LA-3383

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See Attached Errata Sheet

LOS ALAMOS SCIENTIFIC LABORATORY
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Fission Product Yields from Fast (~1 MeV) Neutron Fission of Pu-239

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Please attach this sheet to LA-3383 and make the indicated corrections to the Table.

Delete the following lines from Table III, pages 21 and 22 of LA-3383.

35	82	0.001	0.260
36	82	0.000	0.260
38	87	0.000	1.150
41	96	0.008	5.250
42	96	0.000	5.250
50	115	0.000	0.095
53	130	0.009	2.350
54	130	0.000	2.350
61	150	0.014	1.150
62	150	0.000	1.150

The entry for Z = 35, A = 82 was definitely an error. The other deletions are made in view of the possible practical application of the calculations. In the report, the cumulative yields were given for infinite time, but since the half-lives shown below (Ref: Sullivan, W. H., "Trilinear Chart of Nuclides") are so long, it would be practical to consider these nuclides as pseudo-stable.

Z	A	Half-life (years)
37	87	4.7×10^{10}
40	96	$> 2 \times 10^{16}$
49	115	6×10^{15}
52	130	$> 10^{21}$
60	150	$> 10^{16}$

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LOS ALAMOS SCIENTIFIC LABORATORY
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LOS ALAMOS • NEW MEXICO

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Fission Product Yields from Fast (~1 MeV) Neutron Fission of Pu-239

by

Carl A. Anderson, Jr.

ABSTRACT

The sixteen measured yields of fission products from fast fission of Pu-239 published through June, 1965 are given. Information is presented which indicates the restricted range of mass numbers within which mirroring, or reflection, of data is applicable. Use of this information enables generation of fairly reliable guesses for six reflected data points. A curve fit to these data provides interpolated estimates of unmeasured mass chain yields. A modified equal-charge-displacement hypothesis is used to estimate independent and cumulative fission yields of nuclides.

It is hoped that future measurements of fission product yields from fast fission of Pu-239 will make the speculative portions of this report unnecessary.

ACKNOWLEDGMENTS

The author appreciates the helpful information provided by James Terrell on the subject of neutron yield versus mass number. Kurt Wolfsberg, Rolf Peterson, and Morris Battat very kindly reviewed the manuscript and offered valuable suggestions. The staff of the Los Alamos Scientific Laboratory Technical Library assisted in the literature search.

INTRODUCTION

In the shield design and safety analysis of a plutonium fueled fast reactor, it is necessary to determine the radiation which results from fission product decay. To do so, it is first necessary to have good information concerning the fission product nuclide yields.

For lack of sufficient information on plutonium fission, some fast plutonium reactor designers (e.g., Ref. 1) still rely on inappropriate treatments based on thermal fission of U-235 (e.g., Ref. 2). Two extensive compilations of fission product yields, those of Katcoff,[3,4] contain too few measured values of mass chain yields for Pu-239 fast fission* to enable determination of nonmeasured yields by interpolation. Indeed, only one report[5] contains a curve of yield versus mass number for fast fission of Pu-239 on the basis of Katcoff's compilation; this curve agrees better with the experimental data than does the widely used Pu-239 fast fission yield mass number distribution of Burris and Dillon.[6] A recent compilation of fission product yields by Zysin[7] raises the possibility of improving the situation, since it tabulates fast Pu-239 fission yields for 16 mass numbers, as opposed to yields for 8 mass numbers in Katcoff's compilations. Unfortunately, checking a few of the references given by Zysin indicates a number of errors in his compilation (but these are really rather minor errors in so impressive a collection of data as Zysin's). Consequently, the literature was

*Fast fission is rather loosely defined as fission induced by neutrons with energies of the order of 1 or 2 MeV.

searched for original data. This search, while not uncovering data for additional mass numbers, revealed 8 errors in the 29 values given by Zysin, as well as 7 omissions. Virtually all of the errors are due to Zysin's consideration of values listed by Katcoff as original measurements. Thus, for example, the measured yield of Cs-137[8] was corrected by Katcoff for the 1958 value of its half-life[3] and recorrected for the 1960 value of its half-life.[4] Zysin lists all three values as independent determinations. In another error, Brightsen, et al.[9] erroneously list the Pu-239 thermal fission yield of Zr-95 as a fast fission yield, and Zysin copies the error.

MASS CHAIN YIELD DATA

The results of the literature search are given in Table I. Most of the plus-minus deviations given in column 2 are known to be standard deviations of the means, or standard errors, but some of the deviations can only be assumed to be so because the authors are not specific. The plus-minus deviations in column 7 are the standard deviations of the means based on the preceding assumption, using equal weighting of the data. Inclusion of the standard errors is of importance, since they indicate the liberties which may be taken in plotting a curve through the points. The compilations of Katcoff and Zysin are included for comparison.

TABLE I

MEASURED PU-239 FAST FISSION YIELDS

Nuclide	Original Data Yield	Ref.	Earlier Compilations: Katcoff (Ref. T1) Yield	Katcoff (Ref. T2) Yield	Zysin (Ref. T3) Yield	Chain Yield Based on Original Data	Notes
$_{38}Sr^{89}$	1.8 ± 0.2	T6	---	---	1.8 ± 0.2	1.8 ± 0.2	
$_{38}Sr^{89}$	2.12 ± 0.09	T7	2.2	2.2	2.2	2.12 ± 0.09	
$_{40}Zr^{95}$	5.3 ± 0.5	T6	---	---	5.3 ± 0.5 5.6	5.3 ± 0.5	1
$_{40}Zr^{97}$	5.01 5.41	T8 T8	5.2	5.2	5.2	5.2 ± 0.2	
$_{40}Mo^{99}$	6.04 5.70 6.07 5.5 ± 0.4 5.9 ± 0.6	T8 T8 T8 T6 T9	5.9	6.0	5.9 6.0 5.5 ± 0.4 5.9 ± 0.6	5.78 ± 0.24	2
$_{44}Ru^{103}$	6.0 ± 0.7 5.7 ± 1.0	T9 T10	---	---	6.0 ± 0.7 5.7 ± 1.0	5.85 ± 0.61	
$_{44}Ru^{106}$	4.8 ± 0.6 4.6 ± 0.8	T9 T10	---	---	4.8 ± 0.6 4.6 ± 0.8	4.7 ± 0.5	
$_{46}Pd^{109}$	1.67 1.48 1.60	T8 T5 T5	1.9	2.0	1.9 2.0	1.64 ± 0.06	3
$_{47}Ag^{111}$	0.55 ± 0.06 0.45 ± 0.03 0.237	T9 T6 T5	---	---	0.55 ± 0.06 0.45 ± 0.03	0.50 ± 0.03	4
$_{46}Pd^{112}$	0.127 0.177	T5 T5	0.14	0.14	0.14	0.152 ± 0.025	
53 hr $_{48}Cd^{115}$	0.045 0.075 0.09 ± 0.01 0.098 ± 0.008	T5 T5 T9 T6	0.069	0.067	0.069 0.067 0.09 ± 0.01 0.098 ± 0.008	---	
Total $_{48}Cd^{115}$	0.095 ± 0.010	T9	---	---	0.095 ± 0.010	0.095 ± 0.010	
33.5 day $_{52}Te^{129}$	0.45 ± 0.09	T9	---	---	0.45 ± 0.09	---	
Total $_{52}Te^{129}$	1.17	T9	---	---	1.17	1.17	
$_{52}Te^{132}$	3.5 ± 1.0	T9	---	---	3.5 ± 1.0	3.75 ± 1.0	5
$_{55}Cs^{137}$	7.45 ± 0.20	T4	6.6	6.8	6.6 6.8 7.45 ± 0.20	6.85 ± 0.20	3
$_{56}Ba^{140}$	5.4 ± 0.5 5.14 4.91 5.06 4.9 ± 0.4	T9 T8 T8 T8 T6	5.0	5.0	5.4 ± 0.5 5.0 4.9 ± 0.4	5.11 ± 0.21	6
$_{62}Sm^{153}$	0.50 0.45	T8 T8	0.48	0.48	0.48	0.475 ± 0.025	

Notes:
1. Zysin reproduces error of Ref. T8 App. B
2. Ref. T8 mean = 5.94 ± 0.12
3. Half-life correction applied to original data
4. 0.237 rejected
5. Chain yield/Te-132 yield = 1.07
6. Ref. T8 mean = 5.04 ± 0.07

REFERENCES FOR TABLE I

T1. Katcoff, S., "Fission-Product Yields from U, Th and Pu," Nucleonics 16, No. 4, 78 (1958).

T2. Katcoff, S., "Fission-Product Yields from Neutron-Induced Fission," Nucleonics 18, No. 11, 201 (1960).

T3. Zysin, Yu. A., A. A. Lbov, and L. I. Sel'chenkov, Fission Product Yields and Their Mass Distribution (Consultants Bureau, New York, 1964), Russian publication in 1963.

T4. Kafalas, P. and C. E. Crouthamel, "The Absolute Yield of Cs-137 in Fast-Neutron Fission of U-235 and Pu-239," J. Inorg. Nucl. Chem. 4, 239 (1957).

T5. Ford, G. P. and J. S. Gilmore, "Mass Yields from Fission by Neutrons Between Thermal and 14.7 Mev," Los Alamos Scientific Laboratory Report LA-1997 (1956).

T6. Petrzhak, K. A. et al., "Yields of a Number of Fission Products in the Fission of Uranium-235, Uranium-238, and Plutonium-239 by Neutrons," AEC-TR-4696 (1961) Russian publication in 1960.

T7. Bayhurst, B. P., "Fission Yields of Sr^{90}," TID-5787 (1956).

T8. Steinberg, E. P. and M. S. Freedman, "Summary of Results of Fission-Yield Experiments," in Radiochemical Studies: The Fission Products, C. D. Coryell and N. Sugarman, Eds., (McGraw-Hill Book Company, Inc., New York, 1951), Book 3, pp. 1378-1390; and Engelkemeir, D. W. et al., "Determination of Absolute Fast-Neutron Fission Yields in Pu-239," pp. 1331-1333.

T9. Bonyushkin, E. K. et al., "Fragment Yield in the Fission of U-233 and Pu-239 by Fast Neutrons," At. Energ. USSR 10, 13 (1961).

T10. Bak, M. A. et al., "Yields of Ru-103 and Ru-106 on Fission of U-235 and Pu-239 by Fast Neutrons," At. Energ. USSR 6, 577 (1959).

MIRRORING

To supplement, and to make the most efficient use of, the small amount of data available, the technique of mirroring, or reflection, is used. The relation

$$Pu^{239} + n^1 \rightarrow M_{light} + M_{heavy} + \nu n^1 , \qquad (1)$$

where

M = fission product,

ν = a constant,

n^1 = neutron,

has been widely used, but is not generally applicable. Petrzhak,[10] for example, incorrectly assumed the applicability of the above relation for all of his data, using $\nu = 3.0$. The following discussion indicates the limited extent to which mirroring may be used. Terrell[11,12] has derived the relation (assuming a continuous mass distribution):

$$\int_0^{M_i - \nu(M_i)} Y(M)\, dM = \int_0^{M_i} y(M)\, dM + \frac{1}{2}\frac{dy}{dM} \left\langle \sigma^2(\nu; M) \right\rangle + \dots , \qquad (2)$$

where

M_i = initial fission fragment mass,

y = initial mass yield,

Y = final mass yield,

$\nu(M_i)$ = average number of neutrons emitted by fragment of mass M_i,

$\sigma^2(x) = \overline{x^2} - \overline{x}^2$, the conditional variance.

Differentiating Eq. 2 with respect to M_i (and noting that, since the correction term involving σ^2 is both small and fairly independent of M_i, the differential of the correction term may be neglected) one writes

$$Y[M_i - \nu(M_i)] \left[1 - \frac{d\,\nu(M_i)}{d\,M_i}\right] = y(M_i) \ . \tag{3a}$$

This relation applies equally for the light and for the heavy fission fragment which occur in a given fission, whence

$$Y[M_{Li} - \nu(M_{Li})] \left[1 - \frac{d\,\nu(M_{Li})}{d\,M_{Li}}\right] = y(M_{Li}) \tag{3b}$$

and

$$Y[M_{Hi} - \nu(M_{Hi})] \left[1 - \frac{d\,\nu(M_{Hi})}{d\,M_{Hi}}\right] = y(M_{Hi}) \ . \tag{3c}$$

Since, by definition,

$$y(M_{Li}) \equiv y(M_{Hi}) \ , \tag{4}$$

and if

$$\frac{d\,\nu(M_{Li})}{d\,M_{Li}} = \frac{d\,\nu(M_{Hi})}{d\,M_{Hi}} \ , \tag{5}$$

(the validity of Eq. 5 will be discussed later) then

$$Y[M_{Li} - \nu(M_{Li})] = Y[M_{Hi} - \nu(M_{Hi})] \ . \tag{6}$$

Let

$$M_{Lf} = M_{Li} - \nu(M_{Li}) \ , \tag{7}$$

where

M_f = final fission product mass.

It is also known that

$$M_{Hi} + M_{Li} = A_f \ , \tag{8}$$

where

A_f = mass of fissionable (compound) nucleus.

From Eqs. 6, 7, and 8:

$$Y(M_{Lf}) = Y[A_f - M_{Lf} - \nu(M_{Hi}) - \nu(M_{Li})] \ , \tag{9}$$

and defining the total neutron yield associated with the light fission fragment of mass M_{Li} as

$$\nu = \nu(M_{Hi}) + \nu(M_{Li}) \ , \tag{10}$$

there results

$$Y(M_{Lf}) = Y(A_f - M_{Lf} - \nu) \ , \tag{11a}$$

and, similarly,

$$Y(M_{Hf}) = Y(A_f - M_{Hf} - \nu) \; . \qquad (11b)$$

This can be a very useful result. It states that, if one knows the total number of neutrons associated with the fission product mass chain M_{Lf} and if one knows the fission yield for that mass chain, then one knows the fission yield of the mirror imaged mass chain $A_f - M_{Lf} - \nu$. The restriction is that Eq. 5 must be valid.

Just as there is not much data on fission product yields from fast fission of Pu-239, so there is not much on neutron yields for fast fission of Pu-239. However, the available data[11] on neutron yield versus mass number for thermal neutron induced fission of U-233, U-235 and Pu-239, and for spontaneous fission of Cf-252 show a striking similarity (Fig. 1). Terrell draws the conclusion[12] "It is remarkable that the results for these different types of fission look so much alike when shown as functions of fragment mass. It is suggested that the excitation of the fragments depends more on the properties of the fragments than on the mass ratio, and leads to the idea of a universal neutron yield curve." Thus, it does not appear unreasonable to assume that the curve of neutron yield versus mass number for Pu-239 fast fission will follow the same pattern.

Equations 5 and 10 indicate that Eq. 11 is valid only when

$$\frac{d\nu}{d\,M_{Hi}} = 0 \; . \qquad (12)$$

where ν is now plotted against M_{Hi}. The data referred to above show Eq. 12 to be true only for fissions in which the heavy fragment falls on the high mass side of the heavy mass peak (and, concomitantly, the light fragment falls on the low mass side of the light mass peak). For thermal fission of Pu-239, Eq. 12 is valid in the mass number range 137 to 153, in which range $\nu \cong 3.15$ (± 0.2 for $139 < M_H < 149$, ± 0.6 for $M_H = 153$). A further restriction on the use of

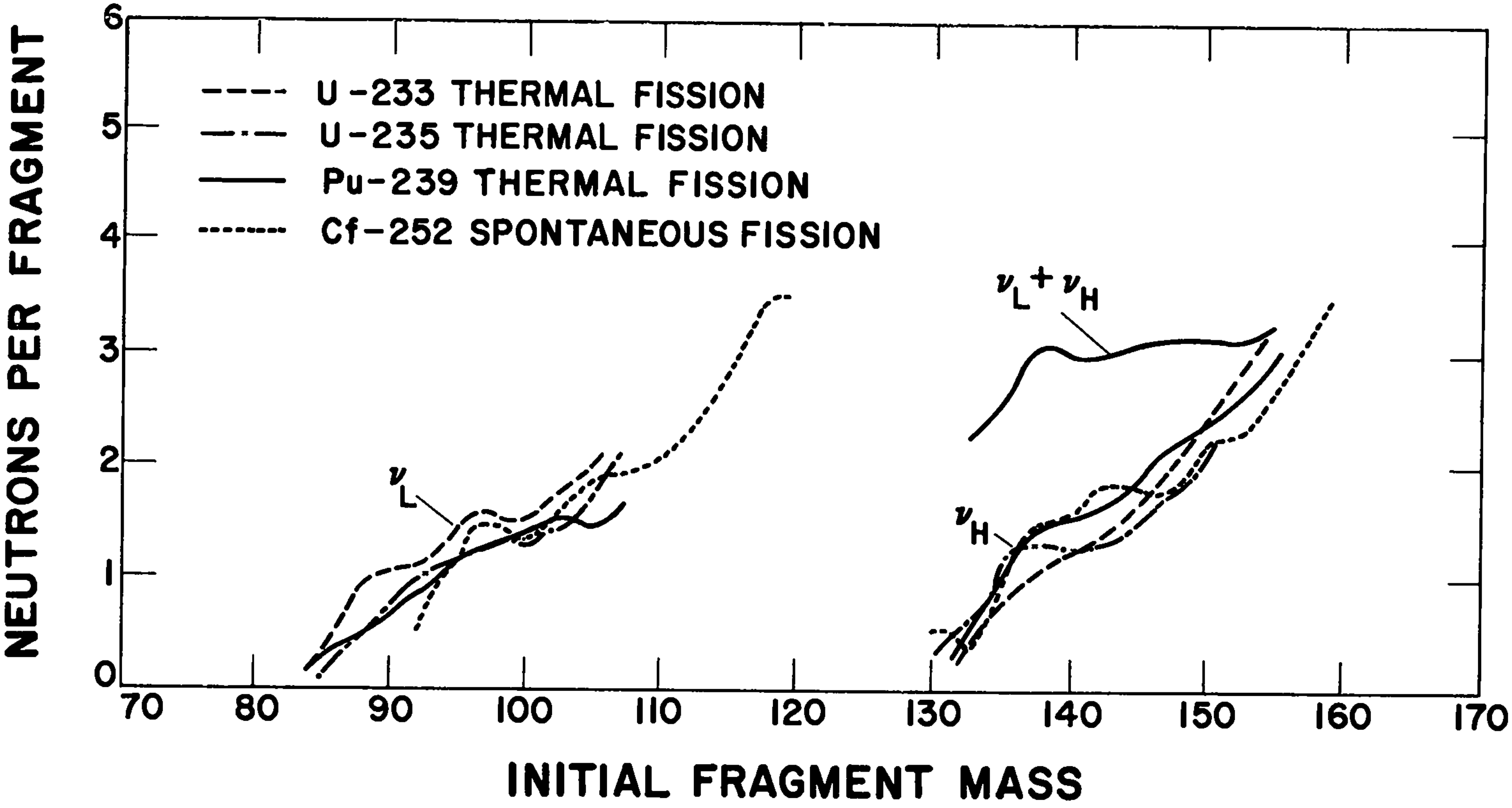

Fig. 1. Neutron Yield versus Initial Fragment Mass Number (from Ref. 11). ν_L, ν_H = neutron yields associated with light and heavy fission fragments, respectively.

Eq. 11 is that ν must be known; because of the difficulty of associating a measured neutron yield with a particular mass chain, ν is known only at mass numbers far from those at which Eq. 12 is invalid. Thus, one may only apply mirroring for Pu-239 fast fission within the range $137 < M_H < 153$.

Since $\bar{\nu}$, the average number of neutrons per fission, is 2.89 ± 0.03 for thermal neutron induced fission of Pu-239 and 3.12 ± 0.15 for fission of Pu-239 by 2.1 MeV neutrons,[13] a value of $\nu = 3.40$ will be used. The spread in neutron yield data (Fig. 1) indicates a possible error of ± 0.5 mass unit in the extrapolation to Pu-239 fast fission. Combining all these errors indicates that mirroring may be used for Pu-239 fast fission data with $\nu = 3.40 \pm 0.55$ for $139 < M_H < 149$, the probable error increasing to ± 0.75 at $M_H = 153$.

It should be mentioned that sharp peaks and valleys in the fission product mass chain yield curve will not be made apparent by the mirroring technique.

MASS CHAIN YIELD CURVES

The data in Table I are plotted as open circles in Fig. 2. Careful use of the technique of mirroring, discussed above, enables generation of additional pseudo-data points (shown as closed circles in Fig. 2) at mass numbers 83.6, 96.6, 139.6, 141.6, 146.6, and 147.6 (reflections of the mass chain yields at mass numbers 153, 140, 97, 95, 90, and 89). A best fit curve is drawn subject to the constraint that the sum of the yields under each peak must be 100%. Figure 2 also shows the curves of Burris and Dillon[6] and of Weaver, et al.[5] for comparison.

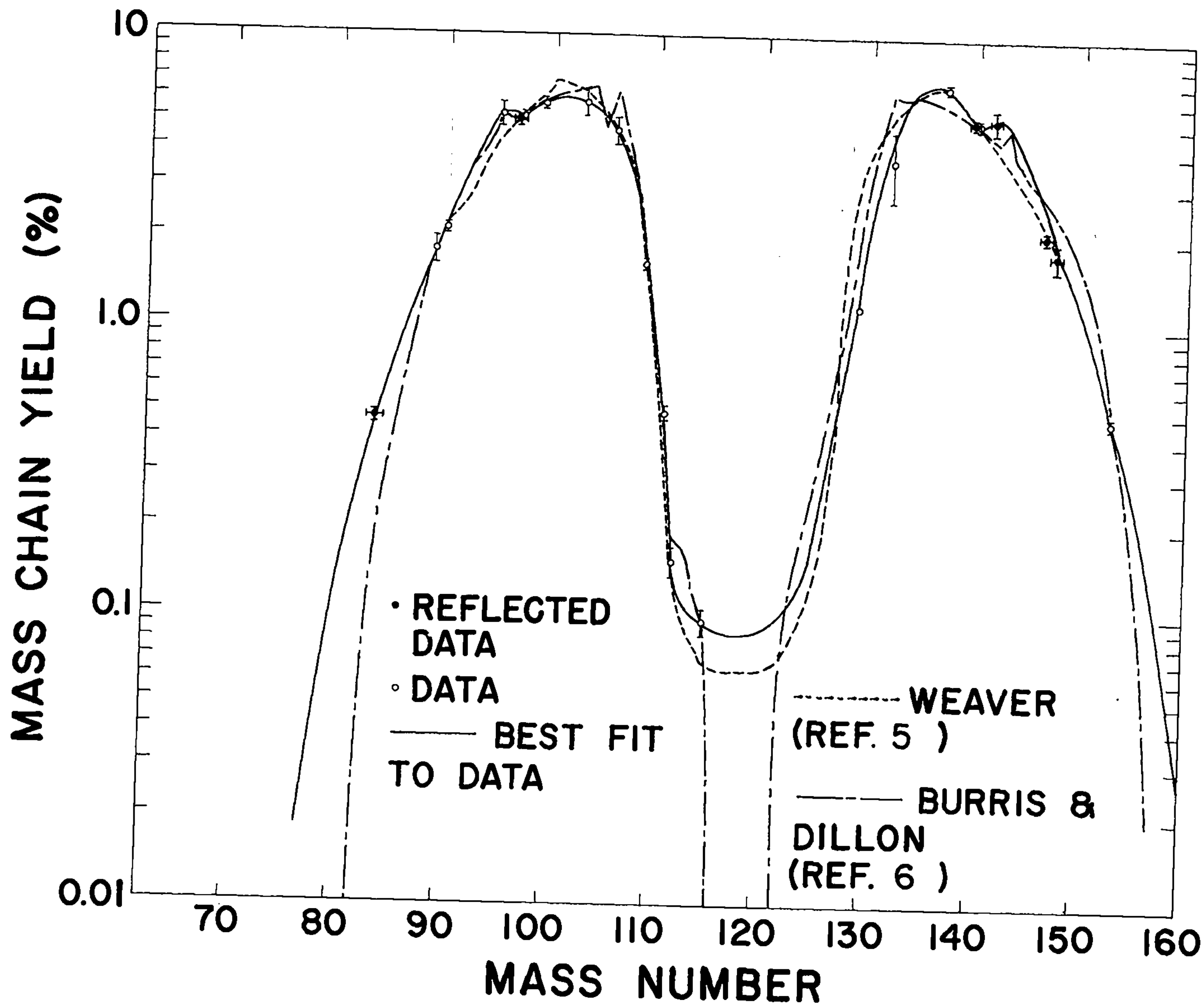

Fig. 2. Fission Product Mass Chain Yields for Pu-239 Fast Fission. Data and Three Fitted Curves.

It should be noted that the mass chain yields most open to question are those in the valley, partly because there are no data from mass number 115 to mass number 129, and partly because the valley yields are most sensitive to changes in the energy of neutrons inducing fission.

Figure 3 reproduces the Pu-239 fast fission yield data and compares them with curves based on experimental fission product yields[3,4,7] for thermal fission of Pu-239 and U-235 (these yields were not checked). Two conclusions from this comparison should be emphasized. The first conclusion is that the U-235 thermal fission yield curve is a bad approximation to the Pu-239 fast fission yield data and should not be used as such. The second conclusion is that Pu-239 fission product mass chain yields are not strongly dependent on energy, except in the valley. This is important because of the wide variation in "fast" neutron spectra which were used for measurement of the fast fission yields under discussion. Thus, in the work of Ford,[14] data are given for fast fission of Pd-109, Pd-112, and Cd-115 from two different "fast" spectra; one a degraded fission spectrum from a fast reactor and the other spectrum from a thick U-235 converter capsule in a reactor thermal column. Several experimenters (e.g., Ref. 10) used a U-235 plate in a reactor thermal column as the source of fast neutrons. The fission energy neutrons passed through about 1 cm of B_4C (a thermal neutron shield) to reach the sample. Inasmuch as the B_4C scattered about 10% of the fission energy neutrons directed from the U-235 plate to the sample, the spectrum at the sample was probably degraded somewhat.

Table II lists the fission product mass chain yields obtained, by interpolation and extrapolation, from Fig. 2. Three significant figures are used merely for consistency, and do not, of course, imply that the numbers are that well known. These yields will now be used to derive the fission product nuclide yields.

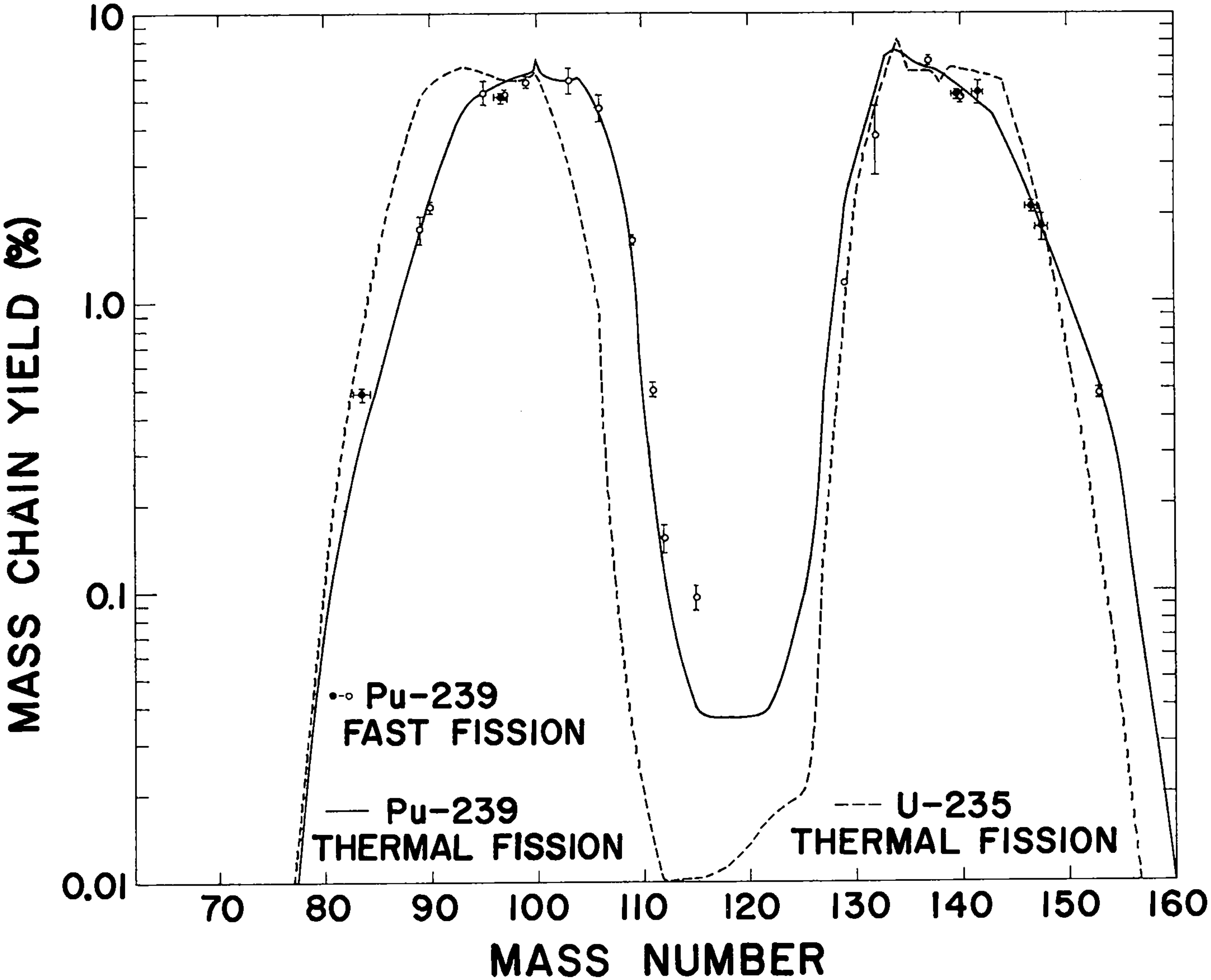

Fig. 3. Comparison of Experimental Data.

TABLE II

MASS CHAIN YIELDS

A	Mass Chain Yield	A	Mass Chain Yield
76	0.00	120	0.089
77	0.019	121	0.092
78	0.039	122	0.097
79	0.070	123	0.110
80	0.110	124	0.129
81	0.178	125	0.167
82	0.26	126	0.28
83	0.38	127	0.43
84	0.52	128	0.71
85	0.69	129	1.20
86	0.90	130	2.35
87	1.15	131	3.40
88	1.43	132	4.55
89	1.80	133	5.70
90	2.12	134	6.45
91	2.60	135	6.85
92	3.15	136	6.95
93	3.80	137	6.85
94	4.60	138	6.10
95	5.30	139	5.30
96	5.25	140	5.10
97	5.20	141	5.35
98	5.50	142	5.40
99	5.80	143	4.90
100	6.00	144	4.30
101	6.00	145	3.55
102	6.00	146	2.85
103	5.85	147	2.25
104	5.60	148	1.75
105	5.30	149	1.43
106	4.70	150	1.15
107	3.70	151	0.89
108	2.70	152	0.70
109	1.67	153	0.48
110	0.82	154	0.36
111	0.50	155	0.26
112	0.15	156	0.180
113	0.11	157	0.120
114	0.099	158	0.072
115	0.095	159	0.045
116	0.089	160	0.026
117	0.087	161	0.014
118	0.086	Sum =	98.981
119	0.086		
Sum =	100.508	Grand Sum =	199.489

FISSION PRODUCT NUCLIDE YIELDS

The equal charge displacement hypothesis[15] has usually been used to determine the independent yields of members of a mass chain. More recent studies by Wolfsberg and others[16,17] indicate that adjustment of the most probable charge by reference to U-235 thermal neutron fission data results in better agreement with experiment for other fission processes. Assuming that Wolfsberg's is the best available treatment of the yield of a nuclide for which the mass chain yield is known, we write:[17]

$$Y_c(Z, A) = Y_c(A) \{0.5 + 0.5 \text{ Erf} [(Z - Zp(A) + 0.5)/\sigma\sqrt{2}]\}, \tag{13}$$

where

Z = atomic number of fission product,

A = mass number of fission product,

$Zp(A)$ = most probable charge,

σ = a characteristic of the Gaussian distribution assumed for $Y_c(Z, A)$,

$Y_c(A)$ = mass chain yield,

$Y_c(Z, A)$ = cumulative yield of nuclide (Z, A),

$$\text{Erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt, \text{ the error function.} \tag{14}$$

$Zp(A)$, the most probable charge, is given by (for $82 \le A \le 100$)

$$Zp(A) = 0.4237A - 2.19 + 0.5(Z_F - 92) - (0.21(A_F - 236) + 0.19(\nu - 2.43) \quad (15a)$$

(for A ≥ 135)

$$Zp(A) = 0.4331A - 6.06 + 0.5(Z_F - 92) - 0.21(A_F - 236) + 0.19(\nu - 2.43), \quad (15b)$$

where

Z_F = atomic number of fissionable nucleus,

A_F = mass number of compound nucleus,

ν = average number of neutrons emitted per fission.

Although not enough measurements have been made for low yield mass numbers,[17] linear interpolation is assumed to be satisfactory for 101 ≤ A ≤ 134, whence (for 101 ≤ A ≤ 134)

$$Zp(A) = 0.349A + 5.24 + 0.5(Z_F - 92) - 0.21(A_F - 236) + 0.19(\nu - 2.43). \quad (15c)$$

The Appendix contains the computer program used for the calculations, which were performed on the IBM 7094 computer. Table III gives the resultant values of independent and cumulative fission product yields versus Z and A for Pu-239 fast fission. The mass chain yields given above were used, along with $\sigma = 0.59$ (from Ref. 17) and E = 1.0 MeV, where E is the energy of neutrons causing fission. The choice of σ is open to question.[16,17] The value of $Y_c(Z, A)$ is not very dependent on E, since it can be affected only by the dependence of $Y_c(A)$ on E (which Fig. 3 shows to be slight) and the dependence of ν on E (which Eq. 15 shows to have little effect).

For a given A, the computer terminates the fission product decay chain calculation at the first value of Z corresponding to a stable nuclide. This means that a few shielded nuclides, such as Sb-122, are not included in the results--but this is an inconsiderable omission since the yields of such nuclides are extremely small.

See Attached Errata Sheet

TABLE III

INDEPENDENT AND CUMULATIVE FISSION PRODUCT YIELDS VERSUS Z AND A FOR PU-239 FAST FISSION

Z	A	PERCENT YIELD INDEPENDENT	PERCENT YIELD CUMULATIVE
30	77	0.007	0.007
30	78	0.006	0.006
30	79	0.003	0.003
31	77	0.010	0.017
31	78	0.023	0.029
31	79	0.030	0.033
31	80	0.023	0.023
31	81	0.011	0.012
31	82	0.003	0.003
32	77	0.002	0.019
32	78	0.016	0.039
32	79	0.034	0.066
32	80	0.066	0.090
32	81	0.090	0.102
32	82	0.073	0.077
32	83	0.039	0.040
32	84	0.012	0.013
32	85	0.002	0.002
33	77	0.000	0.019
33	78	0.000	0.039
33	79	0.004	0.070
33	80	0.020	0.109
33	81	0.071	0.173
33	82	0.151	0.228
33	83	0.215	0.254
33	84	0.190	0.203
33	85	0.107	0.110
33	86	0.038	0.039
33	87	0.009	0.009
33	88	0.001	0.001
34	77	0.000	0.019
34	78	0.000	0.039
34	79	0.000	0.070
34	80	0.001	0.110
34	81	0.005	0.178
34	82	0.032	0.259
34	83	0.119	0.374
34	84	0.277	0.479
34	85	0.413	0.522
34	86	0.403	0.442
34	87	0.256	0.264
34	88	0.102	0.103
34	89	0.026	0.027
34	90	0.004	0.004
35	79	0.000	0.070
35	81	0.000	0.178
~~35~~	~~82~~	~~0.001~~	~~0.260~~
35	83	0.006	0.380
35	84	0.040	0.520
35	85	0.162	0.684
35	86	0.415	0.858
35	87	0.691	0.955
35	88	0.745	0.849
35	89	0.541	0.567
35	90	0.240	0.244
35	91	0.071	0.072
35	92	0.013	0.013
35	93	0.002	0.002
~~36~~	~~82~~	~~0.000~~	~~0.260~~
36	83	0.000	0.380
36	84	0.000	0.520
36	85	0.006	0.690
36	86	0.042	0.900
36	87	0.191	1.145
36	88	0.543	1.392
36	89	1.030	1.598
36	90	1.218	1.463
36	91	0.999	1.071
36	92	0.533	0.546
36	93	0.183	0.184
36	94	0.040	0.040
36	95	0.005	0.005
37	85	0.000	0.690
37	87	0.005	1.150
37	88	0.038	1.430
37	89	0.199	1.797
37	90	0.627	2.090
37	91	1.346	2.417
37	92	1.894	2.440
37	93	1.770	1.954
37	94	1.099	1.139
37	95	0.422	0.428
37	96	0.089	0.090
37	97	0.012	0.012
37	98	0.001	0.001
~~38~~	~~87~~	~~0.000~~	~~1.150~~
38	88	0.000	1.430
38	89	0.003	1.800
38	90	0.030	2.120
38	91	0.181	2.598
38	92	0.687	3.127
38	93	1.687	3.641
38	94	2.746	3.884
38	95	2.836	3.264
38	96	1.674	1.764
38	97	0.647	0.659
38	98	0.172	0.173
38	99	0.029	0.029
38	100	0.003	0.003
39	89	0.000	1.800
39	90	0.000	2.120
39	91	0.002	2.600
39	92	0.022	3.150
39	93	0.157	3.799
39	94	0.700	4.584
39	95	1.912	5.176
39	96	2.952	4.716
39	97	3.033	3.692
39	98	2.217	2.390
39	99	1.065	1.094
39	100	0.325	0.328
39	101	0.084	0.085
39	102	0.016	0.016
39	103	0.002	0.002
40	90	0.000	2.120
40	91	0.000	2.600
40	92	0.000	3.150
40	93	0.001	3.800
40	94	0.016	4.600
40	95	0.123	5.299
40	96	0.526	5.242
40	97	1.444	5.136
40	98	2.764	5.154
40	99	3.498	4.591
40	100	2.896	3.224
40	101	1.770	1.854
40	102	0.810	0.826
40	103	0.268	0.270
40	104	0.064	0.064
40	105	0.011	0.011
40	106	0.001	0.001
41	93	0.000	3.800
41	95	0.001	5.300
~~41~~	~~96~~	~~0.008~~	~~5.250~~
41	97	0.064	5.200
41	98	0.343	5.497
41	99	1.173	5.765
41	100	2.555	5.779
41	101	3.451	5.306
41	102	3.537	4.363
41	103	2.683	2.953
41	104	1.509	1.573
41	105	0.628	0.639
41	106	0.181	0.182
41	107	0.034	0.034
41	108	0.004	0.004
42	95	0.000	5.300
~~42~~	~~96~~	~~0.000~~	~~5.250~~
42	97	0.000	5.200
42	98	0.003	5.500
42	99	0.035	5.800
42	100	0.219	5.999
42	101	0.683	5.989
42	102	1.572	5.936
42	103	2.640	5.593
42	104	3.285	4.858
42	105	3.066	3.707
42	106	2.037	2.220
42	107	0.906	0.940
42	108	0.279	0.283
42	109	0.054	0.054
42	110	0.006	0.006
43	99	0.000	5.800
43	101	0.011	6.000
43	102	0.064	6.000
43	103	0.255	5.848
43	104	0.728	5.586
43	105	1.523	5.230
43	106	2.236	4.455
43	107	2.202	3.142
43	108	1.527	1.810
43	109	0.680	0.735
43	110	0.181	0.187
43	111	0.045	0.045
43	112	0.004	0.004
44	99	0.	5.800
44	101	0.000	6.000
44	102	0.000	6.000
44	103	0.002	5.850
44	104	0.014	5.600
44	105	0.070	5.300
44	106	0.242	4.698
44	107	0.546	3.688
44	108	0.846	2.656
44	109	0.833	1.568
44	110	0.493	0.680
44	111	0.275	0.320
44	112	0.057	0.061
44	113	0.022	0.023
44	114	0.008	0.008
44	115	0.002	0.002
45	103	0.000	5.850
45	105	0.000	5.300
45	106	0.002	4.700
45	107	0.012	3.700
45	108	0.044	2.700
45	109	0.101	1.669
45	110	0.137	0.817
45	111	0.170	0.490
45	112	0.076	0.139
45	113	0.066	0.089
45	114	0.053	0.060
45	115	0.034	0.036
45	116	0.016	0.016
45	117	0.006	0.006
45	118	0.002	0.002
46	105	0.000	5.300
46	106	0.000	4.700
46	107	0.000	3.700
46	108	0.000	2.700
46	109	0.001	1.670
46	110	0.003	0.820
46	111	0.010	0.500
46	112	0.011	0.150
46	113	0.021	0.109
46	114	0.036	0.097
46	115	0.051	0.087
46	116	0.054	0.070
46	117	0.044	0.050
46	118	0.026	0.030
46	119	0.014	0.014
46	120	0.005	0.005
46	121	0.001	0.001
47	107	0.	3.700
47	109	0.000	1.670
47	111	0.000	0.500
47	112	0.000	0.150
47	113	0.001	0.110
47	114	0.002	0.099
47	115	0.008	0.095
47	116	0.019	0.088
47	117	0.034	0.084
47	118	0.048	0.078
47	119	0.051	0.065
47	120	0.043	0.049
47	121	0.028	0.029

See Attached
Errata Sheet

TABLE III (CONTINUED)

47122	0.014	0.014
47123	0.005	0.005
47124	0.002	0.002
48111	0.000	0.500
48112	0.000	0.150
48113	0.000	0.110
48114	0.000	0.099
48115	0.000	0.095
48116	0.001	0.089
48117	0.003	0.087
48118	0.008	0.086
48119	0.020	0.085
48120	0.037	0.086
48121	0.053	0.082
48122	0.057	0.071
48123	0.051	0.056
48124	0.036	0.037
48125	0.020	0.021
48126	0.011	0.011
48127	0.004	0.004
48128	0.001	0.001
49113	0.	0.110
49115	0.000	0.095
49117	0.000	0.087
49118	0.000	0.086
49119	0.001	0.086
49120	0.003	0.089
49121	0.010	0.092
49122	0.025	0.096
49123	0.049	0.105
49124	0.075	0.112
49125	0.097	0.118
49126	0.123	0.134
49127	0.108	0.112
49128	0.076	0.077
49129	0.040	0.041
49130	0.018	0.018
49131	0.004	0.004
~~50115~~	~~0.~~	~~0.095~~
50117	0.000	0.087
50118	0.000	0.086
50119	0.000	0.086
50120	0.000	0.089
50121	0.000	0.092
50122	0.001	0.097
50123	0.005	0.110
50124	0.016	0.129
50125	0.047	0.165
50126	0.132	0.266
50127	0.255	0.367
50128	0.404	0.481
50129	0.497	0.537
50130	0.533	0.552
50131	0.316	0.320
50132	0.128	0.128
50133	0.035	0.035
50134	0.006	0.006
51121	0.000	0.092
51123	0.000	0.110
51125	0.002	0.167
51126	0.014	0.280
51127	0.062	0.429
51128	0.218	0.699
51129	0.592	1.129
51130	1.409	1.961
51131	1.883	2.203
51132	1.763	1.892
51133	1.164	1.199
51134	0.517	0.523
51135	0.159	0.160
51136	0.022	0.022
51137	0.002	0.002
52125	0.000	0.167
52126	0.000	0.280
52127	0.001	0.430
52128	0.011	0.710
52129	0.070	1.199
52130	0.380	2.341
52131	1.133	3.335

52132	2.344	4.236
52133	3.437	4.636
52134	3.457	3.980
52135	2.474	2.634
52136	1.034	1.057
52137	0.266	0.267
52138	0.038	0.038
52139	0.003	0.003
53127	0.000	0.430
53129	0.001	1.200
~~53130~~	~~0.009~~	~~2.350~~
53131	0.064	3.400
53132	0.311	4.547
53133	1.036	5.672
53134	2.321	6.301
53135	3.664	6.298
53136	4.140	5.197
53137	2.975	3.243
53138	1.252	1.291
53139	0.327	0.331
53140	0.059	0.059
53141	0.007	0.007
54129	0.000	1.200
~~54130~~	~~0.000~~	~~2.350~~
54131	0.000	3.400
54132	0.003	4.550
54133	0.028	5.700
54134	0.148	6.449
54135	0.545	6.843
54136	1.690	6.887
54137	3.253	6.496
54138	3.677	4.968
54139	2.656	2.987
54140	1.384	1.443
54141	0.503	0.510
54142	0.110	0.111
54143	0.013	0.013
55133	0.000	5.700
55135	0.007	6.850
55137	0.351	6.847
55138	1.103	6.071
55139	2.145	5.132
55140	2.988	4.431
55141	2.970	3.481
55142	1.856	1.967
55143	0.671	0.685
55144	0.148	0.149
55145	0.019	0.019
55146	0.001	0.001
56135	0.000	6.850
56137	0.003	6.850
56138	0.029	6.100
56139	0.167	5.299
56140	0.656	5.088
56141	1.770	5.250
56142	2.954	4.920
56143	2.894	3.578
56144	1.795	1.944
56145	0.678	0.697
56146	0.158	0.160
56147	0.023	0.023
56148	0.002	0.002
57139	0.001	5.300
57140	0.012	5.100
57141	0.099	5.350
57142	0.473	5.394
57143	1.270	4.849
57144	2.108	4.052
57145	2.142	2.839
57146	1.386	1.546
57147	0.574	0.596
57148	0.150	0.152
57149	0.026	0.026
57150	0.003	0.003
58140	0.000	5.100
58141	0.000	5.350
58142	0.006	5.400
58143	0.051	4.900

58144	0.246	4.298
58145	0.691	3.530
58146	1.202	2.748
58147	1.332	1.928
58148	0.952	1.103
58149	0.466	0.492
58150	0.145	0.147
58151	0.027	0.027
58152	0.003	0.003
59141	0.000	5.350
59143	0.000	4.900
59144	0.002	4.300
59145	0.020	3.550
59146	0.101	2.849
59147	0.315	2.244
59148	0.609	1.713
59149	0.798	1.290
59150	0.672	0.819
59151	0.356	0.383
59152	0.124	0.127
59153	0.024	0.024
59154	0.003	0.003
60143	0.	4.900
60144	0.000	4.300
60145	0.000	3.550
60146	0.001	2.850
60147	0.006	2.250
60148	0.037	1.750
60149	0.138	1.428
60150	0.317	1.136
60151	0.449	0.833
60152	0.422	0.549
60153	0.226	0.250
60154	0.086	0.089
60155	0.020	0.020
60156	0.003	0.003
61147	0.000	2.250
61149	0.002	1.430
~~61150~~	~~0.014~~	~~1.150~~
61151	0.057	0.889
61152	0.146	0.695
61153	0.211	0.461
61154	0.215	0.304
61155	0.138	0.159
61156	0.056	0.058
61157	0.014	0.014
61158	0.002	0.002
62147	0.	2.250
62149	0.000	1.430
~~62150~~	~~0.000~~	1.150
62151	0.001	0.890
62152	0.005	0.700
62153	0.019	0.480
62154	0.055	0.359
62155	0.095	0.254
62156	0.102	0.161
62157	0.069	0.083
62158	0.028	0.030
62159	0.007	0.008
62160	0.001	0.001
63151	0.000	0.890
63153	0.000	0.480
63155	0.006	0.260
63156	0.019	0.180
63157	0.035	0.118
63158	0.037	0.067
63159	0.027	0.035
63160	0.012	0.013
63161	0.003	0.003
64155	0.000	0.260
64156	0.000	0.180
64157	0.002	0.120
64158	0.005	0.072
64159	0.010	0.045
64160	0.012	0.025
64161	0.008	0.012
65159	0.000	0.045
65161	0.002	0.014
66161	0.000	0.014

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APPENDIX

IBM-7094 PROGRAM FOR ESTIMATION OF FISSION PRODUCT YIELDS (FORTRAN II LANGUAGE)

Note: In addition to the information shown in Table III of this report, the computer provides:

1. Printout of selected isomer yields that are of importance for fission product heating calculations.
2. Punched card output of nuclide and isomer yields.
3. Printout of mass chain yield, most probable Z, and first stable Z versus A.
4. Printout of fissionable nuclide, fission energy (E) and Gaussian distribution characteristic (σ) used in the calculations.

Necessary inputs are:

1. Mass chain yields.
2. Identification of fissionable nucleus (23 ≡ U-233, 25 ≡ U-235, 28 ≡ U-238, and 49 ≡ Pu-239).
3. σ
4. E

```
      COMMONYC.YI

      COMMONYC.YI
      OIMENSIONZP(170).YC(75.170).YI(75.170).F(170).A(170)
     1.Z(75).ZMAX(170)
      OIMENSIONAM(18).AG(18).ZM(18).YIM(18).YIG(18).YCM(18).
     1YCG(18).AA(15).AB(15).YIA(15).YIB(15).YCA(15).YCB(15)
    1 FORMAT(12F6.3)
   89 FORMAT(I2.8X.2I5.10X.2E10.3)
   90 FORMAT(I2.7X.2F6.1.9X.2E10.3)
  100 FORMAT(24H0                   PERCENT YIELO)
  101 FORMAT(30H0 Z  A  INOEPENDENT CUMULATIVE)
  102 FORMAT(2I3.F9.3.F11.3)
  103 FORMAT(4F9.3)
  104 FORMAT(34H0       A        F       ZP       ZMAX)
  105 FORMAT(18F4.0)
  106 FORMAT(I4.2F4.2.4I15)
  107 FORMAT(35H FISSION OF Z        A     ENERGY SIGMA)
  108 FORMAT(3X.F12.0.F7.0.F6.1.F8.2)
  110 FORMAT(7X.2F6.1.2F10.3)
  111 FORMAT(39H0ISOMERS Z    A  INOEPENDENT CUMULATIVE)
C--------------------
C      ZF=ATOMIC NUMBER    AF=MASS NUMBER+1
C      F(IA)=MASS CHAIN YIELO OF WEAVER ET AL
C      YC=CUMULATIVE YIELD OF NUCLIDE Z.A
C      YI=INOEPENOENT YIELD OF NUCLIOE.Z.A
C      E=MEDIAN ENERGY OF NEUTRON CAUSING FISSION. MEV
C      SIG=CHARACTERISTIC OF GAUSSIAN DISTRIBUTION
C      ZMAX=FIRST STABLE NUCLIOE
C--------------------
      READINPUTTAPE10.106.IOPT.SIG.E.SPARE1.SPARE2.
     1SPARE3.SPARE4
   13 READINPUTTAPE10.1.(F(IA).IA=76.161)
      IF(IOPT-23)42.41.42
   41 ZF=92.0
      AF=234.0
      C1=0.115
      GNUT=2.50
   42 CONTINUE
      IF(IOPT-25)44.43.44
   43 ZF=92.0
      AF=236.0
      CI=0.135
      GNUT=2.43
   44 CONTINUE
      IF(IOPT-28)46.45,46
   45 ZF=92.0
      AF=239.0
      C1=0.138
      GNUT=2.41
   46 CONTINUE
      IF(IOPT-49)13.47.13
   47 ZF=94.0
      AF=240.0
      CI=0.111
      GNUT=2.87
      UELZ=0.5*(ZF-92.0)-0.21*(AF-236.0)+0.19*(GNUT+CI*E-2.43)
      DO2IA=76,161
    2 A(IA)=FLOATF(IA)
      DO3IA=76.100
    3 ZP(IA)=0.4237*A(IA)-2.19+UELZ
      DO4IA=101.134
    4 ZP(IA)=0.3494*A(IA)+5.24+DELZ
      DO5IA=135.161
    5 ZP(IA)=0.4331*A(IA)-6.06+DELZ
      DO11IZ=30,70
      DO11IA=76.161
      Z(IZ)=FLOATF(IZ)
      IF(Z(IZ)-ZP(IA)+0.5)10.6.6
   10 YC(IZ.IA)=F(IA)*(0.5-0.5*ERRI69((ZP(IA)-Z(IZ)-0.5)
     1/(1.414*SIG)))
      GOTO11
    6 YC(IZ.IA)=F(IA)*(0.5+0.5*ERRI69((Z(IZ)-ZP(IA)+0.5)
     1/(1.414*SIG)))
   11 CONTINUE
      DO7IZ=30.70
      YC(IZ.75)=0.0
      DO7IA=76.161
      YC(29.IA)=0.0
    7 YI(IZ.IA)=YC(IZ.IA)-YC(IZ-1.IA)
      READINPUTTAPE9.105.(ZMAX(IA).IA=76.161)
      DO40IA=76.161
      IZM=ZMAX(IA)
      IZM1=IZM+1
      DO40IZ=IZM1.70
   40 YC(IZ.IA)=0.0
      AFI=AF-1.0
      WRITEOUTPUTTAPE9.107
      WRITEOUTPUTTAPE9.108.ZF.AFI.E.SIG
      WRITEOUTPUTTAPE9.104
      WRITEOUTPUTTAPE9.103.(A(IA).F(IA).ZP(IA).Z MAX(IA).IA=76,161)
      WRITEOUTPUTTAPE9.100
      WRITEOUTPUTTAPE9.101
      DO12IZ=30.70
      DO12IA=76.161
      IF(YC(IZ.IA)-0.001)12.8.8
    8 WRITEOUTPUTTAPE9.102.IZ.IA.YI(IZ,IA).YC(IZ.IA)
      WRITEOUTPUTTAPE11.89.IOPT.IZ.IA.YI(IZ.IA).YC(IZ.IA)
   12 CONTINUE
      DO56K=1.18
      YIM(K)=0.0
      YCM(K)=0.0
      AG(K)=0.0
      ZM(K)=0.0
      YIG(K)=0.0
      YCG(K)=0.0
   56 AM(K)=0.0
      DO57K=1.15
      AA(K)=0.0
      AB(K)=0.0
      YIA(K)=0.0
      YIB(K)=0.0
      YCA(K)=0.0
   57 YCB(K)=0.0
      ZM(1)=34.0
      ZM(2)=36.0
      ZM(3)=36.0
      ZM(4)=39.0
      ZM(5)=41.0
      ZM(6)=41.0
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      ZM(7)=43.0
      ZM)8)=43.0
      ZM(9)=45.0
      ZM)10)=45.0
      ZM)11)=52.0
      ZM)12)=52.0
      ZM(13)=52.0
      ZM)14)=52.0
      ZM)15)=53.0
      ZM)16)=54.0
      ZM(17)=54.0
      ZM(18)=56.0
      AM(1)=83.0
      AM(2)=83.0
      AM)3)=85.0
      AM)4)=91.0
      AM)5)=95.0
      AM)6)=97.0
      AM(7)=99.0
      AM)8)=102.0
      AM(9)=103.0
      AM(10)=105.0
      AM)11)=127.0
      AM)12)=129.0
      AM)13)=131.0
      AM)14)=133.0
      AM(15)=131.0
      AM)16)=133.1
      AM)17)=135.0
      AM(18)=137.0
      DO51K=1.18
   51 AG(K)=AM(K)+0.1
      DO52K=11.15
      AA(K)=AM)K)+0.1
   52 AB(K)=AM)K)+0.2
      YIM)1)=0.5*YI(34,83)
      Y(M(2)=0.5*YI)36.83)
      YIM(3)=0.5*YI)36.85)
      YIM(4)=0.5*YI(39.91)
      YIM|5)=0.5*YI(41.95)
      YIM(6)=0.5*Y((41.97)
      YIM(7)=0.5*YI(43.99)
      YIM(8)=0.5*YI)43.102)
      YIM)9)=0.5*YI(45.103)
      YIM(10)=0.5*YI(45.105)
      YIM)11)=0.5*YI(52.127)
      YIM(12)=0.5*YI(52.129)
      YIM(13)=0.5*YI(52.131)
      YIM(14)=0.5*YI(52.133)
      YIM(16)=0.5*YI(54.133)
      YIM(17)=0.5*YI(54.135)
      YIM(18)=0.5*YI(56.137)
      DO53K=1.18
   53 YIG(K)=YIM)K)
      DO54K=11.15
      YIA(K)=YIM(K)
   54 YIB(K)=0.0
      YCM(1)=0.56*)YC(34.83)-YI|34.83))+YIM)1)
      YCG(1)=0.44*(YC(34.83)-YI(34.83))+YIM)1)
      YCM(2)=YC(36.83)-YIM)2)
      YCG(2)=YC(36.83)
      YCM(3)=YC)36.85)-YIM)3/
      YCG)3)=0.19*YCM)3)+YIM(3)
      YCM(4)=0.6*)YC)39.91)-YI(39.91))+YIM(4)
      YCG)4)=YC)39.91)
      YCM)5)*0.03*)YC(41.95)-YI(41.95))+YIM(5)
      YCG)5)=YC(41.95)
      YCM(6)=0.98*)YC)41.97)-YI)41.97))+YIM(6)
      YCG)6)=YC)41.97)
      YCM(7)=0.76*)YC(43.99)-YI(43.99))+YIM(7)
      YCG(7)=YC(43.99)
      YCM(8)=0.5*YC(43.102)
      YCG(8)=YCM)8)
      YCM(9)=YC(45.103)-YIM(9)
      YCG(9)*YC)45.103)
      YCM(10)=YC(45.105)-YIM)10)
      YCG(10)=YC)45.105)
      YCM(11)=0.22*)YC)52.127)-YI(52.127))+YIM)11)
      YCA(11)=0.78*)YC(52.127)-YI(52.127))+YIM)11)
      YCB(11)=0.98*YCM(11)
      YCM)12)=0.36*)YC(52.129)-YI(52.129))+YIM(12)
      YCA)12)=0.64*(YC(52.129)-YI(52.129))+YIM(12)
      YCB(12)=YCM)12)
      YCM(13)=0.15*)YC(52.131)-YI(52.131))+YIM)13)
      YCA)13)=0.85*)YC(52.131)-YI(52.131))+YIM)13)
      YCB(13)=0.2*YCM)13)
      YCM(14)=0.72*)YC(52.133)-YI(52.133))+YIM(14)
      YCA(14)=0.28*(YC)52.133)-YI(52.133))+YIM(14)
      YCH(14)=0.13*YCM(14)
      YCA(15)=YCA)13)+YCB(13)
      YCB(15)=0.8*YCM(13)
      YCM(16)=0.024*)YC)54.133)-YI)54.133))+YIM(16)
      YCG(16)=YC(54.133)
      YCM)17)=0.3*)YC)54.135)-YI(54.135))+YIM(17)
      YCG(17)=YC(54.135)
      YCM(18)=0.92*(YC(56.137)-YI(56.137))+YIM)18)
      YCG)18)=YC(56.137)
      WR(TEOUTPUTTAPE9.111
      DO62K=1.18
      IF)YCM)K)-0.001)60.61.61
   61 WRITEOUTPUTTAPE9.110.)ZM(K),AM)K).YIM(K).YCM)K))
      WR(TEOUTPUTTAPE11.90.(IOPT.ZM)K).AM)K).YIM)K).YCM(K))
   60 CONTINUE
      IF(YCG)K)-0.001)62.63.63
   63 WRITEOUTPUTTAPE9.110.(ZM(K).AG)K).YIG(K).YCG)K))
      WRITEOUTPUTTAPE11.90.(IOPT.ZM(K).AG(K),YIG(K).YCG(K))
   62 CONTINUF
      DO66K=1.15
      IF)YCA)K)-0.001)64.65.65
   65 WRITEOUTPUTTAPE9.110.(ZM(K).AA(K).YIA(K).YCA)K))
      WR(TEOUTPUTTAPE11.90.)IOPT.ZM)K).AA(K).YIA(K).YCA(K))
   64 CONTINUF
      IF(YCB)K)-0.001)66.67.67
   67 WRITEOUTPUTTAPE9.110.)ZM|K).AB(K).YIB(K).YCB)K))
      WRITEOUTPUTTAPE11.90.)IOPT.ZM)K).AB)K),YIB(K).YCB(K))
   66 CONTINUE
      GO1013
      END)1.0.0.0.0.0.0.0.0.1.0.0.0.0.0)
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