ORNL/TM-6245
ENDF-262

Review and Combination of Experimental Results for Neutron Emission per Fission of ^{232}Th

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Printed in the United States of America. Available from
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Price: Printed Copy $4.00; Microfiche $3.00

ORNL/TM-6245
ENDF-262
Dist. Category UC-79d

Contract No. W-7405-eng-26

Neutron Physics Division

REVIEW AND COMBINATION OF EXPERIMENTAL RESULTS FOR NEUTRON EMISSION PER FISSION OF ^{232}Th

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Date Published - May, 1978

Prepared by the
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operated by
UNION CARBIDE CORPORATION
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DEPARTMENT OF ENERGY

ABSTRACT

An analysis has been made of the existing experimental data for $\bar{\nu}(E)$ of ^{232}Th, the average number of neutrons emitted per fission of ^{232}Th. This analysis suggests that a single linear function of the neutron energy describes the data within their uncertainties. The parameters of the linear function and their uncertainties are given.

An evaluation has been made of the existing experimental data on $\bar{\nu}_t(E)$ of ^{232}Th, where $\bar{\nu}_t(E)$, the average total number of neutrons emitted per fission, is the sum of $\bar{\nu}_p(E)$ and $\bar{\nu}_d(E)$, the average numbers of prompt and delayed neutrons emitted per fission. This evaluation was made for possible inclusion in Version V of the Evaluated Nuclear Data File. The values of $\bar{\nu}_t(E)$ of ^{232}Th included in ENDF/B-IV were compiled in November 1966 and modified in May 1969,[1] with a further modification of the delayed-neutron yield made in 1974 on the basis of an evaluation by Cox.[2]

A detailed evaluation of the neutron energy dependence of $\bar{\nu}(E)$ of ^{232}Th was performed in 1972 by Manero and Konshin,[3] who assumed a polynomial to describe the data and established the degree of the polynomial in the fitting procedure. They noted that only one experimental point existed between 4 and 14 MeV and that the precision of the measurements in the energy region above 14 MeV was poor. They also noted that the reporting of the experimental uncertainties was not consistent from one data set to the next.

Manero and Konshin described the neutron energy dependence of $\bar{\nu}_p(E)$ for ^{232}Th by two polynomials, the first being of second degree and applying to the energy range from the fission threshold energy to 1.6 MeV and the second polynomial containing only the first power of the neutron energy and covering the neutron energy range 1.6 to 16 MeV. They stated that the second degree polynomial was not justified statistically but that four different experiments obtained values of $\bar{\nu}_p(E)$ below 1.6 MeV which suggests a nonlinear behavior of $\bar{\nu}_p(E)$ in that energy region. In an earlier evaluation, Davey[4] had used two linear relations for $\bar{\nu}_p(E)$ that intersect at 1.57 MeV.

Figure 1 shows a plot of $R_p(E)$, the existing data for the ratio of $\bar{\nu}_p(E)$ for ^{232}Th to $\bar{\nu}_p$ (spontaneous fission, $\bar{\nu}_p = 3.756$) for ^{252}Cf. The comments of Manero and Konshin[3] concerning the quality of the data near 14 MeV, the paucity of data between 4 and 14 MeV, and the suggested nonlinear dependence of $\bar{\nu}_p(E)$ on E can be appreciated by examining Fig. 1. Only the data of ref. 16 have become available since ref. 3. Most experimental measurements of $\bar{\nu}(E)$ for ^{232}Th recorded $\bar{\nu}_p(E)$ relative to $\bar{\nu}_p$ for ^{252}Cf or to $\bar{\nu}_p(E)$ for some other isotope that could in turn be related to $\bar{\nu}_p$ for ^{252}Cf as described in ref. 3. The data of ref. 16 were normalized using $\bar{\nu}_p$ for ^{252}Cf. The solid line in Fig. 1 represents the values $R_p(E)$ for ^{232}Th recommended in the present paper. Since $\bar{\nu}_p$ for ^{252}Cf is also subject to evaluation, for the remainder of this discussion the magnitude of $\bar{\nu}(E)$ will be considered relative to $\bar{\nu}_p$ for ^{252}Cf.

Howerton[5] suggests that the onset of reactions such as second chance fission $\sigma(n,n',f)$ makes it unlikely that a strictly linear dependence of $R_p(E)$ on E would be expected above $\sim$ 5 MeV. An examination of Fig. 1 shows that the slope of a linear relation of $R_p(E)$ vs E depends upon the energy range chosen for determining the parameters of a linear relation. Table I lists the experimental values[6-16] of $R_p(E)$ shown in Fig. 1, along with the associated uncertainties, and the values recommended in this work. Linear least-squares analyses of the various experimental data sets (refs. 12, 13, or 14) yield values of the slope which differ by more than 50%. As an example, for the energy range 1.3 to 4.1 MeV, slopes derived from the data sets of refs. 10 and 11 differ by a factor of two when analyzed using a weighted least squares method. Manero and

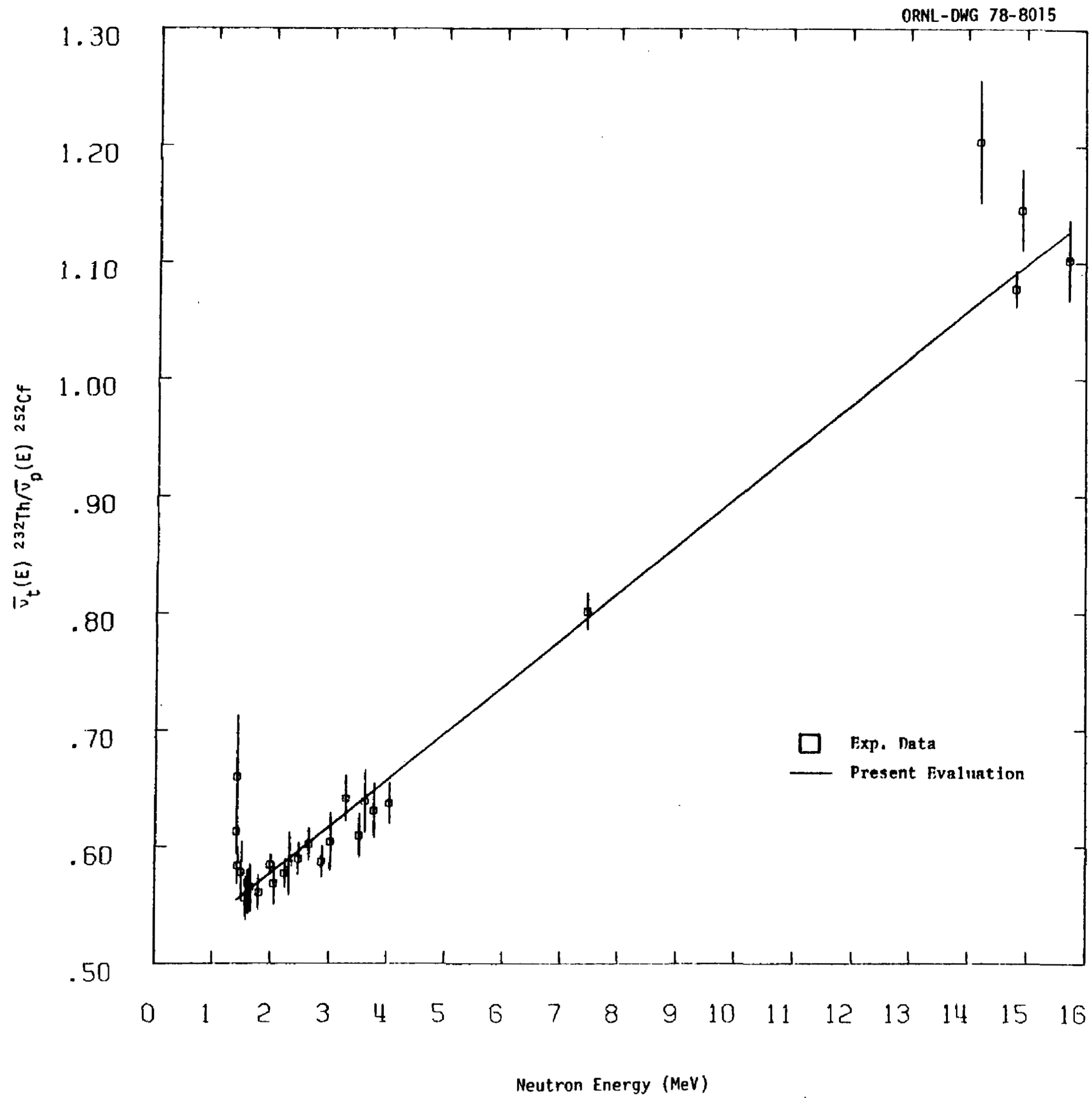

Fig. 1. Ratio of $\overline{\nu}_t(E)$ for ^{232}Th to $\overline{\nu}_p$ for ^{252}Cf as a function of neutron energy 1.4 to 16 MeV. (Experimental data from refs. 6-16.)

TABLE I. Ratios $R_p(E)$ of $\overline{\nu}_p(E)$ for ^{232}Th to $\overline{\nu}_p$ for ^{252}Cf

	Exp. Values			Present Evaluation
E(MeV)	$R_p(E)^a$	$\Delta R_p(E)^b$	Ref. No.	$R_p(E)^c$
3.5000	0.6097	0.0190	4	0.6387
1.4000	0.6603	0.0530	5	0.5583
2.3000	0.5857	0.0270	6	0.5928
3.7500	0.6310	0.0240	6	0.6482
15.7000	1.1022	0.0350	6	1.1054
14.2000	1.2034	0.0530	7	1.0481
1.6000	0.5695	0.0110	8	0.5660
1.4200	0.5841	0.0160	9	0.5591
1.6100	0.5522	0.0100	10	0.5664
1.8000	0.5612	0.0150	10	0.5736
2.2300	0.5775	0.0130	10	0.5901
2.6400	0.6022	0.0140	10	0.6058
3.6000	0.6390	0.0270	10	0.6425
7.4500	0.8022	0.0160	10	0.7898
14.8000	1.0769	0.0160	10	1.0710
14.9000	1.1448	0.0350	10	1.0748
1.3900	0.6132	0.0200	11	0.5579
1.9800	0.5847	0.0090	11	0.5805
3.0000	0.6044	0.0250	11	0.6195
4.0200	0.6374	0.0180	11	0.6586
1.4800	0.5785	0.0260	12	0.5614
1.5600	0.5564	0.0190	12	0.5645
1.6400	0.5660	0.0190	12	0.5675
2.0500	0.5687	0.0180	12	0.5832
2.4600	0.5895	0.0140	12	0.5989
2.8600	0.5873	0.0140	12	0.6142
3.2700	0.6414	0.0200	12	0.6299
1.6500	0.5639	0.0200	13	0.5679
1.3500	0.5677	0.0155	14	0.5564
1.5000	0.5717	0.0083	14	0.5622

TABLE I. -continued-

1.6250	0.5805	0.0069	14	0.5669
1.7000	0.5650	0.0069	14	0.5698
1.8000	0.5642	0.0072	14	0.5736
1.9130	0.5797	0.0080	14	0.5780
2.1000	0.5896	0.0091	14	0.5851
16.0000	1.0801	0.0206	14	1.1169

[a] $R_p(E) = \overline{\nu}_p(E)/\overline{\nu}_p(^{252}Cf) = \overline{\nu}_p(E)/3.756$

[b] Uncertainties, quoted by author, for least square fitting the weights used were $[\Delta R]^{-2}$

[c] Values are from the relation: $R_p(E) = 0.5047 + 0.0383 \times E$.

Konshin made a single linear fit to the data shown in Table I which differs from their recommended values (from the two-segment fit) above 1.6 MeV by about 0.8%. Although the observed values of $R_p(E)$ for ^{232}Th may depart from a linear dependence on E near the fission threshold energy, the quantity and quality of the data do not seem to justify more than a single linear function of E to describe the data.

Table II, which was taken from ref. 3, lists the experimental data[17-22] on $\bar{\nu}_d(E)$, the average number of delayed neutrons emitted per fission. There is no differential experimental data on $\bar{\nu}_d(E)$ between 3.5 and 14 MeV. It was assumed that a linear function of the neutron energy described the experimental data shown in Table II adequately, and the $\bar{\nu}_d(E)$ values calculated from the relation are shown in Table II. A value of 0.054 ± 0.002 was derived for the intercept $\bar{\nu}_d(o)$ for ^{232}Th which is in accord with the value of 0.055 ± 0.001 given in the evaluation of Tuttle.[23] Interpolated values of $\bar{\nu}_d(E)$ were divided by $\bar{\nu}_p$ for ^{252}Cf (3.756) and added to the experimental values for $R_p(E)$ to yield $R_t(E)$. These values of $R_t(E)$ were fit to a linear function of neutron energy to derive the recommended results for ^{232}Th. Table III gives the linear relations found for $R_p(E)$, $\bar{\nu}_d(E)$, and $R_t(E)$ along with the parameters and the elements of the parameter covariance matrix, and the linear relation given in ENDF/B-IV. For comparison Table IV gives the derived experimental values for $R_t(E)$ along with the recommended values and the difference between the experimental and recommended values divided by the experimental error. For convenience Table V gives the relative covariance matrix calculated using the parameters for $R_t(E)$ given in Table III.

TABLE II. Delayed Neutrons from ^{232}Th Fission[a]

E(MeV)	Exp. Values $\bar{\nu}_d$(E)	Exp. Values $\Delta\bar{\nu}_d$	Ref. No.	Present Evaluation $\bar{\nu}_d$(E)[b]
2.4000	0.0537	0.0044	15	0.0500
3.3000	0.0502	0.0041	15	0.0484
15.0000	0.081[c]	0.006	15	0.028
14.5000	0.075[c]	0.006	16	0.028
14.0000	0.0140	0.0050	17	0.0294
3.1000	0.0570	0.0050	18	0.0487
14.9000	0.0300	0.0030	18	0.0278
14.9000	0.0300	0.0030	19	0.0278
1.3000	0.0465	0.0030	20	0.0519
1.3500	0.0490	0.0025	20	0.0518
1.4000	0.0540	0.0020	20	0.0518
1.5000	0.0505	0.0020	20	0.0516
1.6000	0.0530	0.0025	20	0.0514

[a]From ref. 3.

[b]Calculated using the relation: $\bar{\nu}_d(E) = 0.0543 - 0.00178 \times E$.

[c]These values not included in analysis.

TABLE III. Evaluated Output Linear Relations for $\overline{\nu}$ Data and Variance Coefficients for ^{232}Th

$$X = A + \delta a + (B + \delta b) \times E(\text{MeV})$$

	Data	A	δA	B	δb	C11[a]	C12[a]	C22[a]	χ^2/DF[b]
Present	$R_p(E)$	0.505	0.004	0.038	0.001	9.00×10^{-6}	-1.65×10^{-6}	0.644×10^{-6}	1.6
Present	$\overline{\nu}_d(E)$	0.054	0.002	-0.0018	0.0002	1.21×10^{-6}	-0.11×10^{-6}	0.022×10^{-6}	2.3
Present	$R_t(E)$	0.519	0.0038	0.0378	0.0010	9.00×10^{-6}	-1.65×10^{-6}	0.644×10^{-6}	1.6
ENDF/B-IV[c]	$R_t(E)$	0.495		0.042					

[a]Elements of parameter (output) covariance matrix: $\delta A = (\chi^2/DF)^{1/2} \times C11^{1/2}$

[b]Chi square divided by degrees of freedom

[c]Based on $\overline{\nu}_p$ for ^{252}Cf = 3.748

TABLE IV. Average Number of Neutrons Emitted per Fission of ^{232}Th Relative to $\overline{\nu}_p$ for ^{252}Cf, Experimental and Evaluated

E(MeV)	Derived Exp. Values $R_t(E)$	Derived Exp. Values $\delta R_t(E)$	Evaluated $R_t(E)^a$	$\Delta/\delta R_t(E)^b$
3.5000	0.6225	0.0190	0.6514	-1.52
1.4000	0.6741	0.0530	0.5721	1.92
2.3000	0.5990	0.0270	0.6061	-0.26
3.7500	0.6436	0.0240	0.6609	-0.72
15.7000	1.1090	0.0350	1.1123	-0.09
14.2000	1.2109	0.0530	1.0556	2.93
1.6000	0.5832	0.0110	0.5797	0.32
1.4200	0.5979	0.0160	0.5729	1.57
1.6100	0.5659	0.0100	0.5800	-1.41
1.8000	0.5748	0.0150	0.5872	-0.83
2.2300	0.5909	0.0130	0.6035	-0.97
2.6400	0.6154	0.0140	0.6189	-0.25
3.6000	0.6518	0.0270	0.6552	-0.13
7.4500	0.8130	0.0160	0.8006	0.77
14.8000	1.0841	0.0160	1.0783	0.36
14.9000	1.1520	0.0350	1.0821	2.00
1.3900	0.6270	0.0200	0.5717	2.76
1.9800	0.5982	0.0090	0.5940	0.47
3.0000	0.6174	0.0250	0.6325	-0.61
4.0200	0.6499	0.0180	0.6711	-1.18
1.4800	0.5922	0.0260	0.5751	0.66
1.5600	0.5701	0.0190	0.5781	-0.42
1.6400	0.5797	0.0190	0.5812	-0.08
2.0500	0.5822	0.0180	0.5967	-0.80
2.4600	0.6028	0.0140	0.6121	-0.67
2.8600	0.6004	0.0140	0.6273	-1.92
3.2700	0.6543	0.0200	0.6427	0.58
1.6500	0.5776	0.0200	0.5815	-0.20

TABLE IV. -continued-

1.3500	0.5815	0.0155	0.5702	0.73
1.5000	0.5854	0.0083	0.5759	1.15
1.6250	0.5942	0.0069	0.5806	1.97
1.7000	0.5786	0.0069	0.5834	-0.70
1.8000	0.5778	0.0072	0.5872	-1.31
1.9130	0.5932	0.0082	0.5915	0.21
2.1000	0.6030	0.0091	0.5985	0.49
16.0000	1.0870	0.0206	1.1236	-1.78

[a]Calculated from the relation: $R_t(E) = 0.5192 + 0.0378 \times E$

[b]Δ = Exp. value of $R_t(E)$ - evaluated value

TABLE V. Relative Covariance Matrix[a]

	E	1	2	3	4	5
1	1.40	2.690E-05				
2	2.00	2.381E-05	2.194E-05			
3	4.00	1.503E-05	1.662E-05	2.115E-05		
4	8.00	2.312E-06	8.916E-06	2.770E-05	5.491E-05	
5	16.00	-1.286E-05	-2.749E-07	3.553E-05	8.737E-05	1.492E-04

[a]Calculated from the output parameters of Table III for ^{232}Th.

REFERENCES

1. Evaluated Nuclear Data File (ENDF/B) of the National Neutron Cross Section Center, a detailed list of the evaluators for the particular isotope (defined with a MAT number, e.g., Mat 1296 for ^{232}Th, ENDF/B-IV). The ENDF/B data tape is available from the National Neutron Cross Section Center.

2. S. A. Cox, "Delayed Neutron Data: Review and Evaluation," ANL-NDM-5, April 1974.

3. F. Manero and V. H. Konshin, At. Energy Review 10, 637 (1972).

4. W. G. Davey, Nucl. Sci. Eng. 44, 345 (1971).

5. R. J. Howerton, private communication; also see R. J. Howerton, Nucl. Sci. Eng. 46, 42 (1971).

6. B. D. Kuzminov, L. S. Kutsaeva, and I. I. Bondarenko, At. Energy 4, 187 (1958); Sov. J. At. Energy 4, 187 (1958); and J. Nucl. Energy 9, 153 (1959). Normalized to thermal $\bar{\nu}_p$ for ^{235}U = 2.47, renormalized to 2.407.

7. A. B. Smith, R. G. Nobles, and S. A. Cox, Phys. Rev. 115, 1242 (1959). Normalized to $\bar{\nu}_p$ at 1.4 MeV for ^{233}U = 2.63, renormalized to 2.53.

8. A. B. Kuzminov, Rep. AEC-tr-3944 (1959); Nejtronfiz 241 (1961). Normalized to thermal $\bar{\nu}_p$ for ^{235}U = 2.47, renormalized to 2.407.

9. J. Leroy, J. Phys. Radium 21, 45 (1960); see also S. Blaise, M. Gaudin, R. Joly, J. Leroy, and G. Vendryes, J. Phys. Radium 19 (1958). Normalized to thermal $\bar{\nu}_p$ for ^{235}U = 2.47, renormalized to 2.407.

10. J. W. Meadows and J. F. Whalen, Rep. WASH-1033, 2 (1961). Normalized to thermal $\bar{\nu}_p$ for ^{235}U = 2.43, renormalized to 2.407.

11. Yu. A. Vasil'ev, Yu. S. Zamyatnin, E. I. Sirotin, P. V. Toropov, E. F. Fomushkin, and V. I. Shamarukhin, Fiz. Delen, Atom. Jader, 121 (1962).

12. H. Conde and M. Holmberg, Proc. Symp. Physics and Chemistry of Fission, Salzburg, 2, 57 (1965), IAEA, Vienna; Ark. Fys. 29, 33 (1965); E. Conde and N. Starfelt, Nucl. Sci. Eng. 11, 397 (1961). Normalized to $\bar{\nu}_p$ for ^{252}Cf = 3.775, renormalized to 3.756.

13. D. S. Mather, P. Fieldhouse, and A. Moat, Nucl. Phys. 66, 149 (1965). Normalized to $\bar{\nu}_p$ for ^{235}Cf = 3.782, renormalized to 3.756.

14. L. I. Prokhorova and G. N. Smirenkin, Jadern. Fiz. 7, 961 (1968); Sov. J. Nuc. Energy 7, 579 (1968). Normalized to thermal $\bar{\nu}_p$ for ^{235}U = 2.414, renormalized to 2.407.

15. V. G. Vorobeva, P. P. Dyachenko, N. P. Kolosov, B. D. Kuzminov, A. Sergachev, L. D. Smirenkina, and A. Lajtai, Proc. Conf. Nuclear Data for Reactors, Helsinki, 2, 177 (1970), IAEA, Vienna; At. Energy 29, 130 (1970); Sov. At. Energy 29, 835 (1970).

16. J. Caruana, J. W. Boldeman, and R. L. Walsh, "$\bar{\nu}_p$ for Neutron Fission of ^{232}Th near Threshold," Australian Atomic Energy Commission Research Establishment, to be published. Normalized to $\bar{\nu}_p$ for ^{252}Cf = 3.745, renormalized to 3.756.

17. B. P. Maksyutenko, At. Energy 7, 474 (1960); Sov. J. At. Energy 7, 943 (1960).

18. V. I. Shpakov, K. A. Petrzhak, M. A. Bak, S. S. Kovalenko, and O. I. Kostochkin, At. Energy 11, 539 (1961); Sov. J. At. Energy 11, 1190 (1962).

19. A. Notea, Rep. IA-1190, 95 (1969).

20. C. F. Masters, M. M. Thorpe, and D. B. Smith, Nucl. Sci. Eng. 36, 202 (1969).

21. Los Alamos Scientific Laboratory, Rep. LA-4227-MS 17 (1969); included in LA-4320-MS (1969).

22. S. A. Cox, Dowling Whiting E. E., Rep. ANL-7610, 45 (1970).

23. R. J. Tuttle, Nucl. Sci. Eng. 56, 37 (1975).

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