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# NEUTRON MULTIPLICITIES FOR THE TRANSPLUTONIUM NUCLIDES

N. E. Holden and M. S. Zucker
Brookhaven National Laboratory, Upton, New York

## 1. Introduction

This paper continues, with respect to the transplutonium nuclides, earlier efforts[1,2,3] to collate and evaluate data from the scientific literature on the prompt neutron multiplicity distribution from fission and its first moment $\langle\nu\rangle = \sum \nu P_\nu$.

The isotopes considered here for which $P_\nu$ and or $\langle\nu\rangle$ data (or both) were found in the literature are of americium (Am), curium (Cm), berkelium (Bk), californium (Cf), einsteinium (Es), fermium (Fm), and nobelium (No).

The motivation behind the work continues to be providing the safeguards field with the information increasingly required as calculation and assay methods are refined, particularly with regard to neutron correlation counting. Some of the transplutonium nuclides are obviously of greater immediate importance than the others. However, even parameters of the more exotic nuclides are of value since they contribute to an understanding of the systematics involved. This enables development of semi-empirical relations which in turn can be used to improve measured value or predict parameters when experimental results are not available.[4,5] The methodology for evaluating $\langle\nu\rangle$ and $P_\nu$ data is the same as in our earlier papers.[3]

## 2. Nuclides Considered

The result for $\langle\nu\rangle$ are presented in Table I. $P_\nu$ data for $^{242,244,246,248}$Cm, $^{246,250,252,254}$Cf, $^{257}$Fm, and $^{252}$No have been evaluated and are presented in Tables II, III, IV, and V (Cm), Tables VI (Cf), and Table VII ($^{252}$No and $^{257}$Fm).

Data on $Q_n$, the probability that n neutrons are actually detected (in contrast to $\nu$ being emitted; $n \leq \nu$ ) were available for $^{254,256,257}$Fm. The $P_\nu$ are related to the $Q_n$ by

$$P_\nu = \sum Q_n [n!/\nu!(n-\nu)!] \varepsilon^{-n} (\varepsilon-1)^{n-\nu},$$

where $\varepsilon$ is the detector efficiency. The value of $\varepsilon$ cited by the experimenter has an uncertainty associated with in due to experimental inaccuracies and/or the experimenter having based the efficiency calibration on a value for $\langle\nu\rangle$ of a nuclide ($^{252}$Cf, $^{240}$Pu, etc.) which was not the best available. Thus there is justification for varying $\varepsilon$ about the quoted value. Application of the above formula in a straightforward way to $Q_n$ sets for $^{254,256,257}$Fm even allowing for variations in $\varepsilon$ however did not yield physically meaningful results: some of the $P\nu$ would be negative, greater than unity, et cet. The reason for this is still being investigated, but is believed probably due to the relatively poor statistical accuracy of the available ($Q_n$) data for the Fm isotopes. The computer program for carrying out the above operation successfully treated cases from the literature where the experimenter had cited both the $Q_n$ and $P_\nu$ sets, so the computer program itself has been ruled out as a factor.

Thus the only Fm nuclide for which $P_\nu$ data could be evaluated was that for $^{257}$Fm, for which there was one set available.

The literature on $^{252}$Cf is extensive and since our most recent evaluation leaves that in reference 3 unchanged save for correction of a minor error referred to there, only the consensus set of $P_\nu$ is cited here.

The detailed list of literature citations can be obtained from the authors.

## 3. References

1. N. E. Holden and M. S. Zucker, Proc. ANS/INMM Topical Meeting on Safeguards and Technology, Hilton Head, S.C., Nov.28-Dec.2, 1983. Trans Amer. Nucl. Soc. 45, suppl.1, 23 (1983).
2. N. E. Holden and M. S. Zucker, BNL-NCS-35513-R. IAEA Advisory Group Meeting on Neutron Standard Reference Data, 12-16 Nov. 1984, at Geel, Belgium.
3. M. S. Zucker and N. E. Holden, Proc. 6th ESARDA Symp. on Safeguards and Nucl. Material Management, Venice, Italy, May 14-18, 1984, p.341.
4. G. Edwards, D. J. S. Findlay, and E. W. Lees, Annals of Nuclear Energy, Vol.8, p.105-114, Pergamon Press Ltd., 1981.
5. "Apparatus Characterization as a Standard for Neutron Correlation Counting", M. S. Zucker, 4th ESARDA Symposium, p.A1, April 27-29, 1982, Petten, Netherlands.

Table I
Recommended $\langle\nu\rangle$ Values for Am, Cm, Bk, Cf, Es, Fm, and No Nuclides

| Nuclide | Value(Uncert.) | Nuclide | Value(Uncert.) |
|---|---|---|---|
| $^{241}$Am | 3.22 (0.04) | $^{250}$Cf | 3.51 (0.04) |
| $^{242}$Am | 3.26 (0.03) | $^{251}$Cf | 4.1 (0.5) |
| $^{242}$Cm | 2.54 (0.02) | $^{252}$Cf | 3.757 (0.010) |
| $^{243}$Cm | 3.43 (0.14) | $^{254}$Cf | 3.85 (0.06) |
| $^{244}$Cm | 2.72 (0.02) | $^{253}$Es | 4.7 |
| $^{245}$Cm | 3.75 (0.10) | $^{254}$Es | 4.2 |
| $^{246}$Cm | 2.93 (0.03) | $^{244}$Fm | 4. (1.) |
| $^{247}$Cm | 3.80 (0.15) | $^{246}$Fm | 4. (1.) |
| $^{248}$Cm | 3.13 (0.03) | $^{254}$Fm | 4.0 (0.3) |
| $^{250}$Cm | 3.30 (0.08) | $^{255}$Fm | 4.0 (0.5) |
| $^{249}$Bk | 3.40 (0.05) | $^{256}$Fm | 3.63 (0.06) |
| $^{246}$Cf | 3.1 (0.1) | $^{257}$Fm | 3.87 (0.05) |
| $^{249}$Cf | 4.1 (0.3)-Neutron fission | $^{252}$No | 4.20 (0.30) |
| $^{249}$Cf | 3.4 (0.4)-Spontaneous fission | | |

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Table II
$P_\nu$ for $^{242}Cm$

| | Hicks 56 | Halperin 80 | Zhang 86 | Consensus | Std. Dev. |
|---|---|---|---|---|---|
| $P_0$ | .0166474- | .0228731 | .0242443 | .0212330 | .0040 |
| $P_1$ | .1675552 | .1340439 | .1358229 | .1467407 | .0123 |
| $P_2$ | .3371507 | .3291282 | .3137804 | .3267331 | .0118 |
| $P_3$ | .3187923 | .3309347+ | .3147053- | .3258277 | .0121 |
| $P_4$ | .1263352- | .1463370 | .1398818 | .1375090 | .0102 |
| $P_5$ | .0414207 | .0281274- | .0441874 | .0378415 | .0100 |
| $P_6$ | .0033156+ | .0020694 | .0033459 | .0025912 | .0007 |
| $P_7$ | .0003477 | .0000463 | .0014512 | .0007551 | .0007 |
| $P_8$ | .0000000 | .0000000 | .0003602+ | .0001867 | .0003 |
| $\langle\nu\rangle$ | 2.5400000* | 2.5400000* | 2.5400000* | 2.5400000* | .02 |
| $\langle\nu(\nu-1)\rangle$ | 5.111 | 5.043 | 5.242 | 5.132 | .01 |
| $\langle\nu(\nu-1)(\nu-2)\rangle$ | 8.036 | 7.339 | 8.674 | 8.036 | .037 |
| $\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$ | .7923 | .7817 | .8123 | .7955 | .0135 |
| $\langle\nu^2\rangle-\langle\nu\rangle^2$ | 1.200 | 1.133 | 1.330 | 1.271 | .101 |
| $\langle\nu^2\rangle$ | 7.651 | 7.503 | 7.782 | 7.672 | .101 |

+ means $P_\nu$ deviates by > + σ
− means $P_\nu$ deviates by < − σ
* data sets made to conform to this value

Table V
$P_\nu$ for $^{248}Cm$

| | Boldeman 73 | Stoughton 73 | Consensus | Std. Dev. |
|---|---|---|---|---|
| $P_0$ | .0063061 | .0071623 | .0067353 | .0004 |
| $P_1$ | .0622306 | .0578604 | .0598493 | .0027 |
| $P_2$ | .2272634 | .2130636 | .2205316 | .0095 |
| $P_3$ | .3458147 | .3559098 | .3505830 | .0071 |
| $P_4$ | .2423394 | .2632239 | .2343747 | .0153 |
| $P_5$ | .0907301 | .0879519 | .0893533 | .0020 |
| $P_6$ | .0206091 | .0127780 | .0167206 | .00[illegible] |
| $P_7$ | .0033775 | .0000000 | .0016888 | .00[illegible] |
| $\langle\nu\rangle$ | 3.1300000* | 3.1300000* | 3.1300000* | .03 |
| $\langle\nu(\nu-1)\rangle$ | 8.038 | 7.889 | 7.939 | .100 |
| $\langle\nu(\nu-1)(\nu-2)\rangle$ | 16.359 | 15.312 | 15.835 | .082 |
| $\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$ | .8196 | .8052 | .8126 | .0102 |
| $\langle\nu^2\rangle-\langle\nu\rangle^2$ | 1.363 | 1.222 | 1.292 | .100 |
| $\langle\nu^2\rangle$ | 11.160 | 11.019 | 11.089 | .100 |

* data sets made to conform to this value

Table III
$P_\nu$ for $^{244}Cm$

| | Diven 56 | Hicks 56 | Dakovskii 74 | Zhang 84 | Consensus | Std. Dev. |
|---|---|---|---|---|---|---|
| $P_0$ | .0125012 | .0055033- | .0278773+ | .0135301 | .0150030 | .0093 |
| $P_1$ | .1245025 | .1184166 | .0917623- | .1207293 | .1161725 | .0169 |
| $P_2$ | .3032534 | .3013825 | .3094042 | .3031280- | .2990427 | .0104 |
| $P_3$ | .3170112- | .3514534+ | .3332404 | .3358124 | .3331614 | .0162 |
| $P_4$ | .2011534+ | .1768431 | .1832425 | .1773601 | .1837768 | .0117 |
| $P_5$ | .0267232- | .0412210 | .0550183+ | .0467404 | .0428783 | .0110 |
| $P_6$ | .0172741- | .0054600 | .0021472- | .0101641 | .0087914 | .0066 |
| $P_7$ | .0000000 | .0000000 | .0000000 | .0010977- | .0002766 | .0005 |
| $\langle\nu\rangle$ | 2.7200000* | 2.7200000* | 2.7200000* | 2.7200000* | 2.7200000* | .03 |
| $\langle\nu(\nu-1)\rangle$ | 5.989 | 5.016 | 5.937 | 6.033 | 5.939 | .085 |
| $\langle\nu(\nu-1)(\nu-2)\rangle$ | 10.505 | 9.469 | 9.885 | 10.341 | 10.101 | .318 |
| $\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$ | .8095 | .7881 | .8018 | .8114 | .8027 | .0113 |
| $\langle\nu^2\rangle-\langle\nu\rangle^2$ | 1.314 | 1.1374 | 1.269 | 1.325 | 1.260 | .085 |
| $\langle\nu\rangle^2$ | 8.709 | 8.5350 | 8.667 | 8.723 | 8.659 | .085 |

+ means $P_\nu$ deviates by > + σ
− means $P_\nu$ deviates by < − σ
* data sets made to conform to this value

Table VI
$P_\nu$ for Cf Nuclides

| | $^{246}Cf$ Dakovskii 73 | $^{250}Cf$ Hoffman 80 | $^{252}Cf$ Consensus | Std. Dev. | $^{254}Cf$ Hoffman 80 |
|---|---|---|---|---|---|
| $P_0$ | .0005084 | .0038191 | .002164 | .000061 | .0001977 |
| $P_1$ | .1135987 | .0365432 | .205563 | .000233 | .0190236 |
| $P_2$ | .3545989 | .1673371 | .125613 | .000442 | .1228406 |
| $P_3$ | .2742853 | .2945382 | .274332 | .000367 | .2430383 |
| $P_4$ | .2208497 | .2982732 | .305169 | .000615 | .1941768 |
| $P_5$ | .1259680 | .1651196 | .185229 | .000460 | .0745282 |
| $P_6$ | .0381731 | .0472215 | .066066 | .000243 | .0130039 |
| $P_7$ | .0000000 | .0040174 | .014140 | .000347 | .0021988 |
| $P_8$ | .0000000 | .0031188 | .001860 | .000099 | .0000070 |
| $P_9$ | .0000000 | .0003080 | .000057 | .000029 | .0000000 |
| $P_{10}$ | .0000000 | .0000978 | .0000007 | .0000007 | .0000000 |
| $\langle\nu\rangle$ | 3.1030000* | 3.5100000* | 3.757000* | .010 | 3.8300000* |
| $\langle\nu(\nu-1)\rangle$ | 8.190 | 10.344 | 11.968 | .006 | 12.501 |
| $\langle\nu(\nu-1)(\nu-2)\rangle$ | 18.125 | 25.192 | 31.436 | .092 | 33.707 |
| $\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$ | .8533 | .8396 | .8465 | .0004 | .8436 |
| $\langle\nu^2\rangle-\langle\nu\rangle^2$ | 1.403 | 1.334 | 1.590 | .006 | 1.529 |
| $\langle\nu^2\rangle$ | 11.290 | 13.834 | 15.703 | .003 | 16.351 |

* data sets made to conform to this value

Table IV
$P_\nu$ for $^{246}Cm$

| | Stoughton 73 | Dakovskii 76 | Consensus | Std. Dev. |
|---|---|---|---|---|
| $P_0$ | .0130533 | .0173031 | .0151182 | .0031 |
| $P_1$ | .0824850 | .0700683 | .0762789 | .0088 |
| $P_2$ | .2512020 | .2742057 | .2627039 | .0162 |
| $P_3$ | .3522395 | .3376076 | .3449236 | .0103 |
| $P_4$ | .2258728 | .2102377 | .2180833 | .0110 |
| $P_5$ | .0638529 | .0831960 | .0735895 | .0139 |
| $P_6$ | .0091644 | .0052810 | .0072227 | .0027 |
| $\langle\nu\rangle$ | 2.9300000* | 2.9300000* | 2.9300000* | .03 |
| $\langle\nu(\nu-1)\rangle$ | 6.921 | 6.960 | 6.940 | .027 |
| $\langle\nu(\nu-1)(\nu-2)\rangle$ | 12.593 | 12.817 | 12.703 | .159 |
| $\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$ | .8062 | .8107 | .8084 | .0033 |
| $\langle\nu^2\rangle-\langle\nu\rangle^2$ | 1.266 | 1.303 | 1.283 | .027 |
| $\langle\nu^2\rangle$ | 9.031 | 9.890 | 9.870 | .027 |

* data sets made to conform to this value

Table VII
$P_\nu$ for $^{252}No$ and $^{257}Fm$

| | $^{252}No$ Lazarev 74 | $^{257}Fm$ Hoffman 80 |
|---|---|---|
| $P_0$ | .0369148 | .0205736 |
| $P_1$ | .0576843 | .0520335 |
| $P_2$ | .0924873 | .1172380 |
| $P_3$ | .1437439 | .1957003 |
| $P_4$ | .1832432 | .2627898 |
| $P_5$ | .1831510 | .2007776 |
| $P_6$ | .1655905 | .1061861 |
| $P_7$ | .0642573 | .0333033 |
| $P_8$ | .0282040 | .0073979 |
| $P_9$ | .0028776 | .0000000 |
| $\langle\nu\rangle$ | 4.2000001* | 3.8700000* |
| $\langle\nu(\nu-1)\rangle$ | 17.634 | 13.600 |
| $\langle\nu(\nu-1)(\nu-2)\rangle$ | 60.129 | 41.771 |
| $\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$ | 1.0006 | .9080 |
| $\langle\nu^2\rangle-\langle\nu\rangle^2$ | 4.214 | 2.493 |
| $\langle\nu^2\rangle$ | 21.854 | 17.470 |

* data sets made to conform to this value



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