.36 |
| $^{139}Cs$ | 1283.2 | 7.3±0.6[f] | 6.20±0.78 | 5.28±0.42 | 6.32±0.88 |
| $^{139}Ba$ | 165.8 | 23.8±0.3[q] | 6.69±1.85 | 5.53±0.22 | 6.84±2.10 |
| $^{140}Cs$ | 602.4 | 55.7±3.5[l] | 2.85±0.36 | 3.92±0.32 | 2.71±0.41 |
| $^{140}Ba$ | 537.6 | 24.2±0.2 | 4.96±0.36 | 5.37±0.11 | 4.91±0.41 |
| $^{140}La$ | 487.0 | 45.9±0.4[r] | 5.17±0.45 | 5.38±0.11 | 5.14±0.51 |
| $^{140}La$ | 1596.6 | 95.4±0.1 | 4.99±0.42 | 5.38±0.11 | 4.94±0.47 |
| $^{141}Ba$ | 190.3 | 46.0±3.0 | 4.88±0.63 | 5.21±0.31 | 4.84±0.71 |
| $^{142}Ba$ | 1204.0[s] | 22.6±3.1[s] | 2.78±0.45 | 4.58±0.37 | 2.54±0.50 |
| $^{143}Ce$ | 293.3 | 43.4±2.0 | 3.98±0.34 | 4.35±0.06 | 3.93±0.39 |
| $^{144}La$ | 397.4 | 90.0±5.0 | 3.19±0.34 | 3.62±0.29 | 3.13±0.39 |
| $^{145}Ce$ | 724.3 | 63.9±3.9[t] | 3.21±0.37 | 2.99±0.06 | 3.24±0.42 |
| $^{146}Ce$ | 218.3 | 20.5±3.2 | 2.28±0.40 | 2.45±0.10 | 2.26±0.45 |
| $^{147}Nd$ | 531.0 | 13.1±0.8 | 1.95±0.19 | 2.03±0.06 | 1.94±0.21 |
| $^{151}Pm$ | 340.1 | 22.3±0.5 | 1.16±0.09 | 0.75±0.02 | 1.21±0.10 |

[a]Values taken from our previous evaluation, Table II of Ref. 2, unless otherwise noted.
[b]Values taken from current ENDF/B evaluation, Ref. 17.
[c]Kocher, Ref. 6.
[d]Glendenin *et al.*, Ref. 7.
[e]Gamma ray due to decay of $^{97}Nb^m$; branching ratio corrected for the fraction of $^{97}Zr$ decay populating $^{97}Nb^m$. The branching ratio given in Ref. 2 is incorrect.
[f]From *Table of Isotopes*, Ref. 8.
[g]Dickens and Love, Ref. 9.
[h]Harmatz, Ref. 10.
[i]Reversed from yields given in Ref. 17 for these isomers.
[j]Deduced yield of the parent $^{102}Mo$.
[k]Deduced from data reported by Niizeki *et al.*, Ref. 11.
[l]Table VI of Ref. 2.
[m]Deduced yield of the parent $^{112}Pd$.
[n]Deduced from level diagram given in Ref. 8; there is a discrepancy between the tabulated and graphical branching ratio in this reference.
[o]$T_{1/2}(^{130}Sb^m)=6.5$ min; $T_{1/2}(^{130}Sb)=40$ min.
[p]Table II, Ref. 3.
[q]Gehrke, Ref. 12.
[r]Debertin *et al.*, Ref. 13.
[s]Sum data for nearly degenerate doublet. Relative branching ratios from Ref. 8, combined with absolute branching ratio for $E_\gamma=255$ keV from Ref. 2.
[t]Branching ratio deduced by Reus and Westmeier, Ref. 14. Uncertainty deduced from data of Yamamoto *et al.*, Ref. 15.


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