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Prompt Neutron Multiplicities for the Transplutonium Nuclides

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I. Introduction

The neutron emission multiplicity distribution, P_ν is the probability that a given fission will result in the emission of ν neutrons. The basic method used by all experimenters to generate P_ν data involves a way of detecting each fission as it occurs in a sample of the nuclide under study and correlates this fission with the detection of the emitted neutrons. Since the efficiency, ε, of the neutron detector for the detection of a single neutron is less than unity, allowance for those neutrons emitted but not detected must be made, with the resulting probability, Q_n, of actually observing n neutrons even if ν were emitted ($n < \nu$) being just:

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

The P_ν are constants of nature, whereas the Q_n depend upon the efficiency of the particular detector used. From the above expression it follows directly that P_ν is given in terms of the observed relative frequencies of observation, Q_n, by the expression:

$$P_\nu = \Sigma Q_n [n!/\nu!(n-\nu)!] \varepsilon^{-n} (\varepsilon-1)^{n-\nu} \qquad (2)$$

Knowledge of the detector efficiency which is essential to relate the observed frequencies Q_n, to the multiplicities, P_ν, is usually determined from the count rate with a calibrating nuclide, whose nubar value is well known, i.e. some standard nuclide.

$$g = \varepsilon <\nu> q \qquad (3)$$

where q is the fission rate of the sample of the calibrating nuclide and g is the gross count rate for the calibrating nuclide. (The efficiency is thus inversely related to the assumed value of $<\nu>$.) This is possible because $<\nu>$ can be determined independently of the determination of P_ν and with greater accuracy than if it were calculated from the P_ν distribution using

$$<\nu> = \Sigma \nu P_\nu . \qquad (4)$$

In deriving the $<\nu>$ values for the various spontaneous fissioning nuclides, one primary standard value is assumed, for ^{252}Cf. From an earlier evaluation[1], a value of $<\nu>$ = 3.757 +_ 0.010 neutrons/fission is derived. In addition to this primary standard, a secondary standard for the various fissile nuclides is assumed, for ^{235}U, i.e., the value at 2200 meters/second neutron energy. From a previous preliminary evaluation[2], a value of $<\nu>$ = 2.414 +_ 0.007 neutrons/fission is determined.

In the following sections, we will review the direct determination of $<\nu>$ values and then describe the method of comparing different sets of P_ν values. It might be noted that there are substantially more measurements of the average prompt neutron emission multiplicity value than there are of the neutron multiplicity distribution.

II. Average Prompt Neutron Emission Probability, $<\nu_p>$

The average number of neutrons released in fission is of interest for sustaining chain reactions in nuclear reactors and is also a measure of the average excitation energy left in a fission fragment immediately after scission. The systematic variation of fission properties for the various heavy nuclides must account for the variation in $<\nu_p>$. In this study, we have restricted ourselves to those nuclides which spontaneously fission or which are fissionable with neutrons of thermal energies, i.e. E_n = 0.0253 electron volts.

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DISCLAIMER

^{252}Cf is one of the better known nuclides and is of great interest for safeguards because it is the standard against which other nuclides have been measured and with which equipment and techniques are tested. In recent years, $<\nu_p>$ measurements for ^{252}Cf by liquid scintillator techniques and by manganese bath techniques have begun to converge, leading to the presently recommended value of ν_p = 3.757 +_ 0.010 neutrons/fission[1]. Using this standard value and the recommended value for ^{235}U and for ^{240}Pu of 2.414 +_ 0.007 neutrons/fission and 2.154 +_ 0.005 neutrons/fission, respectively[2], the average neutron multiplicities for the various nuclides of the transplutonium elements have been reevaluated. In general, the weighted average of all measurements for each nuclide has been recommended in Table XIX. For some nuclides, no direct measurement of the average multiplicity has been made and the estimated value, which has been calculated from the measurement of fission yields, has been recommended.

III. Method of Comparing Different P_ν Sets

The Q_n and P_ν can be considered vectors, whose components are probabilities, related by an operation and its inverse which converts one set of probabilities into the other, i.e. equation (1) and (2). Certain ratios composed of specific functions of the various moments of the distributions are independent of the efficiency, e.g. $<\nu(\nu-1)....(\nu-k)> / <\nu>^{k+1} = <n(n-1)...(n-k)> / <n>^{k+1}$. A particular case is Diven's parameter, for k = 1, $<\nu(\nu-1)> / <\nu>^2$, which can be considered as a measure of the shape of the P_ν distribution. However, another indicator of the distribution's shape , which is not conserved, (independent of ε) is the ratio of the mean square deviation to the square of the mean : $<(\nu-<\nu>)^2> / <\nu>^2 = (<\nu^2> - <\nu>^2) / <\nu>^2$.

For each given experiment, the equations (1) and (2) were used with the quoted distribution P_ν and the reported efficiency ε to derive the original Q_n set. The efficiency was then varied until the calculated $<\nu>$ ($\Sigma\ \nu\ P_\nu$) value was obtained corresponding to the recommended value. In those few cases where the experimentalist did not report the efficiency, a reasonable value was assumed appropriate to the experimental conditions and then the above procedure was also followed.

After various sets of P_ν for the same nuclide are transformed so that each set yields the same $<\nu>$, any remaining differences between the corresponding P_ν can be ascribed to systematic errors other than those in ε or $<\nu>$, or to random errors (e.g. counting statistics) in the respective experiments. Evaluation of the standard deviation of corresponding values of P_ν gives a realistic estimate of the uncertainty involved in determining the P_ν. Our earlier work[3] contains more details on the method.

IV. Recommendations and Discussion

The recommended values for $<\nu>$ and P_ν for the various nuclides of americium, curium, berkelium, californium, einsteinium, fermium and nobelium are given in the Tables in section VI. Although there are data of some sort available for twenty-six of these nuclides, data on the multiplicity distributions are only available for twelve of the nuclides and no recommendations could be made for two of those. Some Q_n sets for fermium nuclides did not produce physically meaningful results no matter how ε was varied. The reason for this difficulty is still under investigation, but it is probably due to poor statistical accuracy of the Q_n data involved.

If one plots the various recommended sets of P_ν given here as well as those previously determined versus $(\nu-<\nu>)$ on the same figure, a continuous curve drawn through the data points will have a width or standard deviation of 1.094 +_ 0.007, for the various nuclides of uranium, plutonium and curium. This calculation takes into account Sheppard's correction[4] for sampling from the mid-point of a histogram to approximate the width of a continuous distribution. All nuclides agree within 4% with the calculated average. For the various nuclides of californium, fermium and nobelium, however, the standard deviation or width for the various recommended sets of P_ν is 1.41 +_ 0.14.

If one now selects only the spontaneously fissioning nuclides, the standard deviation for the curium and californium elements are 1.087 +_ 0.007 and 1.224 +_ 0.014, respectively, as compared to a standard deviation of 1.100 +_ 0.007 for the spontaneously fissioning nuclides of plutonium.

It might also be noted that the variation of ν with mass number for a given element and fission type has approximately the same slope for the curium and californium nuclides, i.e. 0.094 +_ 0.001.

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VI. Tabulated Results

Table I Measured Nubar Values for ^{241}Am

Author (Year)	Ref.	Measured Value	Revised Value	Comment
Jaffey(70)	5	3.219 (0.021)		
Lebedev(58)	6	3.14 (0.05)	3.07 (0.05)	No efficiency correction
Cuninghame(57)	7	3. (0.5)		Calc. from Fission Yields

Table II Measured Nubar Values for ^{242m}Am

Author (Year)	Ref.	Measured Value	Revised Value
Howe(81)	8	3.269 (0.145)	
Jaffey(70)	5	3.264 (0.024)	3.265 (0.024)
Fultz(66)	9	3.24 (0.12)	3.22 (0.12)
Kroshkin(70)	10	3.28 (0.10)	3.26 (0.10)

Table III Measured Nubar Values for ^{242}Cm

Author (Year)	Ref.	Measured Value	Revised Value
Zhang(84)	11	2.562 (0.020)	2.572 (0.020)
Halperin(80)	12	2.532 (0.013)	2.530 (0.013)
Hicks(56)	13	2.65 (0.09)	2.53 (0.09)
Crane(55)	14	2.33 (0.11)	2.48 (0.11)

Table IV Measured Nubar Values for ^{243}Cm, ^{247}Cm and ^{250}Cm

Nuclide	Author (Year)	Ref.	Measured Value	Revised Value	Comment
^{243}Cm	Zhuraviev(73)	15	3.39 (0.14)	3.40 (0.04)	Neut. Fiss.
^{243}Cm	Jaffey(70)	5	3.430 (0.047)	3.432 (0.047)	Neut. Fiss.
^{247}Cm	Zhuraviev(73)	15	3.79 (0.15)	3.80 (0.15)	Neut. Fiss.
^{250}Cm	Orth(71)	16	3.31 (0.08)	3.30 (0.08)	Spont.Fiss.

Table V Measured Nubar Values for ^{244}Cm

Author (Year)	Ref.	Measured Value	Revised Value
Zhang(84)	11	2.72 (0.02)	2.74 (0.02)
Schmidt(83)	17	2.73 (0.16)	2.74 (0.16)
Golushko(73)	18	2.68 (0.03)	
Prokhorova(73)	19	2.70 (0.014)	
Jaffey(70)	5	2.692 (0.024)	2.700 (0.024)
Kroshkin(70)	10	2.77 (0.08)	2.76 (0.08)
Bol'shov(64)	20	2.71 (0.04)	2.69 (0.04)
Diven(56)	21	2.81 (0.06)	2.68 (0.06)
Hicks(56)	13	2.84 (0.09)	2.71 (0.09)

Table VI Measured Nubar Values for ^{245}Cm

Author (Year)	Ref.	Measured Value	Revised Value
Howe(83)	22	3.60 (0.06)	3.64 (0.06)
Kroshkin(70)	10	3.83 (0.16)	3.81 (0.16)
Jaffey(70)	5	3.832 (0.034)	3.84 (0.03)

Table VII Measured Nubar Values for ^{246}Cm

Author (Year)	Ref.	Measured Value	Revised Value
Stoughton(73)	23	2.86 (0.06)	2.88 (0.06)
Dakovskii(73)	24	2.98 (0.03)	3.01 (0.03)
Golushko(73)	18	2.927 (0.027)	2.93 (0.03)
Prokhorova(72)	19	2.950 (0.015)	2.95 (0.015)
Thompson(70)	25	3.20 (0.22)	3.17 (0.22)

Table VIII Measured Nubar Values for ^{248}Cm

Author (Year)	Ref.	Measured Value	Revised Value
Boldeman(73)	26	3.092 (0.007)	3.12 (0.007)
Stoughton(73)	23	3.14 (0.06)	3.16 (0.06)
Golushko(73)	18	3.173 (0.022)	3.17 (0.02)
Prokhorova(72)	19	3.157 (0.015)	3.16 (0.015)
Orth(71)	16	3.11 (0.09)	3.10 (0.09)

Table IX Measured Nubar Values for ^{249}Bk

Author (Year)	Ref.	Measured Value	Revised Value
Kosyakov(72)	27	3.395 (0.026)	3.40 (0.03)
Pyle(57)	28	3.72 (0.16)	3.55 (0.16)

Table X Measured Nubar Values for ^{246}Cf

Author (Year)	Ref.	Measured Value	Revised Value
Dakovski(73)	29	3.14 (0.09)	3.18 (0.09)
Pyle(57)	28	2.92 (0.19)	2.79 (0.19)

Table XI Measured Nubar Values for ^{249}Cf

Author (Year)	Ref.	Measured Value	Revised Value	Comment
Unik(73)	30	4.4 nu		Neut.Fiss
Volodin(72)	31	4.06 (0.04)	4.08 (0.04)	Neut.Fiss
		3.4 (0.4)	3.4 (0.4)	Spont.Fiss
Kurchatov(71)	32	4.0 (0.5)		Neut.Fiss
Zamyatnin(70)	33	4.60 (0.21)	4.56 (0.21)	Neut.Fiss
Flynn(69)	34	6. (1.5)		Neut.Fiss

Table XII Measured Nubar Values for ^{250}Cf

Author (Year)	Ref.	Measured Value	Revised Value
Hoffman(80)	35	3.49 (0.04)	3.51 (0.04)
Orth(71)	16	3.53 (0.09)	3.52 (0.09)

Table XIII Measured Nubar Values for ^{252}Cf

Author (Year)	Ref.	Measured Value	Revised Value	Comment
Smith(83)	36	3.767 (0.007)	3.767 (0.01)	Manganese Bath Technique
Spencer(82)	37	3.782 (0.008)		Liquid Scintillator Technique
Edwards(82)	38	3.761 (0.029)		Boron Pile Technique
Aleksandrov(80)	39	3.758 (0.015)		Manganese Bath Technique
Zhang(79)	40	3.752 (0.018)		Liquid Scintillator Technique
Bozorgmanesh(77)	41	3.744 (0.023)		Manganese Bath Technique
Boldeman(74)	42	3.747 (0.015)	3.755 (0.016)	Liquid Scintillator Technique
Axton(74)	43	3.725 (0.019)	3.744 (0.022)	Manganese Bath Technique
Mehta(73)	44	3.766 (0.002)		Liquid Scintillator Technique
DeVolpi(70)	45	3.725 (0.015)	3.747 (0.019)	Manganese Bath Technique
White(68)	46	3.796 (0.031)	3.8156 (0.040)	Manganese Bath Technique
Colvin(65)	47	3.713 (0.015)	3.739 (0.021)	Boron Pile Technique
Hopkins(63)	48	3.780 (0.030)	3.777 (0.031)	Liquid Scintillator Technique
Asplund-Nilsson(63)	49	3.808 (0.034)	3.792 (0.040)	Liquid Scintillator Technique

Table XIV Measured Nubar Values for ^{254}Cf

Author (Year)	Ref.	Measured Value	Revised Value
Hoffman(80)	35	3.77 (0.05)	3.79 (0.05)
Orth(71)	16	3.93 (0.05)	3.92 (0.05)

Table XV Measured Nubar Values for ^{251}Cf, ^{253,254}Es, ^{244,246,255}Fm and ^{252}No

Nuclide	Author (Year)	Ref.	Measured Value	Revised Value	Comment
^{251}Cf	Flynn(75)	50	4.1 (0.5)		Neut. Fiss.
^{253}Es	Flynn(76)	51	4.7 nu		Spont. Fiss.
^{254}Es	Flynn(76)	51	4.2 nu		Neut. Fiss.
^{244}Fm	Bogdanov(81)	52	4. (1.)		Spont.Fiss.
^{246}Fm	Bogdanov(81)	52	4. (1.)		Spont.Fiss.
^{255}Fm	Flynn(75)	50	4.0 (0.5)		Neut.Fiss.
^{252}No	Lazarev(74)	53	4.15 (0.30)	4.2 (0.3)	Spont.Fiss.

Table XVI Measured Nubar Values for ^{254}Fm

Author (Year)	Ref.	Measured Value	Revised Value
Unik(73)	30	3.7 nu	
Choppin(56)	54	4.05 (0.19)	3.99 (0.28)

Table XVII Measured Nubar Values for ^{256}Fm

Author (Year)	Ref.	Measured Value	Revised Value
Ter-Akopian(81)	55	3.59 (0.06)	3.61 (0.06)
Dakovski(73)	56	3.73 (0.18)	3.77 (0.18)
Unik(73)	30	3.2 nu	
Flynn(72)	57	3. (1.)	

Table XVIII Measured Nubar Values for ^{257}Fm

Author (Year)	Ref.	Measured Value	Revised Value
Hoffman(80)	35	3.85 (0.05)	3.87 (0.05)
Balagna(73)	58	3.77 (0.02)	3.79 (0.02)
Cheifetz(71)	59	3.97 (0.13)	4.01 (0.14)

Table XIX Recommended Nubar Values for Am, Cm, Bk, Cf, Es, Fm and No Nuclides

Nuclide	Value (Uncertainty)	Nuclide	Value (Uncertainty)
^{241}Am	3.22 (0.04)	^{250}Cf	3.51 (0.04)
^{242m}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		

Table XX Measured and Recommended P_ν for ^{242}Cm

Parameter	Hicks[13]	Halperin[12]	Zhang[11]	Recommended
P_0	0.01665	0.02287	0.02424	0.02125
P_1	0.14755	0.13404	0.15862	0.14674
P_2	0.33715	0.32913	0.31398	0.32675
P_3	0.32679	0.33898	0.31471	0.32683
P_4	0.12634	0.14631	0.13988	0.13751
P_5	0.04143	0.02653	0.04419	0.03738
P_6	0.00334	0.00207	0.00237	0.00259
P_7	0.00075	0.00007	0.00145	0.00076
P_8			0.00056	0.00019
$\langle\nu\rangle$	2.54	2.54	2.54	2.54 +_ 0.02
$\langle\nu(\nu-1)\rangle$	5.11	5.04	5.24	5.13 +_ 0.10
$\langle\nu(\nu-1)(\nu-2)\rangle$	8.04	7.40	8.67	8.04 +_ 0.64
$\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$	0.792	0.782	0.812	0.795 +_ 0.016
$\langle\nu^2\rangle - \langle\nu\rangle^2$	1.20	1.13	1.33	1.22 +_ 0.10
$\langle\nu^2\rangle$	7.65	7.58	7.78	7.67 +_ 0.10

Table XXI Measured and Recommended P_ν for ^{244}Cm

Parameter	Diven[21]	Hicks[13]	Dakovskii[24]	Zhang[11]	Recommended
P_0	0.01280	0.00550	0.02788	0.01384	0.01501
P_1	0.12458	0.11864	0.09174	0.12973	0.11617
P_2	0.30326	0.30138	0.30960	0.28513	0.29984
P_3	0.31201	0.35146	0.33337	0.33581	0.33316
P_4	0.20115	0.17634	0.18024	0.17736	0.18378
P_5	0.02892	0.04122	0.05502	0.04675	0.04298
P_6	0.01728	0.00546	0.00215	0.01028	0.00879
P_7	–	–	–	0.00110	0.00027
$\langle\nu\rangle$	2.72	2.72	2.72	2.72	2.72 +_ 0.02
$\langle\nu(\nu-1)\rangle$	5.99	5.82	5.95	6.00	5.94 +_ 0.09
$\langle\nu(\nu-1)(\nu-2)\rangle$	10.51	9.47	9.88	10.54	10.10 +_ 0.52
$\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$	0.810	0.786	0.804	0.811	0.803 +_ 0.012
$\langle\nu^2\rangle - \langle\nu\rangle^2$	1.31	1.14	1.27	1.32	1.26 +_ 0.09
$\langle\nu^2\rangle$	8.71	8.54	8.67	8.72	8.66 +_ 0.09

Table XXII Measured and Recommended P_ν for ^{246}Cm

Parameter	Stoughton[23]	Dakovskii[24]	Recommended
P_0	0.01305	0.01738	0.01522
P_1	0.08249	0.07007	0.07628
P_2	0.25120	0.27420	0.26270
P_3	0.35224	0.33761	0.34492
P_4	0.22587	0.21026	0.21807
P_5	0.06598	0.08520	0.07559
P_6	0.00917	0.00528	0.00722
$\langle\nu\rangle$	2.93	2.93	2.93 +_ 0.03
$\langle\nu(\nu-1)\rangle$	6.92	6.96	6.94 +_ 0.03
$\langle\nu(\nu-1)(\nu-2)\rangle$	12.59	12.82	12.71 +_ 0.16
$\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$	0.806	0.811	0.808 +_ 0.003
$\langle\nu^2\rangle - \langle\nu\rangle^2$	1.27	1.30	1.29 +_ 0.03
$\langle\nu^2\rangle$	9.85	9.89	9.87 +_ 0.03

Table XXIII Measured and Recommended P_ν for ^{248}Cm

Parameter	Boldeman[26]	Stoughton[23]	Recommended
P_0	0.00631	0.00716	0.00673
P_1	0.06224	0.05706	0.05965
P_2	0.22726	0.21384	0.22055
P_3	0.34581	0.35599	0.35090
P_4	0.24354	0.26522	0.25438
P_5	0.09076	0.08795	0.08936
P_6	0.02070	0.01278	0.01674
P_7	0.00338	-	0.00169
$\langle\nu\rangle$	3.13	3.13	3.13 +_ 0.03
$\langle\nu(\nu-1)\rangle$	8.03	7.89	7.96 +_ 0.10
$\langle\nu(\nu-1)(\nu-2)\rangle$	16.56	15.31	15.94 +_ 0.88
$\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$	0.820	0.805	0.812 +_ 0.010
$\langle\nu^2\rangle - \langle\nu\rangle^2$	1.36	1.22	1.29 +_ 0.10
$\langle\nu^2\rangle$	11.16	11.02	11.09 +_ 0.10

Table XIV Measured P_ν for ^{246}Cf, ^{250}Cf, ^{254}Cf, ^{257}Fm and ^{252}No

Nuclide	^{246}Cf	^{250}Cf	^{254}Cf	^{257}Fm	^{252}No
Parameter	Dakovskii[29]	Hoffman[35]	Hoffman[35]	Hoffman[35]	Lazarev[53]
P_0	0.00051	0.00382	0.00020	0.02057	0.05692
P_1	0.11360	0.03654	0.01902	0.05203	0.05768
P_2	0.23460	0.16734	0.11264	0.11726	0.09249
P_3	0.27428	0.29453	0.26389	0.19970	0.14374
P_4	0.22087	0.29827	0.31834	0.26279	0.18325
P_5	0.12597	0.14514	0.19418	0.20078	0.18315
P_6	0.03017	0.04722	0.07453	0.10617	0.14559
P_7	-	0.00402	0.01500	0.03330	0.09630
P_8	-	0.00312	0.00220	0.00740	0.03820
P_9	-	-	-	-	0.00268
$\langle\nu\rangle$	3.10	3.51	3.85	3.87	4.2
$\langle\nu(\nu-1)\rangle$	8.19	10.34	12.50	13.60	17.65
$\langle\nu(\nu-1)(\nu-2)\rangle$	8.26	25.19	33.71	41.77	
$\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$	0.852	0.840	0.843	0.908	1.001
$\langle\nu^2\rangle - \langle\nu\rangle^2$	1.68	1.53	1.53	2.49	4.21
$\langle\nu^2\rangle$	11.29	13.85	16.35	17.47	21.85