DECAY HEAT ANALYSIS USING THE SUMMATION METHOD

G. Rudstam
The Studsvik Science Research Laboratory
S-611 82 Nyköping, Sweden

Abstract

Decay heat calculations by the summation method have been performed using various data sets, in particular a library based on the JEF1 nuclear data library supplemented by new pieces of nuclidic information. The results are compared to integral measurements carried out at the Studsvik Science Research Laboratory.

1. Introduction

An extensive set of integral decay heat measurements has recently been completed at the Studsvik Science Research Laboratory 1). The results are presently being analyzed. The experiments include the beta and gamma part of the decay heat at the thermal neutron induced fission of ^{235}U and ^{239}Pu and, in addition, the gamma part of the decay heat in the fast fission of ^{238}U. The availability of these new data has incited a new analysis of the decay heat using the summation method in order to compare the integral results with a differential study using an up-to-date set of decay data of the individual fission products. A summation analysis was carried out in 1978 at this laboratory 2). New information on the decay properties of many short-lived fission products has been gathered during recent years, and a new analysis is therefore called for.

The present report deals primarily with the summation analysis. A detailed comparison between the results of the integral and the differential methods will be presented elsewhere.

The first task is to update the fission product library of 1978. This will be done in several steps so that the effect of each step can be checked. The first step is to include all decay data information contained in the library JEF1 3). The fission yields of the 1978 year version of the library were those of the compilation of Rider and Meek 4), supplemented by certain experimental determinations. The inclusion of the JEF1 decay data means the addition of a number of nuclides unknown in 1978. These require yield information, and again the Rider-Meek compilation has been used, backed-up by some values from the ENDF/B-V file 5) where values in the compilation 4) are lacking.

The updated version of the old library FPLIB78 is denoted FPLIB6A.

Next, certain decay data of JEF1 are exchanged for more recent determinations. This concerns both average beta and gamma energies but also half-life data. A set of new average beta energies are available as a byproduct of a project for the determination of the antineutrino spectrum in the vicinity of a nuclear reactor 6). Also, the average gamma energy given in JEF1 is adjusted for a number of nuclides as discussed below. Finally, new half-life data including new nuclides, until now lacking in the JEF1 library, are included. The FPLIB6A library updated in this way is denoted FPLIB6B.

Certain JEF1 average energy errors are either lacking or unrealistically small. Somewhat arbitrarily, averge beta and gamma energy errors smaller than 1 % of the value were replaced by 5 % of the energy value. This changes FPLID6B into FPLIB6C.

We shall now pay attention to the fission yields. Changing the Rider-Meek yields into ENDF/B-V yields changes the library FPLIB6C into FPLIB6D.

The final updating is to use the ENDF/B-V yields supplemented by experimental values. A new study of the yields in thermal-neutron induced fission of ^{235}U[7-9] has given new yields for nuclides, especially isomeric states, hitherto unmeasured, and the compilation[5] can be substantially improved by including these experimental yields. This final version of the 1986 fission product library is denoted FPLIB6E.

2. The fission product library

2.1. Decay data

2.1.1. Average gamma energy

The average gamma energy $\bar{E}_\gamma$ can be determined from the simple expression

$$\bar{E}_\gamma = \sum_i E_{\gamma_i} I_{\gamma_i} \qquad (1)$$

where E_{γ_i} is the energy and I_{γ_i} the intensity (number of gamma-rays per decay) of the i:th gamma-ray. The error of the average gamma-energy is obtained as

$$\Delta\bar{E}_\gamma = \sqrt{\sum_i \{ E_{\gamma_i}^2 (\Delta I_{\gamma_i})^2 + (\Delta E_{\gamma_i})^2 I_{\gamma_i}^2 \}} \qquad (2)$$

It must be pointed out that the formula (2) can only be used if the intensity errors are truly independent of each other. This is usually not the case. The experiments are most often carried out in such a way that only relative yields I_{rel} are obtained. These relative yields are then converted into absolute yields by multiplication by a normalization constant F_d, and we have

$$I_{\gamma_i} = F_d \; I_{rel_i} \qquad (3)$$

Now, Eq. (2) can no longer be used because we have introduced a systematic contribution to the error, namely the uncertainty of the normalization constant F_d. Instead, the error should be calculated from the formula (4) below:

$$\Delta\bar{E}_{\gamma} = \sqrt{F_d^{\,2} \sum_i \{ E_{\gamma_i}^{\,2} (\Delta I_{rel_i})^2 + (\Delta E_{\gamma_i})^2 I_{rel_i}^{\,2} \} + (\Delta F_d)^2 \, (\sum_i E_{\gamma_i} I_{rel_i})^2} \qquad (4)$$

Apparently, the error of the average gamma energy given in the JEF1-file is often calculated using Eq. (2) rather than Eq. (4). This may partly be due to the fact that the error of the normalization constant is not always given but only put equal to zero. The effect is that the error of the average gamma energy is severely underestimated for many nuclides. In order to determine a more realistic error a normalization factor has been calculated from the branching ratios given in Ref.7). When combined with the tables of gamma energies and intensities of JEF1 a new determination of the average gamma energy and its error (from Eq. (4)) results.

The branching ratios of Ref.7) are average values taking into account published ratios and a new and as yet unpublished set of branching ratios9) obtained at Studsvik. Thus, results are used which were not available for the JEF1-library, and this has led to adjustments of the average gamma energies. The new values are given in Table 1 where they can be compared to the present JEF1-values. For nuclides not given in Table 1 the JEF1-average energies are used.

Hardy et al.10) have discussed the effect of the omission of low-intensity gamma-rays in a spectroscopic investigation, which may happen especially for nuclides with high decay energies and complicated decay schemes. The authors give an example showing that, depending on the counting statistics, 10 - 40 % of the gamma-ray intensity may remain undetected. Every gamma-ray which does not appear in the JEF1 list of gamma-rays means loss of gamma effect and leads to a deficit in the average gamma energy.

Thus, we must face the problem that the gamma part of the decay heat as determined by the summation method may be systematically too low.

2.1.2. Average beta energy

As mentioned in the introduction the average beta energies obtained in a study of the antineutrino spectrum in the vicinity of a nuclear reactor[6)] have been used to update the JEF1-library. The new measurements were carried out with a beta spectrometer with its response function determined by a comparison with the electromagnetic spectrometer "Bill" at ILL in Grenoble[11)]. The average beta energies are given in Table 1 together with those of JEF1. For nuclides not listed in Table 1 the values from JEF1 have been used.

2.1.3. Nuclides with either the average beta energy or the average gamma energy unknown

For a number of nuclides information on either the average beta energy or the average gamma energy is lacking. For those cases an approximate value of the missing quantity may be derived in the following way.

The average antineutrino energy will be somewhat larger than the average beta energy. The calculated ratios between the average antineutrino energy and the average beta energy are shown in Fig. 1 for two cases, (Z,A) = (37,93) and (53,140), as a function of the decay energy of the beta-decaying branch. For actual cases with many beta branches an average value of the ratio can be evaluated. If nothing is known about the decay scheme a rough estimate of the average decay energy must be made. The ratio is then taken to be the one corresponding to this decay energy. There is a good chance that this procedure will give a result within 10 % of the true value taking into account that the span of values is only about 20 % in the range of decay energies from 3 to 12 MeV. It may be mentioned that

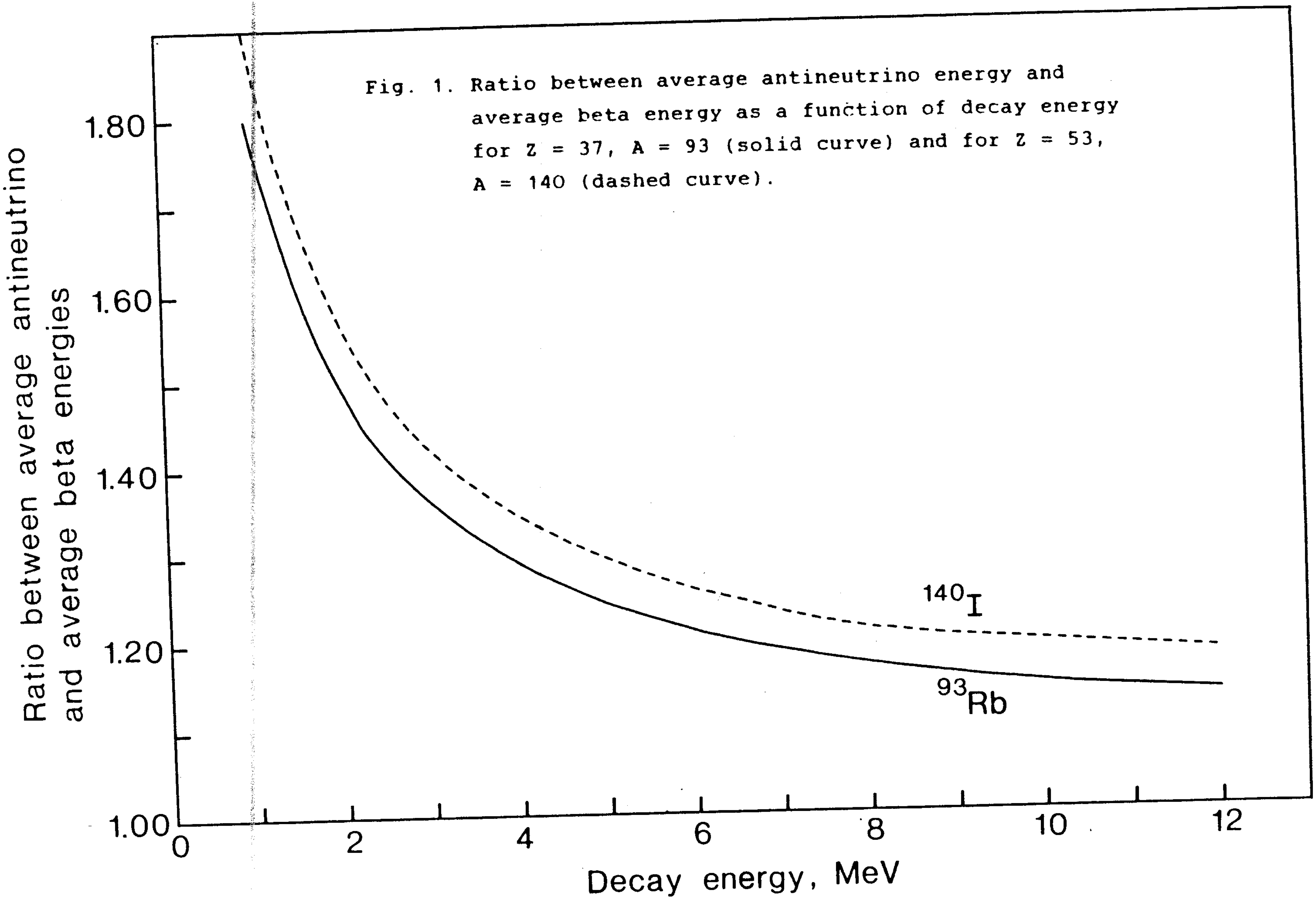

Fig. 1. Ratio between average antineutrino energy and average beta energy as a function of decay energy for Z = 37, A = 93 (solid curve) and for Z = 53, A = 140 (dashed curve).

the ratio in the antineutrino study referred to above was found to be 1.23 ± 0.05. This is an average of the ratio for 35 nuclides over a wide range of energies (average beta energy from about 1 MeV to more than 3 MeV), and the error given is the standard deviation of the population. For little known nuclides this value (R) can be used after an adjustment for the Z-value effect and an increase of the uncertainty to about 10 %. We can then estimate the average gamma energy if the average beta energy is known. The latter quantity is multiplied by 1+R and subtracted from the total decay energy. The remainder is a measure of the average gamma energy provided that the nuclide under study is not a delayed-neutron precursor. If neutrons are emitted with a branching of P_n, the average gamma energy will become low because gamma-rays from the levels depopulated by neutron emission are missing. The average energy of those gamma-rays would be the sum of the average neutron energy $\bar{E}_n$ and the neutron separation energy S_n. This is true for the case that the neutrons populate the ground state of the final nucleus, but it also holds for neutron branches leading to excited states if only the effect of the gamma emission from those states is included in $\bar{E}_\gamma$, Thus we may approximate the average gamma energy by

$$\bar{E}_\gamma \sim Q_\beta - P_n(\bar{E}_n + S_n) - (1+R)\bar{E}_\beta \qquad (5)$$

In a similar way we obtain the average beta energy for cases where only the average gamma energy is known:

$$\bar{E}_\beta \sim \frac{1}{(1+R)} \{Q_\beta - P_n(\bar{E}_n + S_n) - \bar{E}_\gamma\} \qquad (6)$$

The estimate of $\bar{E}_\beta$ in some cases for which no value is given in JEF1 are listed in Table 2.

An estimate of the errors may be obtained if the uncertainties of the quantities appearing in Eqs. (5) and (6) are known.

The nuclides ^{100}Rb and ^{102}Y are included in JEF1 and average gamma energies are also given. The delayed-neutron branching ratios of these nuclides are unknown, however. As they are expected to be large, the use of Eq. (6) would led to a large uncertainty. Until more information becomes available data for these nuclides are taken from Ref.$^{14)}$. This is also done for the nuclides ^{74}Cu, ^{75}Cu, ^{76}Cu, and ^{80}Zn which are not included in JEF1.

2.1.4. Half-life data

The half-life data used for nuclides not present in the JEF1 file and also for other nuclides where the data differ from those of the file (sometimes only the error limit of the branching ratio) are given in Table 3. Since partial half-lives are used in the calculation the table contains the branching ratios to the isomeric state of the daughter and, in case of isomers, also the isomeric transition. The remainder is then the ground state branch.

For a few nuclides there are more than one isomeric state. As the analysis only allows for the ground state and one isomeric state for each nuclide, only the most important of the isomeric states is included in the library. The fission yield of the omitted isomer is included in the yield of the isomer kept or the yield of the ground state.

The omitted isomers are:
^{116m2}In, ^{118m2}In, (4^+,5^+)-isomer of ^{122}In and ^{130}In, ^{152m2}Eu.

2.2. Fission yields

The ENDF/B-V file may be updated by introducing ^{235}U-yields which have not been measured before and therefore not taken into account when constructing the file. This is especially important for isomeric yields which have been treated in a rather superficial manner in the file (often the isotopic yield is simply split equally among the isomers). This updating changes the file FPLIB6D into

FPLIB6E. The yields changed are given in Table 4.

It may happen that the sum of yields does not add up to 200 %. A correction is then made when using the file by multiplying all the yields by the factor $200/Y_{tot}$, where Y_{tot} is the sum of yields (in per cent). The Y_{tot}-value of FPLIB6E is 202.1 % for ^{235}U, 200.3 % for ^{238}U, and 200.2 % for ^{239}Pu.

A library including the JEF1 fission yields[25,26] has not been tested in decay heat calculations. This is because the JEF1 yield table does not include isomeric yields and also because the errors of the yields seem to be unrealistically low. Therefore, only the libraries FPLIBC, FPLIB6D and FPLIB6E have been used in the calculations presented below.

3. Decay heat calculations compared to integral determinations carried out at Studsvik

3.1 Beta heat in the fission of ^{235}U and ^{239}Pu induced by thermal neutrons

The fission product libraries are introduced into the inventory program INVENT[2]. This program evaluates the decay heat values and their errors taking into account the uncertainties of all the physical quantities entering into the calculation, i.e. fission yields (both the error of the cumulative yield and that of the independent yield are used), half-lives, average beta energies, average gamma energies, delayed-neutron branching ratios, capture cross sections, and resonance integrals.

A set of calculations has been carried out with irradiation and cooling times chosen to coincide with the corresponding timing of the integral experiments of Ref.[1]. This facilitates a direct comparison between the results of the two types of treatment. Such a comparison (using FPLIB6C) is done in Fig. 2 for the beta heat developed in ^{235}U irradiated by thermal neutrons. Three series of runs

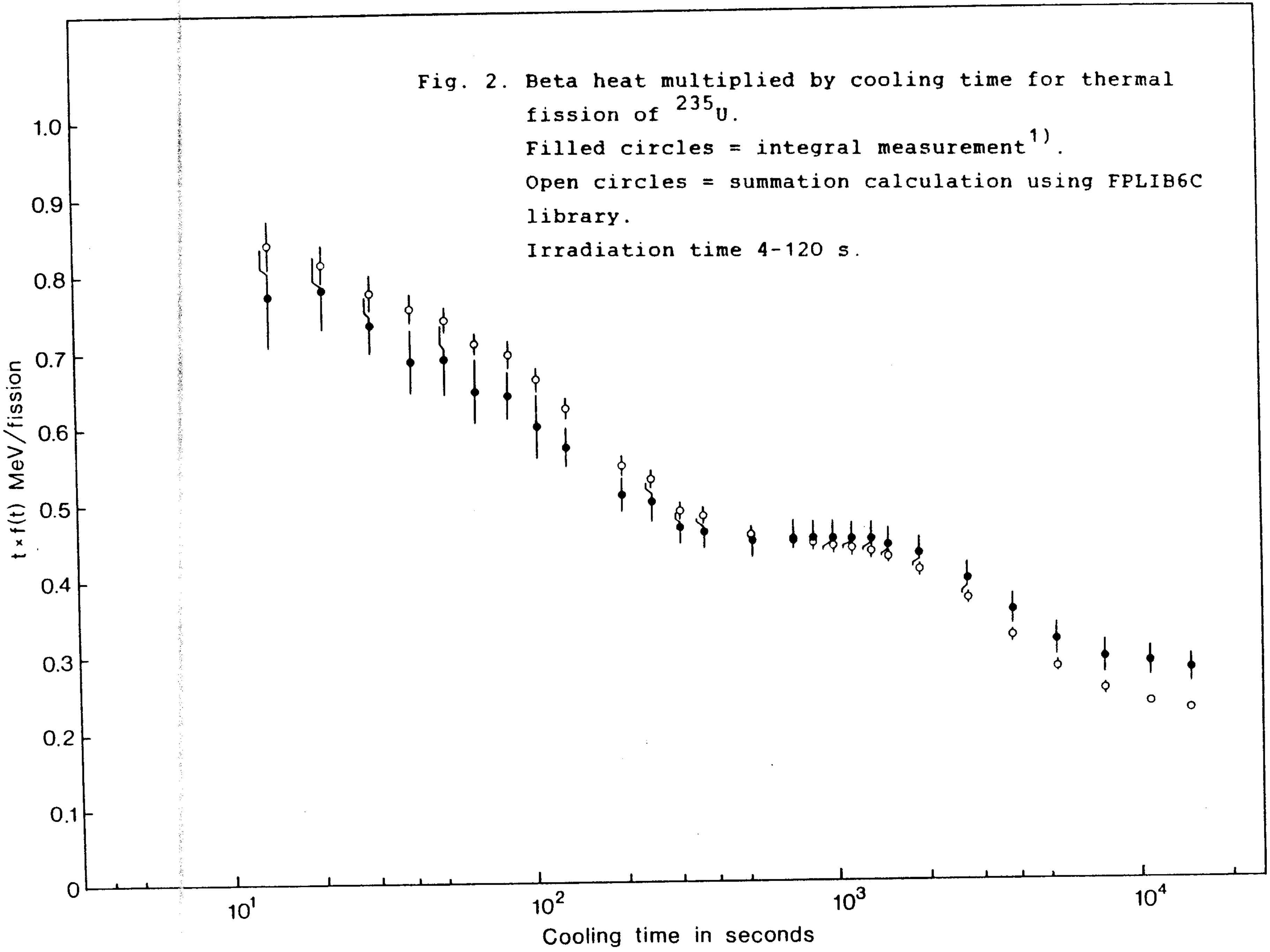

Fig. 2. Beta heat multiplied by cooling time for thermal fission of ^{235}U.
Filled circles = integral measurement$^{1)}$.
Open circles = summation calculation using FPLIB6C library.
Irradiation time 4-120 s.

are included with irradiation times 4 s, 10 s, and 120 s. The differences between the series are minute, and all the data have been plotted in the same figure. As is seen in the figure the summation calculation and the integral determination give coinciding results in the cooling time range 300 -3000 s. For shorter cooling times the summation calculation gives values somewhat above the integral experiment. The deviation is hardly larger than the combined limits of error, however, and the conclusion is that no discrepancy exists. (The reason for the systematic behaviour of the measured values is that the errors of those values are essentially systematic in nature). For long cooling times the summation calculation gives somewhat smaller values than the integral determination.

The corresponding comparison of the beta heat in the thermal neutron induced fission of ^{239}Pu is shown in Fig. 3. In this case only 120 s was used as irradiation time in the integral determination, and the summation calculation was carried out using the same irradiation and cooling times as the experiment. As seen in the figure the agreement between the integral and differential approaches of determining the decay heat is excellent over the whole cooling time range covered.

There are also other integral determinations which can be used for a comparison, notably those of Dickens et al.27) and those of Akiyama and An28). They do not differ appreciably from those of Ref.1). A more detailed comparison between different integral measurements is given in the latter reference.

3.2. Gamma heat in the fission of ^{235}U induced by thermal neutrons

An integral determination of the gamma heat in thermal fission of ^{235}U has been carried out by Johansson and Nilsson29) using the same time schedule as for the beta heat. A summation calculation with the same timing gives

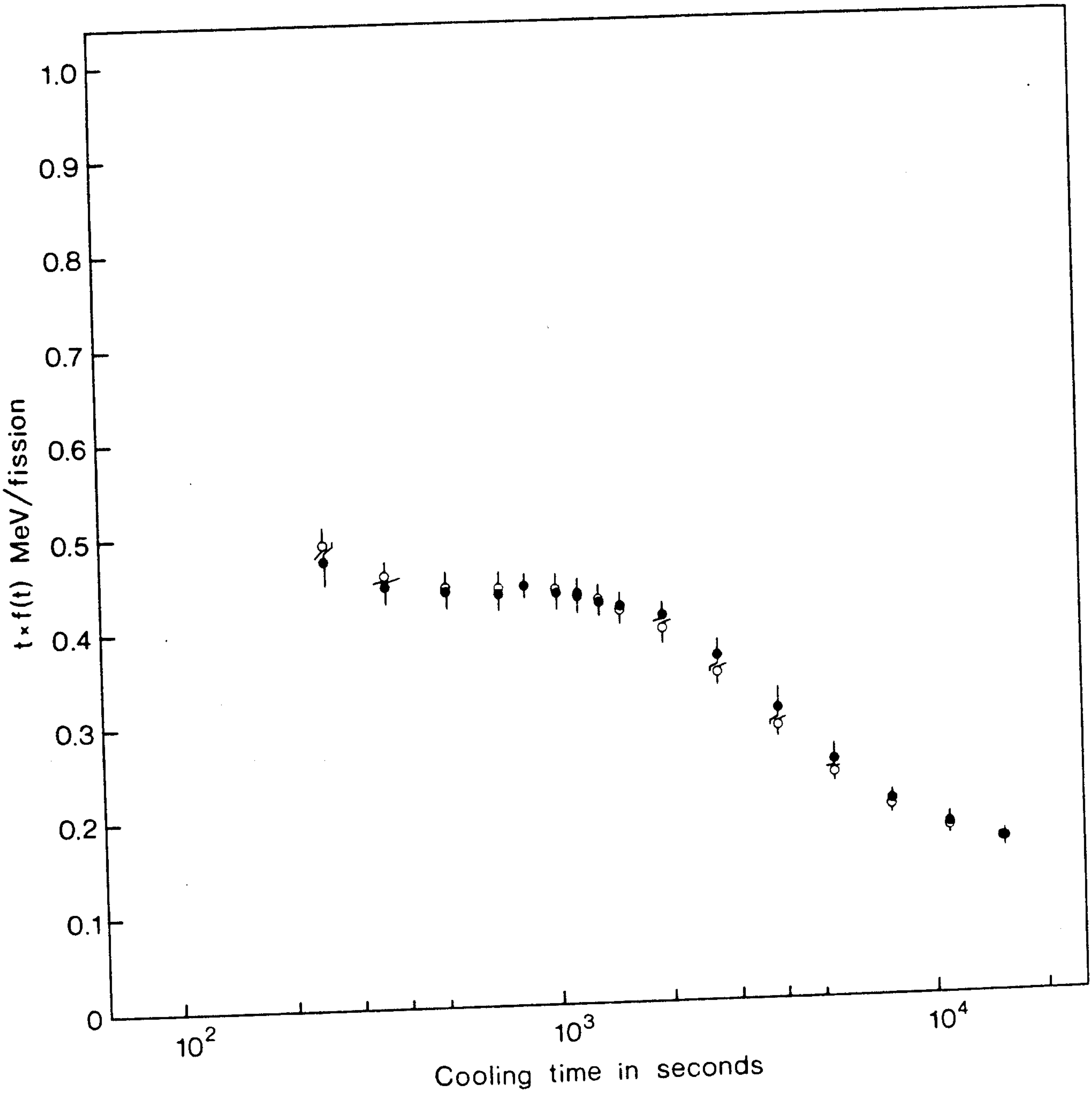

Fig. 3. Beta heat multiplied by cooling time for thermal fission of ^{239}Pu.
Filled circles = integral measurement[1)].
Open circles = summation calculation using FPLIB6C library.
Irradiation time 120 s.

results which can be compared to the integral values in Fig. 4. The agreement is acceptable for long cooling times, but in the range below about 1000 s the summation calculation gives results which are significantly lower, up to about 30 %, than the results of the integral determination. A systematic effect of this kind was discssed in Section 2.1.1. The gamma power in this interval is dominated by relatively short-lived nuclides with high Q_β-values and complicated gamma spectra. There is an obvious risk that the average gamma energy of these nuclides has been underestimated because the lists of gamma lines forming the basis for the energy evaluation may be incomplete.

The conclusion is that we have to look for other ways of determining the average gamma energies. An alternative method is to use the average beta energy as a starting point and to evaluate the average gamma energy from the Q_β value, the calculated average antineutrino energy, the delayed-neutron branching ratio, and the average energy of the delayed neutrons using Eq. (5) of Section 2.1.3. This can be done for all short-lived nuclides for which the average beta energy has been measured directly. The approach is less useful for cases where the average beta energy is merely determined from a set of beta branches obtained from a decay scheme established by gamma measurements only.

4. Comparison with other summation calculations

Summation calculations have been carried out for the cases treated in the preceding section using the libraries FPLIB6E, an irradiation time of 1 s, and cooling times from 0.5 s to 21500 s. The results are compared to summation calculations using FPLIB6C and to summation calculations carried out elsewhere in Figs. 5 - 7. The library FPLIB6D has also been used for ^{235}U, but the results agree within one per cent with those of FPLIB6E, and they are not inclu-

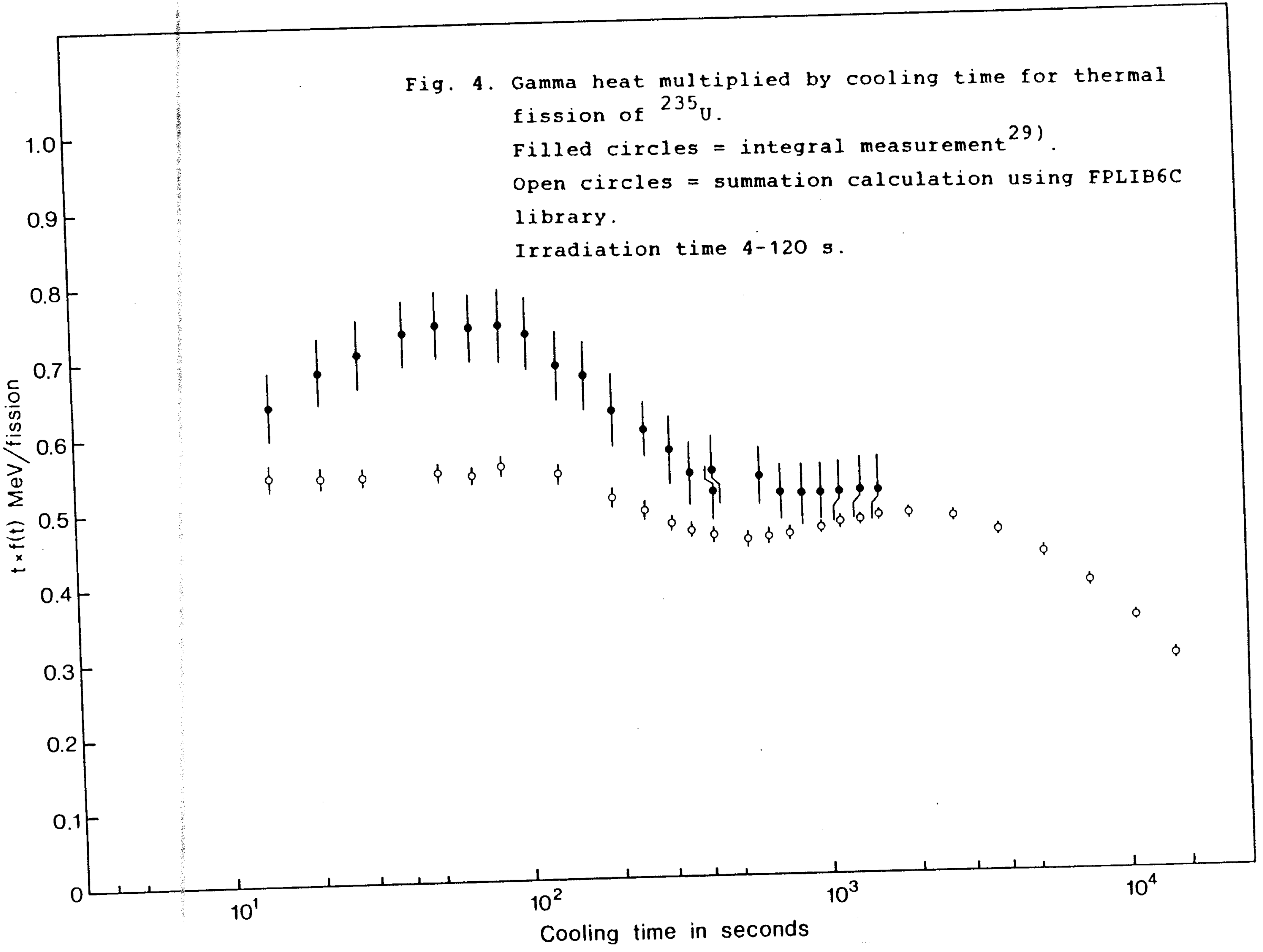

Fig. 4. Gamma heat multiplied by cooling time for thermal fission of ^{235}U.
Filled circles = integral measurement$^{29)}$.
Open circles = summation calculation using FPLIB6C library.
Irradiation time 4-120 s.

ded in the figures.

The overall conclusion is that the present calculation of the beta heat is somewhat higher than most of the others for ^{235}U in the range 500 - 1000 s but agrees with them elsewhere.

For the gamma heat all calculations using the same kind of input data as the present one agree quite well. The Yoshida curve30) lies considerably higher and is in better agreement with the integral experiments. The reason is to be found in the different approach - evaluating the average gamma energy from a theoretical beta strength function for nuclides with Q_β-value > 5 MeV thereby avoiding the use of lists of exerimentally determined gamma lines.

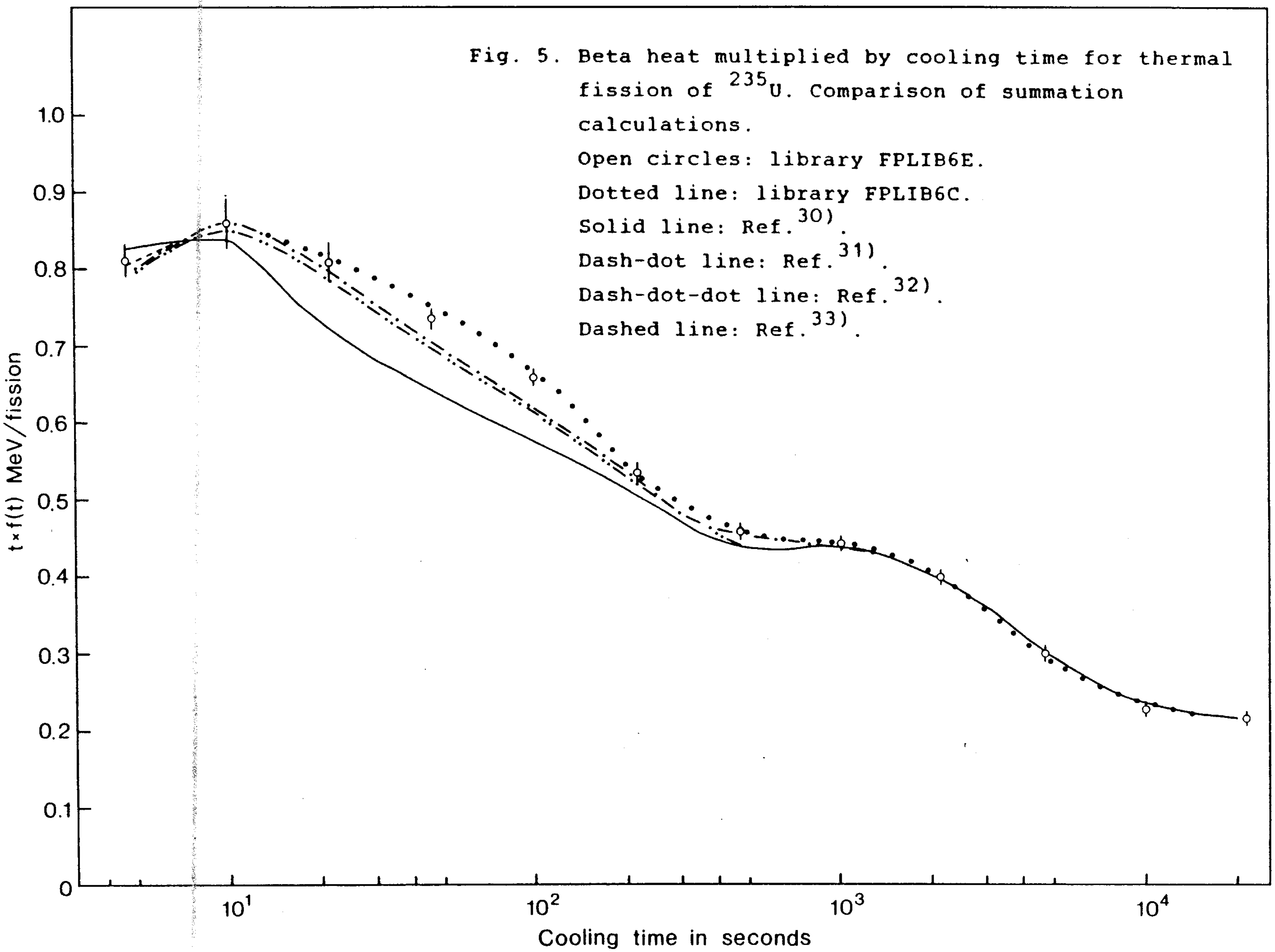

Fig. 5. Beta heat multiplied by cooling time for thermal fission of ^{235}U. Comparison of summation calculations.

Open circles: library FPLIB6E.

Dotted line: library FPLIB6C.

Solid line: Ref.[30].

Dash-dot line: Ref.[31].

Dash-dot-dot line: Ref.[32].

Dashed line: Ref.[33].

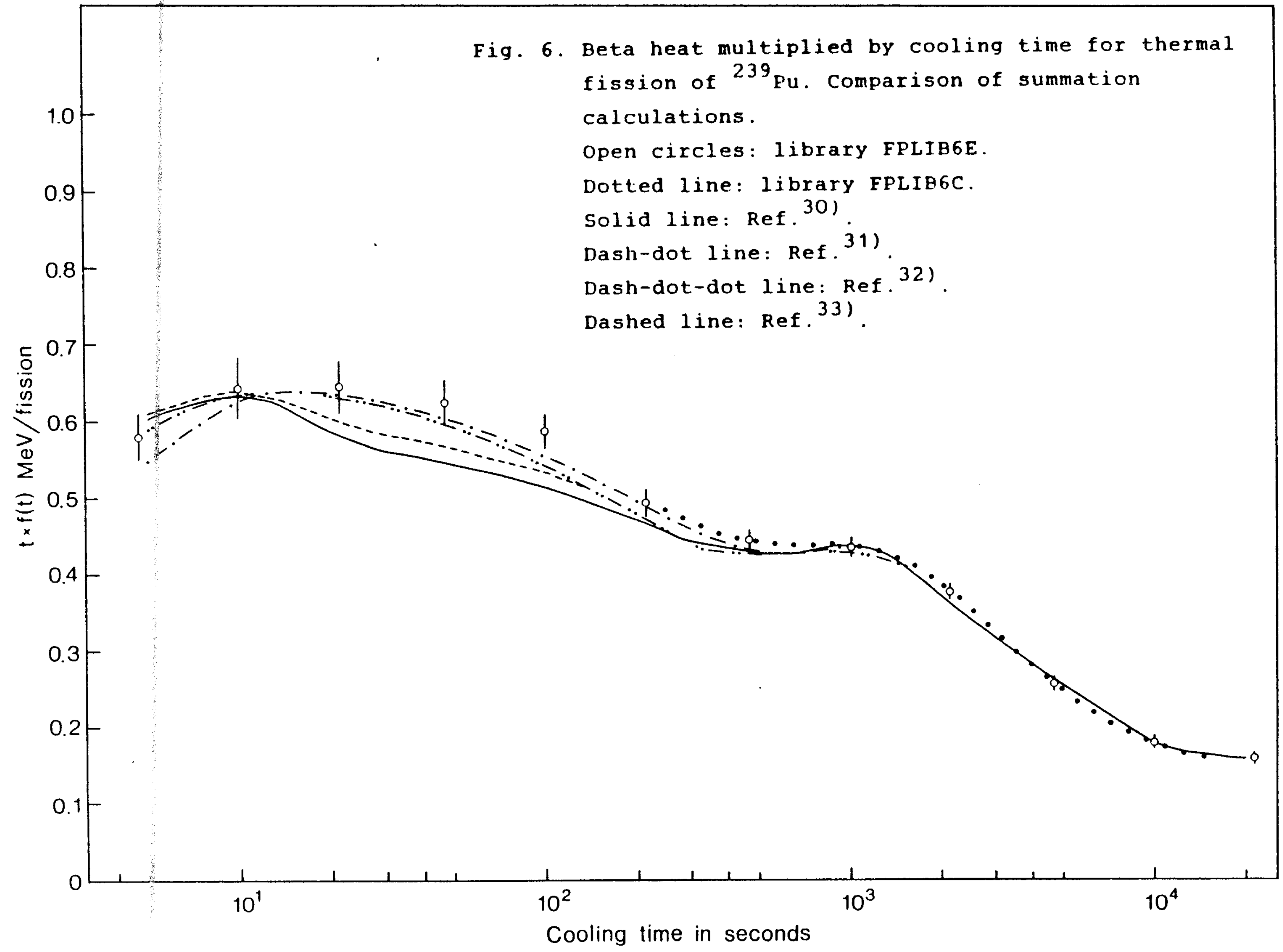

Fig. 6. Beta heat multiplied by cooling time for thermal fission of ^{239}Pu. Comparison of summation calculations.
Open circles: library FPLIB6E.
Dotted line: library FPLIB6C.
Solid line: Ref.30).
Dash-dot line: Ref.31).
Dash-dot-dot line: Ref.32).
Dashed line: Ref.33).

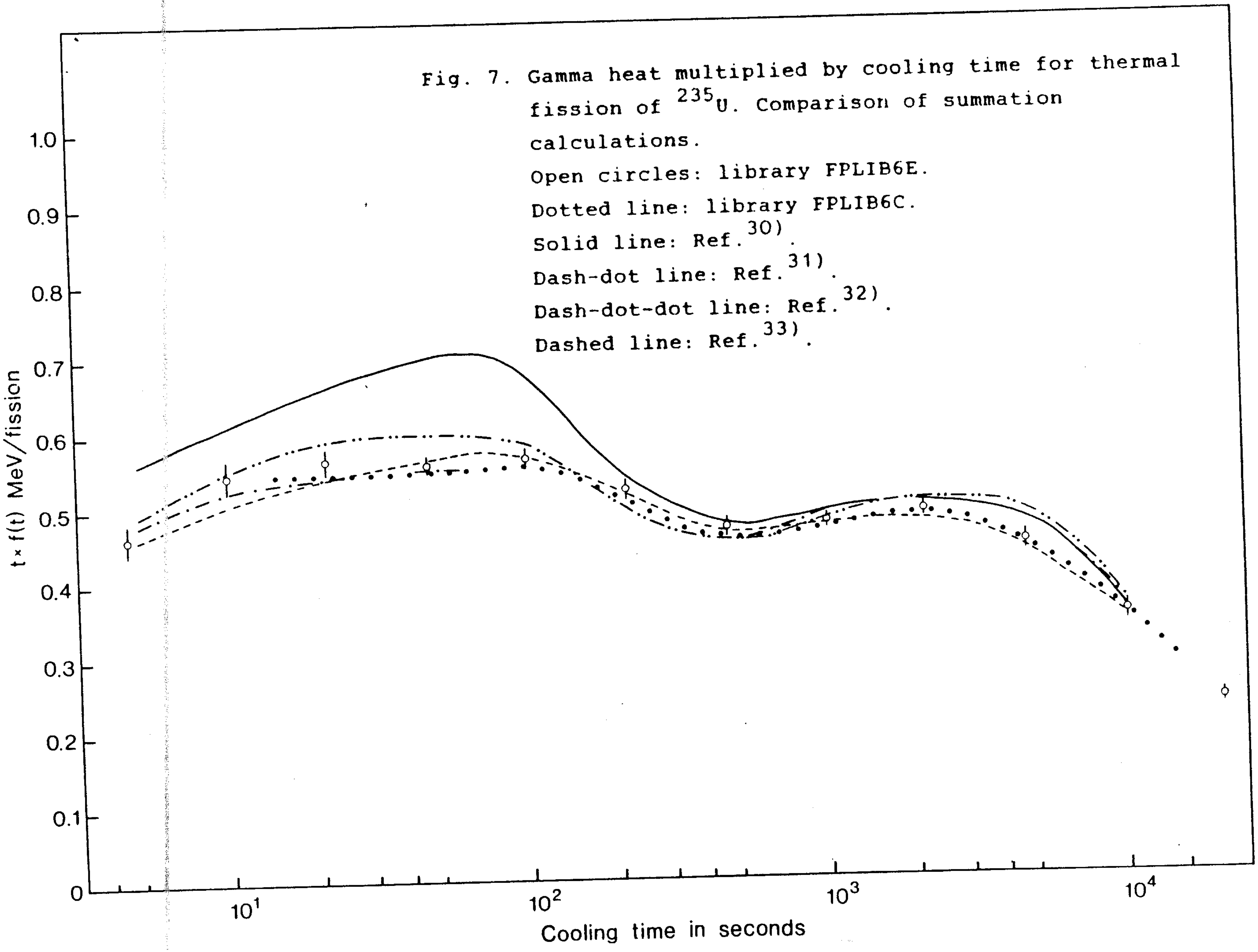

Fig. 7. Gamma heat multiplied by cooling time for thermal fission of ^{235}U. Comparison of summation calculations.
Open circles: library FPLIB6E.
Dotted line: library FPLIB6C.
Solid line: Ref.[30).]
Dash-dot line: Ref.[31).]
Dash-dot-dot line: Ref.[32).]
Dashed line: Ref.[33).]

REFERENCES

1) P.I. Johansson, work in progress.

2) G. Rudstam, J. Radioanal. Chem. 55 (1980) 79.

3) C. Nordborg, private communication (1985).

4) B.F. Rider and M.E. Meek, US Report NEDO-12154-2 (D), 1977.

5) T. England, private communication (1980).

6) G. Rudstam, K. Aleklett, R. von Dincklage, P. Hoff, B. Jonson, G. Nyman, and O. Tengblad, The antineutrino spectrum in the vicinity of a nuclear reactor. Contribution to the 1984 International Chemical Congress of Pacific Basin Societies, Honolulu, December 16-21, 1984, and work in progress.

7) G. Rudstam, P. Aagaard, and H.-U. Zwicky, Yields of Products from Thermal Neutron Induced Fission of ^{235}U, The Studsvik Science Research Laboratory, Report NFL-42 (1985).

8) G. Rudstam, Delay Parameters from Parent and Daughter Counts in the Same Sample, The Studsvik Science Research Laboratory, Report NFL-43 (1985).

9) E. Lund, P. Aagaard, B. Ekström, J. Eriksen, B. Fogelberg, H. Gökturk, and G. Rudstam, work in progress (1986).

10) J. C. Hardy, L.C. Carraz, B. Jonson, and P.G. Hansen, Phys. Letters 71B (1977) 307.

11) W. Mampe, K. Schreckenbach, P. Jench, P.K. Maier, F. Braumandel, J. Larysz, and T. von Egidy. Nucl. Instr. Methods 154 (1978) 127.

12) G. Rudstam, Nucl. Sci. Eng. 80 (1982) 238.

13) A.H. Wapstra and G. Audi, Nucl. Phys. A432 (1985) 1.

14) K. Tasaka, H. Ihara. M. Akiyama, T. Yoshida, Z. Matumato, and R. Nakasima, JNDC Nuclear Data Library of Fission Products, Japan Atomic Energy Research Institute Report JAERI 1287 (1983).

15) E. Lund and B. Fogelberg, private communication (1986).

16) D.A. Lewis, J.C. Hill, F.K. Wohn, and M.L. Gartner, Phys. Rev C22 (1980) 2178.

17) P. Hoff and B. Fogelberg, Nucl. Phys. A368 (1981) 210.

18) J. Münzel, B. Pfeiffer, and H. Wollnik, Z. Phys. A313 (1983) 247.

19) K. Shizuma, J.C. Hill, H. Lawin., M. Shaanan, H.A. Selic, and K. Sistemich, Phys. Rev. C27 (1983) 2869.

20) J.C. Hill, F.K. Wohn, Z. Berant, R.L. Gill, R.E. Chrien, C. Chung, and A. Aprahamian, Phys. Rev. C29 (1984) 1078.

21) F.K. Wohn, K.D. Wünsch, H. Wollnik, R. Decker, G. Jung, E. Koglin, and G. Siegert, Phys. Rev. C17 (1978) 2185.

22) G. Engler, Y. Nir-El, M. Schmid, and S. Amiel, Phys. Rev. C19 (1979) 1948.

23) C. Chung, W.B. Walters, N.K. Aras, F.K. Wohn, D.S. Brenner, Y.Y. Chu, M. Schmid, R.L. Gill, R.E. Chrien, and L.-J. Yuan, Phys. Rev. C29 (1984) 592.

24) G. Skarnemark, thesis, Chalmers University of Technology, Gothenburg, 1977.

25) E.A.C. Crouch, Atomic Data and Nuclear Data Tables 19 (1977) 419.

26) M.F. James, Fission Yields for JEF CNDC (83)/P20 (JEF/DOC-39), private communication from C. Nordborg (1986).

27) J.K. Dickens, T.A. Love, J.M. Connell, and R.W. Peelee, Nucl. Sci. Eng. 74 (1980) 106 and 78 (1981) 126.

28) M. Akiyama and S. An, Proc. Int. Conf. Nucl. Data for Sci. Technology, Antwerp (1982).

29) P.I. Johansson and G. Nilsson, Nukleära resteffekts-data. Fördröjd gammastrålning från ^{235}U, Research Report AES-16, 1977 (in Swedish).

30) T.Y. Yoshida, M. Akiyama, Z. Matumoto, J. Katakura, and R. Nakasima, Proceedings of the NEANDC Specialists Meeting on Yields and Decay Data of Fission Product Nuclides, Brookhaven October 24-27, 1983, BNL 51778.

31) R.E. Schenter, private communication to T.Y. Yoshida (quoted in Ref.30)).

32) B. Duchemin, private communication to T.Y. Yoshida (quoted in Ref.30)).

33) A. Tobias, Research Report RD/B/N4949 (1980).

Table 1

New average beta energies and corrected gamma energies

Nuclide	Average beta energy, MeV Ref.[6)] Rudst	Average beta energy, MeV JEF1	Average gamma energy, MeV Corrected with branching ratios from Ref. 7)	Average gamma energy MeV JEF1
^{77}Zn			0.14±0.02	0.54 ?
^{78}Zn			1.35±0.15	1.44 ±0.04
^{75}Ga			0.40±0.03	0.067±0.001
^{76}Ga			2.07±0.11	2.80 ±0.03
^{77}Ga			0.12±0.01	0.69
^{78}Ga			2.19±0.10	2.49
^{79}Ga			1.92±0.10	2.00
^{80}Ga			2.83±0.20	2.77 ±0.06
^{81}Ga			2.03±0.12	2.03
^{84}Br			1.90 ±0.19	1.74 ±0.07
^{85}Br			0.064±0.004	0.066±0.003
^{86}Br	2.21±0.02	1.93±0.16	2.62 ±0.39	3.25±0.09
^{87}Br	1.70±0.01	1.91±0.06	1.79 ±0.09	2.57±0.05
^{88}Br	1.97±0.01	2.49±0.10	2.13 ±0.10	2.54±0.07
^{89}Br	2.23±0.01	2.65±0.83		
^{90}Br	2.55±0.05	3.20±0.12		
^{87}Kr			0.83±0.08	0.79±0.02
^{88}Kr			1.99±0.11	1.95±0.01
^{89}Kr			1.89±0.09	1.79±0.02
^{90}Kr			1.59±0.13	1.29±0.03
^{91}Kr			1.63±0.15	1.74±0.02
^{92}Kr			1.07±0.09	1.45±0.04
^{93}Kr			2.28±0.49	2.28±0.02
^{94}Kr			1.02±0.25	1.89±0.03

^{89}Rb			2.32±0.12	2.07±0.05
^{90}Rb	2.27±0.25	1.86±0.15	2.62±0.18	2.17±0.02
^{90m}Rb	1.85±0.30	1.28±0.08	3.87±0.34	3.27±0.04
^{91}Rb	1.95±0.01	1.50±0.16	2.36±0.13	2.23±0.03
^{92}Rb	3.82±0.03	3.50±0.02	0.33±0.03	0.52±0.02
^{93}Rb	2.78±0.04	2.66±0.13	1.72±0.08	1.39±0.01
^{94}Rb	2.88±0.07	4.09±0.83	2.07±0.16	2.53±0.07
^{95}Rb	2.97±0.14	2.75±0.02	0.61±0.03	0.73±0.01
^{96}Rb	2.95±0.11	4.16±0.10	1.63±0.14	1.70±0.05
^{93}Sr	1.11±0.03	0.68±0.04		
^{94}Sr	1.04±0.09	0.90±0.21		
^{95}Sr	2.39±0.05	2.09±0.02		
^{96}Sr	2.38±0.05	2.00±0.10		
^{97}Sr	2.46±0.06	2.60±0.35		
^{98}Sr	2.67±0.24	2.53±0.19		
^{99}Sr	2.92±0.10	2.65±0.85		
^{96m}Y	3.23±0.06	3.22±0.07		
^{97}Y	2.27±0.10	2.14±0.30		
^{98}Y	2.50±0.09	2.17±0.15		
^{99}Y	2.69±0.09	2.59±0.30		
^{99}Zr	1.73±0.11	1.50±0.11		
^{113m}Ag			0.71±0.05	0.12±0.002
^{114}Ag			0.22±0.02	0.107±0.003
^{115}Ag			0.87±0.12	0.48±0.02
^{116}Ag			1.96±0.15	2.11±0.05
^{116m}Ag			2.42±0.26	1.20±0.07
^{117}Ag			0.94±0.22	1.09±0.04
^{117m}Ag			0.67±0.08	0.65±0.03
^{119}Ag			1.65±0.29	1.34±0.05
^{120}Ag			0.75±0.13	0.79±0.04
^{121}Ag			→ 0.88±0.08	2.90±0.07

^{119}Cd	0.92±0.07	1.46±0.08
^{119m}Cd	2.56±0.26	2.21±0.07
^{124}Cd	1.82±0.21	1.24±0.01
^{126}Cd	0.57±0.12	0.65±0.03
^{122H}In	3.85±0.58	3.03±0.06
^{123}In	1.11±0.12	1.11±0.05
^{123m}In	0.078±0.021	0.066±0.016
^{124L}In	2.35±0.26	2.70±0.10
^{126L}In	2.91±0.32	2.83±0.06
^{126H}In	4.30±0.49	4.30±0.11
^{127}In	1.19±0.07	1.77±0.02
^{127m}In	0.24±0.04	0.50±0.04
^{128L}In	3.19±0.26	3.07±0.09
^{128H}In	2.22±0.57	3.58±0.72
^{129}In	1.21±0.10	1.98
^{129m}In	0.24±0.03	0.36
^{127}Sn	1.47±0.19	1.86±007
^{127m}Sn	0.57±0.08	0.57±0.07
^{128}Sn	0.64±0.05	0.60±0.02
^{131}Sn	1.77±0.14	4.66
^{132}Sn	1.29±0.05	1.29
^{130m}Sb	3.26±0.17	3.26±0.06
^{131}Sb	1.69±0.14	1.69±0.05
^{132}Sb	2.58±0.21	2.53±0.05
^{132m}Sb	2.35±0.12	2.35±0.02
^{133}Sb	2.14±0.59	2.40±0.15
^{134}Sb	1.73±0.12	2.07±0.07

^{133}Te			0.97±0.03	0.93±0.02
^{134}Te			0.87±0.05	0.89±0.01
^{135}Te			0.20±0.02	0.70
^{136}Te			2.29±0.85	2.12±0.10
^{133m}I			1.58±0.05	1.58
^{134m}I			0.24±0.01	0.24
^{136}I	2.13±0.05	1.95±0.10	2.44±0.17	2.39±0.05
^{136m}I	2.26±0.05	2.14±0.19	2.14±0.21	2.14±0.15
^{137}I	2.41±0.07	1.93±0.25	1.00±0.06	1.14±0.02
^{138}I	2.54±0.02	2.76±0.16	1.19±0.07	1.65±0.03
^{139}I	2.47±0.02	2.01±0.29		
^{137}Xe	1.85±0.25	1.78±0.01	0.20±0.02	0.18±0.01
^{138}Xe			1.11±0.05	1.12±0.01
^{139}Xe	1.85±0.07	1.71±0.07	1.00±0.08	0.89±0.01
^{140}Xe			1.09±0.13	1.11±0.05
^{141}Xe			0.93±0.07	0.76±0.01
^{138m}Cs			0.54±0.06	0.42±0.01
^{139}Cs			0.32±0.04	0.31±0.01
^{140}Cs	2.16±0.02	1.71±0.07	1.37±0.09	2.11±0.04
^{141}Cs			0.77±0.06	0.92±0.02
^{142}Cs	2.92±0.03	2.62±0.19	0.78±0.13	0.89±0.03
^{143}Cs			0.50±0.06	0.108±0.011
^{144}Cs	2.45±.04	3.15±0.16	0.62±0.05	0.97±0.03
^{145}Cs			0.52±0.20	1.86
^{144}Ba	1.12±0.12	0.95±0.05		

Table 2

Calculation of $\bar{E}_\beta$ using Eq. (6)

Nuclide	$\bar{E}_\gamma$, MeV JEF1	Q_β, MeV JEF1	P_n, % Ref.[12]	$\bar{E}_n$, MeV estimated	S_n, MeV Ref.[13]	$\bar{E}$, $_\beta$MeV from Eq. (6)	$\bar{E}_\beta$, MeV Ref.[14]
^{100}Sr	1.46	6.54	5.0	0.5	1.37	2.26	2.51
^{103}Zr	1.83	7.00	-	-	-	2.32	2.40
^{104}Zr	1.46	3.49	0.11	0.1	3.22	0.91	1.74
^{163}Gd	0.33	2.45	-	-	-	0.95	0.98

Table 3

Nuclides with new half-life or branching information

Nuclide	Half-life s	Branch to isomeric state	Internal transition	Half-life,s JEF1
^{74}Cu	1.6 ±0.2$^{a)}$			
^{75}Cu	1.4 ±0.1$^{a)}$			
^{76}Cu	0.35$^{a)}$			
^{77}Zn	2.08±0.04$^{a)}$			1.4 ±0.3
^{78}Zn	1.47±0.15			1.47
^{79}Zn	1.0 ±0.1$^{a)}$			0.35
^{80}Zn	0.53±0.05$^{a)}$			
^{78}Ga	5.49±0.25$^{b)}$			5.49
^{79}Ge	19.1±0.3$^{c)}$			39 ±2
^{79m}Ge	39.0±0.2$^{c)}$		0.043	
^{81}Ge	7.6 ±0.6$^{c)}$			7.6 ±1.0
^{81m}Ge	7.6 ±0.6$^{c)}$			7.5 ±1.0
^{82}Ge	4.0 ±0.35$^{d)}$			4.6
^{82}As	21.0±1.5$^{d)}$			21.0
^{82m}As	13.0±0.6$^{d)}$			13.0
^{85}As	2.03±0.01$^{d)}$			2.05
^{100}Y	0.68±0.02$^{e)}$			0.55±0.15
^{102}Y	0.36±0.04$^{f)}$			0.27±0.07
^{102}Zr	2.9 ±0.2$^{d)}$			2.1
^{99}Nb	15.0±0.2$^{d)}$			14.3

^{105}Mo	36 ±5 d)		36.7
^{113}Rh	0.91±0.08 d)		0.9
^{116m}Ag	8.7 ±0.2 d)		10.5±0.5
^{118}Ag	3.7 ±0.2 d)		3.7
^{124}Ag	0.17±0.03 g)		
^{123}Cd	2.19±0.10 a)	0.23	3.8±0.1
^{124}Cd	1.26±0.06 a)	1.00	1.0±0.2
^{125}Cd	0.75±0.04 a)	0.30	0.5
^{126}Cd	0.60±0.03 a)	1.00	0.506±0.015
^{127}Cd	0.43±0.03 a)	0.25	
^{128}Cd	0.34±0.03 a)	1.00	0.15
^{129}Cd	0.27±0.04 a)	0.25	
^{124}In h)	3.09±0.04 a)		3.2 ±0.3
^{124m}In h)	3.7 ±0.1 a)		2.4 ±0.2
^{125}In	2.50±0.03 a)	0.88	2.33±0.04
^{125m}In	12.2±0.1	1.00	12.2±0.1
^{126}In h)	1.60±0.04 a)		1.50±0.20
^{126m}In h)	1.64±0.01 a)		1.45±0.22
^{127}In	1.30±0.03 a)	0.84	3.7 ±0.1
^{127m}In	3.8 ±0.1 a)	1.00	1.15±0.05
^{128}In h)	0.84±0.04 a)		0.9 ±0.1
^{128m}In h)	0.72±0.07 a)	0.03	0.9 ±0.1
^{129}In	0.59±0.02 a)	0.11	1.20±0.05
^{129m}In	1.26±0.02		0.59±0.03
^{130}In h)	0.33±0.03 a)		
^{130m}In h)	0.53±0.03 a)	0.03	0.53±0.05
^{131}In	0.28±0.01 a)		0.27±0.10
^{131m}In	0.35±0.05 a)		0.27±0.02
^{132}In	0.22±0.03		0.12±0.002

^{129}Sn	134 ±2 d)			144
^{129m}Sn	534 ±36 d)			414
^{130m}Sn	102 ±6	1.00		102 ±6
^{136}Te	17.5 ±0.4 d)			20.7±2.0
^{140}I	0.60 ±0.01 d)			0.86±0.04
^{135m}Xe	939 ±6 d)		1.00	939
^{146}Cs	0.305±0.010 j)			0.189±0.011
^{145}Ba	3.85 ±0.12 k)			4.00
^{146}Ba	2.22 ±0.07 l)			2.0 ±0.4
^{147}Ba	0.72 ±0.07 k)			0.93±0.05
^{148}Ba	0.672±0.007 e)			0.47±0.20
^{144}La	42.1 ±0.7 m)			41.0
^{145}La	25.2 ±2.6 m)			24.2
^{149}La	1.2 ±0.4			0.25
^{145}Ce	179 ±4 d)			178.8
^{147}Ce	56.7 ±2.3 d)			55
^{146}Pr	1440 ±6 d)			1452
^{150}Pr	6.20 ±0.20 d)			6.10

a) Ref.15)

b) Ref.16)

c) Ref.17)

d) Values used in FPLIB78

e) Ref.18)

f) Ref.19)

g) Ref.20)

h) The low spin isomer of ^{126}In, ^{128}In, and ^{130}In is the ground state according to unpublished OSIRIS work by L. Spanier and K. Aleklett. For ^{124}In the situation is unclear, but the low-spin isomer is here assumed to be the ground state in analogy with the other cases. This means that the assignments of JEF1 must be interchanged.

j) Ref.21)

k) Ref.22)

l) Ref.23)

m) Ref.24)

Table 4

New information on independent yields with relative errors of independent yield (=indep.) and cumulative yield (=cum.) used for updating the ENDF/B-V yield library

Nuclide	New information from Refs.7-9)			ENDF/B-V		
	Yield, %	Rel. error, %		Yield, %	Rel. error, %	
		Indep.	Cum.		Indep.	Cum
^{77}Zn	0.0065	46	46	0.0031	64	64
^{78}Zn	0.0065	54	54	0.0035	64	64
^{77}Ga	0.0040	100	28	0.0041	64	32
^{78}Ga	0.0082	70	31	0.0108	64	32
^{81}Ga	0.0050	34	34	0.0071	32	32
^{84m}Br	0.0166	8.4	8.4	0.025	23	8
^{116m}Ag	0.00120	24	24	0.0012	64	64
^{119}Ag	0.0066	42	28	0.0065	64	64
^{120}Ag	0.0028	50	34	0.0049	64	64
^{120m}Ag	0.0083	34	34			
^{121}Ag	0.0034	41	41	0.0041	64	64
^{122}Ag	0.0016	38	38	0.0022	64	64
^{121m}Cd	0.0052	25	24			
^{123}Cd	0.0090	26	24	0.0078	64	45
^{125}Cd	0.0122	21	21	0.0088	64	64
^{126}Cd	0.0111	14	14	0.0116	64	64
^{127}Cd	0.0076	42	42			
^{128}Cd	0.00048	33	33	0.0064	64	64
^{129}Cd	0.00031	19	19			

$^{120m}\mathrm{In}$ ($^{120M}\mathrm{In}+^{120H}\mathrm{In}$)	0.00020	45	45	0.000094	64	45
$^{122m}\mathrm{In}$ ($^{122M}\mathrm{In}+^{122H}\mathrm{In}$)	0.0026	35	35	0.00085	64	64
$^{123}\mathrm{In}$	0.0033	100	26	0.0029	64	11
$^{124m}\mathrm{In}$	0.0031	32	32			
$^{125}\mathrm{In}$	0.0123	51	29	0.0058	64	64
$^{126}\mathrm{In}$	0.0033	100	26	0.027	64	64
$^{126m}\mathrm{In}$	0.0028	32	32			
$^{127}\mathrm{In}$	0.0263	39	31	0.035	64	45
$^{127m}\mathrm{In}$	0.0067	42	31	0.0266	64	45
$^{128}\mathrm{In}$	0.0127	33	32	0.082	64	64
$^{128m}\mathrm{In}$	0.0089	35	35			
$^{129}\mathrm{In}$	0.0026	35	35	0.048	64	64
$^{129m}\mathrm{In}$	0.0060	37	36	0.046	64	64
$^{130}\mathrm{In}$	0.0016	31	31	0.095	64	64
$^{130m}\mathrm{In}$ ($^{130M}\mathrm{In}+^{130H}\mathrm{In}$)	0.0048	28	28			
$^{131}\mathrm{In}$	0.0011	36	36	0.029	64	64
$^{131m}\mathrm{In}$	0.022	36	36			
$^{132}\mathrm{In}$	0.00011	36	36	0.0067	32	32
$^{127m}\mathrm{Sn}$	0.025	46	11	0.0166	64	45
$^{128m}\mathrm{Sn}$	0.0036	28	26	0.0066	64	4
$^{129m}\mathrm{Sn}$	0.159	10	10	0.37	11	6
$^{130m}\mathrm{Sn}$	0.119	22	21			
$^{128m}\mathrm{Sb}$	0.0174	16	12	0.0066	64	4
$^{136}\mathrm{Te}$	2.16	24	24	1.51	23	16
$^{133m}\mathrm{I}$	0.07	100	30	0.069	4	4
$^{134m}\mathrm{I}$	0.266	10	10	0.35	6	6
$^{138m}\mathrm{Cs}$	0.081	38	38	0.16	11	11

Note: M and H stand for medium ($4,5^{+}$) and high ($8^{-},10^{-}$) spin state of indium