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JENDL FP Decay Data File 2000 and the Beta-Decay Theory

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Abstract

JENDL FP Decay Data File 2000 has been developed as one of the special purpose files of the Japanese Evaluated Nuclear Data Library (JENDL), which constitutes a versatile nuclear data basis for science and technology. In the format of ENDF-6 this file includes the decay data for 1087 unstable fission product (FP) nuclides and 142 stable nuclides as their daughters. The primary purpose of this file is to use in the summation calculation of FP decay heat, which plays a critical role in nuclear safety analysis; the loss-of-coolant accident analysis of reactors, for example. The data for a given nuclide are its decay modes, the Q value, the branching ratios, the average energies released in the form of beta- and gamma-rays per decay, and their spectral data. The primary source of the decay data adopted here is the ENSDF (Evaluated Nuclear Structure Data File). The data in ENSDF, however, cover only the measured values. The data of the short-lived nuclides, which are essential for the decay heat calculations at short cooling times, are often fully lacking or incomplete even if they exist. This is mainly because of their short half-life nature. For such nuclides a theoretical model calculation is applied in order to fill the gaps between the true and the experimentally known decay schemes. In practice we have to predict the average decay energies and the spectral data for a lot of short-lived FPs by use of beta-decay theories. Thus the beta-decay theory plays a very important role in generating the FP decay data file.

1. Introduction

So called the summation calculation is a versatile method to evaluate the aggregate behavior of the fission products (FPs) in nuclear reactors, among which the reactor decay heat may be of the primary importance. The FP decay heat plays a critical role in nuclear safety analysis; the loss-of-coolant accident (LOCA) analysis of reactors, for example. Beta-decay of a lot of short-lived FPs takes part in generating the heat especially in short cooling time range (typically < 1000 s) where the LOCA analysis places a special importance. This leads to a need for a very extensive data library, which includes the decay and the yield data of a lot of FP nuclides. It was early 1970's when the necessity for a FP decay data file was first recognized in Japan for reliable prediction of the reactor decay heat. It had taken more than a decade before we completed the first version of the JNDC FP Decay Data Library[1)]. In the course of generating this library, we found that application of beta-decay theories was inevitable in order to fill the gaps between the true and the experimentally known decay schemes of short-lived FPs[2)]. Without the aid of the theory, the agreement between the summation calculation and the integral experiments[3) -7)] remains far from satisfactory[2)].

In late 1980's, the second version of the JNDC FP Decay Data Library (JNDC-V2) was completed [8)], which is based on the improved decay schemes published since 1970's. The summation calculation based on JNDC-V2 reproduces the integral decay-heat experiments quite well. Taking this success into account, the Committee of Standardization of Decay Heat Power was established in the Atomic Energy Society of Japan (AESJ) and it recommended the decay heat curves for U-235, -238, Pu-239, -240 and Pu-241 which are fully based on the results of the JNDC-V2 summation calculations[9)].

2. Role of the Beta-decay Theories in the Decay Heat Calculations

In the summation calculation, the energies released as the beta-ray and the gamma-ray of every contributing FP nuclide are summed up to yield the total decay heat $f(t)$ as

$$f(t) = \sum_{i}^{\text{allFPs}} \left(E_b^{\,i} + E_g^{\,i} \right) \cdot \lambda_i \cdot N_i(t), \qquad (1)$$

where E_b^i, E_g^i, λ_i and $N_i(t)$ stand for the beta- and the gamma-ray energies released per one beta-decay, the decay constant, and the inventory of the i-th FP nuclide at time t, respectively. We have to know the decay properties of each FP nuclide, especially the values of E_b^i and E_g^i, as precisely as possible. They are, however, not always known to the desired exactitude on a firm experimental basis. Then, we have to fill the gaps between the experimentally known and the true decay schemes of FPs with the aid of the beta-decay theories. This is the case especially for short-lives nuclides for which the experimental information is lacking or insufficient even if it is available. The beta-strengths to the high-lying states tend to be missed experimentally. As a result, the beta-ray energy E_b^i is overestimated, and the gamma-ray energy E_g^i is underestimated in a way as is illustrated in Fig. 1.

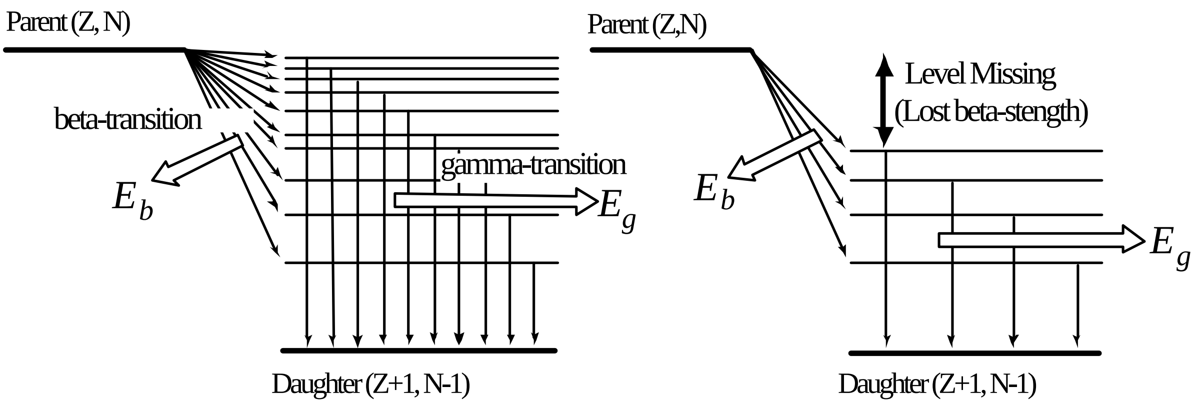

Fig. 1 Effect of lost beta-strength in evaluating the energy-release per decay, E_b^i and E_g^i. When the high-lying levels being missed (the right-hand side), the beta-ray energy E_b^i will be overestimated, and the gamma-ray energy E_g^i underestimated.

JNDC FP Decay Data File (Version 1 and 2) and the American ENDF/B-6 make full use of the Gross Theory of Beta Decay[10). European JEF[11) depends on the Microscopic Theory of Beta-decay[12). Figure 2 compares the results of the summation calculations and the integral measurements of the gamma-ray component of Pu-239 FP decay heat, for which the discrepancy is more conspicuous to see than the beta-ray component and other fissioning systems. The difference between JEF-2.2 and the JNDC-V2 / ENDF/B-6 group comes from the way of application of the beta-decay theories. In JEF-2.2, the theoretical values of the beta- and the gamma-ray energies, E_b^i and E_g^i, are adopted only for very short-lived nuclides for which there is no decay-scheme data available. Even when the beta-strength at high energy seems to be missing as illustrated in Fig. 1, E_b^i and E_g^i are calculated from the decay scheme as it is. In JNDC-V2, however, adopted the value of E_b^i and E_g^i calculated by the Gross Theory for nuclides for which the known decay scheme seemed to be insufficient as was illustrated in the right hand side of Fig.1. The ratio E_{max}/Q was used as a criterion, where E_{max} is the energy of the highest level identified and Q the Beta-decay Q-value. When the ratio E_{max}/Q was less than about 0.7 we applied the theoretical values, though there are many exceptions.

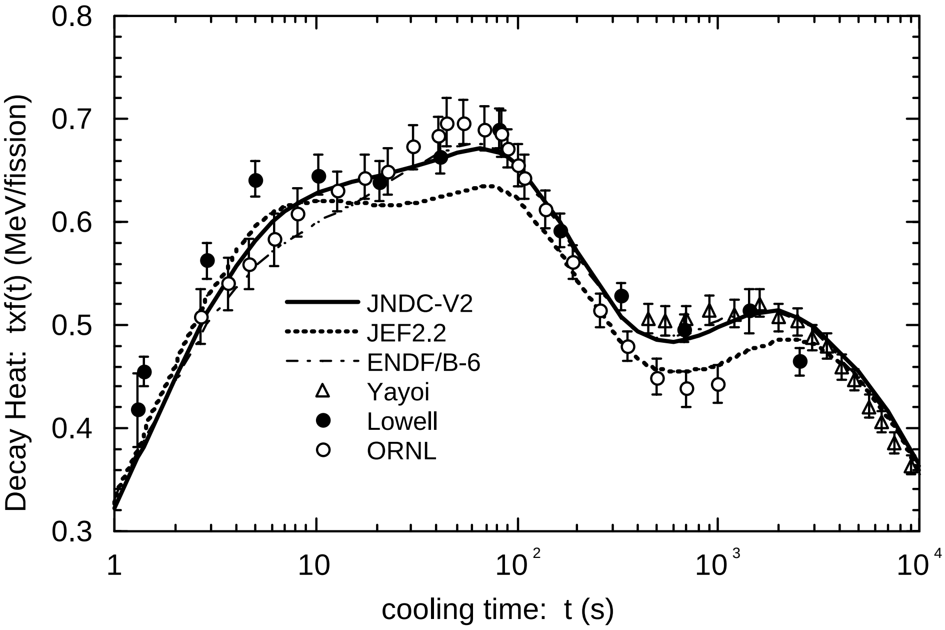

Fig.1 Comparison with Integral Decay-Heat Experiments
Gamma-Component after a Fission Burst in U-235

Fig.2 Gamma-Ray Component of the Pu-239 Decay Heat after a Fission Burst: Comparison among FP Nuclear Data Libraries and Integral Experiments (YAYOI:Refs.3-5, ORNL:Ref.6, Lowell:Ref.7)

3. JENDL FP Decay Data File 2000

JNDC-V2 was released in 1990. The file covers the half-lives, the average decay energies, branching ratios and fission yields of 1078 FPs from A=66 to 172, and 149 stable nuclides appear as their daughter. The decay heat calculation using this file was able to reproduce the integral decay-heat measurements of various fissioning systems quite well[8). This file, however, employs a local format different from the ENDF-6 format which is used in JENDL (Japanese Evaluated Nuclear Data Library). Therefore the file has not been treated as a member of JENDL family. The effort to convert the JNDC-V2 data into JENDL format had started but the procedure is not so simple. One problem was the fact that JNDC-V2 does not include the radiation spectral data. The ENDF-6 format requires the 'completeness' of the data. The 'completeness' means that all the data required by the format should be thoroughly included even if the measured data is not available. The theoretical estimation of lacking data is, therefore, inevitable. Further, the average decay energies for a lot of FPs are theoretically estimated in JNDC-V2 even if the measured data are available as far as the they are considered to be insufficient. In other words, the experimental spectra of such nuclides do not reproduce the values of E_b^i and E_g^i finally adopted in the file. Then, the deficient spectra, which come from the lost beta-strength seen in Fig. 1, must be supplemented theoretically, or more practically to say, by the Gross Theory of beta decay and a continuous gamma-decay model[13]. Only the theoretically supplemented spectra guarantee the consistency with E_b^i and E_g^i. The procedure of the theoretical supplement of the lost spectra is described in Ref. 14) in detail.

JENDL Decay Data File 2000[15] contains the decay data of 1087 FPs from A=66 to 172 and 142 stable nuclides appear as their daughter. In the file, half-life, decay modes, Q values, branching ratios, average decay energies of beta-ray, gamma-ray and alpha-ray are contained. The average beta-ray energy here means the emitted electron energy per decay and it includes the conversion electron energy. The average gamma-ray energy means the emitted gamma-ray plus X-ray energy. As for spectral data, each radiation including the conversion electron and the X-ray is separately given in the file when their measured data are available. The spectral data of delayed neutron are not given in the present file. Only the branching ratio of the delayed neutron decay is given. When doing the summation calculations of the FP decay heat or its spectra, the FP decay data included in JENDL Decay Data File 2000 should be used in combination with the fission yield contained in JENDL-3.3. The some results of the decay heat summation calculations are shown in Figs. 3, 4 and 5 for U-235 burst fission.

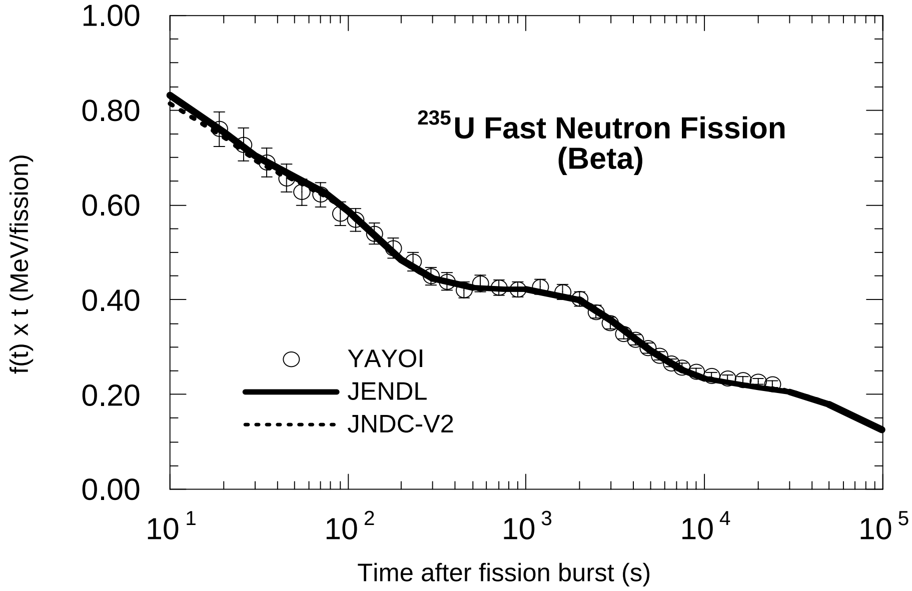

Fig.3 Beta-Ray Component of the U-235 Decay Heat after a Fission Burst
(YAYOI experiments : Refs. 3, 4 and 5)

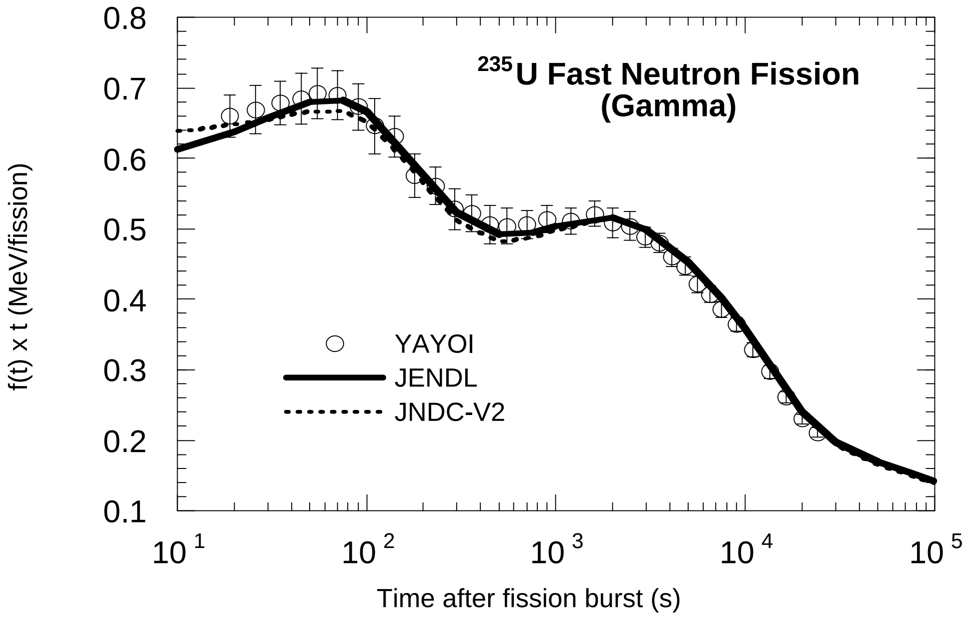

Fig.4 Gamma-Ray Component of the U-235 Decay Heat after a Fission Burst

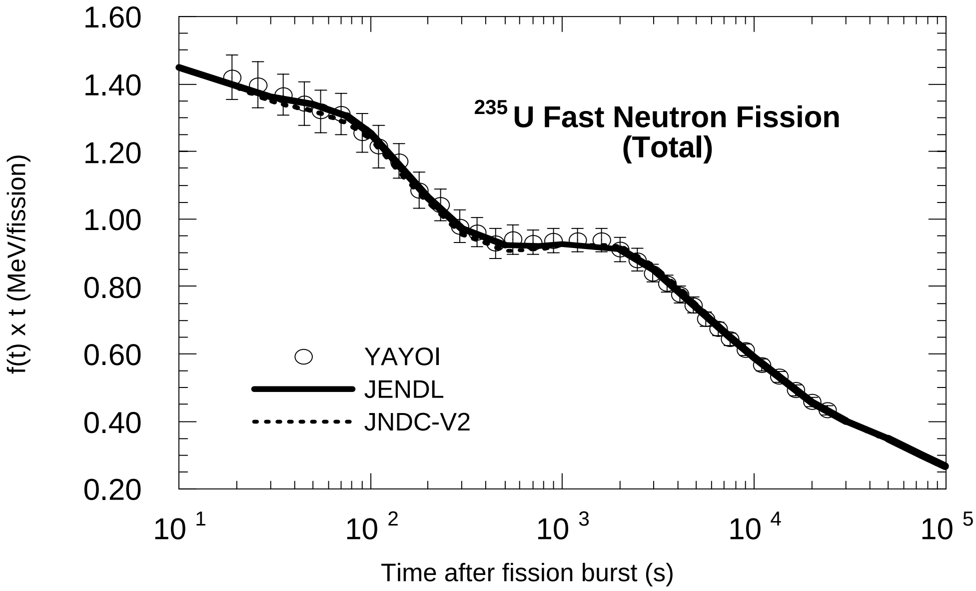

Fig.5 U-235 Decay Heat (Total) after a Fission Burst

Figure 6 compares the measured and the calculated gamma-ray spectra emitted from the aggregate FPs produced by a 10 second fast-neutron irradiation and after 14 second cooling. The ENSDF curve is the summation of the measured spectrum of each contributing nuclide and the JENDL curve is from the spectrum of each FP supplemented by theory[13]. It is easy to see that the theoretical supplementation is essential.

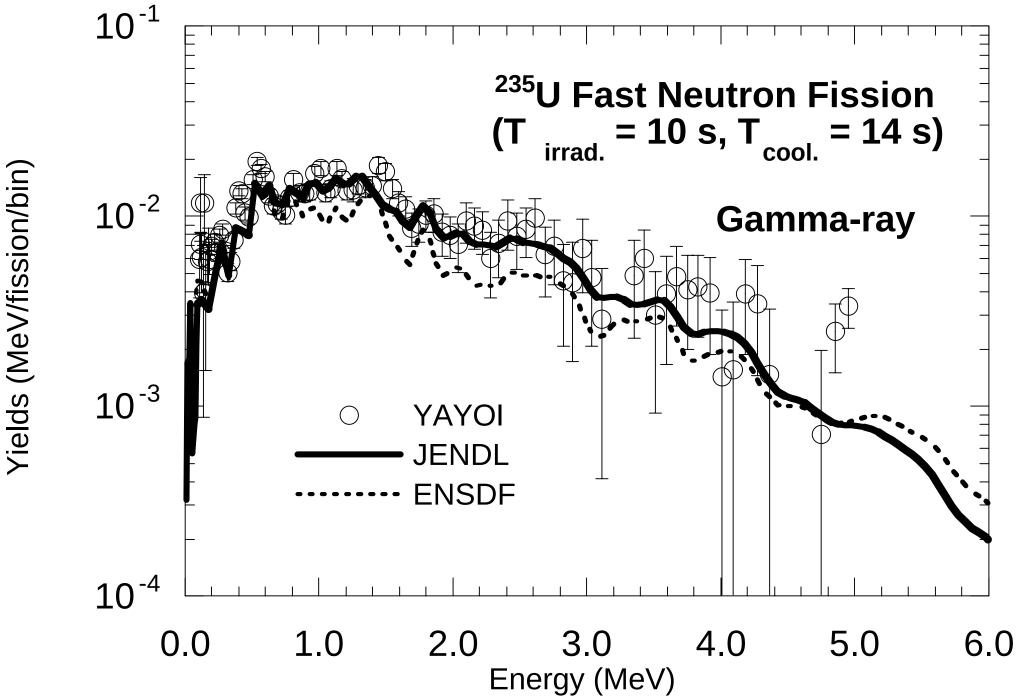

Fig.6 Gamma-Ray Component of the U-235 Decay Heat after a Fission Burst

4. Concluding Remarks

The overall success of JENDL FP Decay Data File (JNDC-V2 and ENDF/B-6 too), which reproduce well the integral experiments quite well as is seen in Figs. 3 through 5, does not always guarantee that the theoretical E_b^i and E_g^i values are always appropriate for each special nuclide. This is because the Gross Theory describes the average or aggregate trend of a lot of decaying nuclides well but not always each special decay of a nuclide. Table I lists the ‘theoretical’ FP nuclides which are important for the summation calculation of the U-235 decay heat. They contribute more than 1% to the total decay heat of U-235 at cooling times 1000, 100 and 10 seconds after a fission burst. For these nuclides we have a good reason that the beta-strengths are missed at high energy. The table also shows the highest level adopted by the Table of Isotopes 8th Edition. The larger the gap between this and the beta Q-value is, the more the possibility of missing beta-strengths at high energies. The experimental determination of the beta-strengths up to the highly-excited daughter states of these nuclides listed in Table I is of primary importance both from the theoretical and the technological point of view. These efforts will not only strengthen the reliability of the summation calculation but also improve the quality of the decay data of each FP nuclide.

Table I List of Important FP Nuclides for which JENDL Applies the Theoretical Beta and Gamma-Ray Energies (Contribution to the total decay heat greater than 1% at 1000, 100 and 10 sec cooling)

Decaying nucleus	**Half-Life (s)**	**Q-value (MeV)**	**Highest Level (MeV)**	**Cooling (s)**	**Contribution (%)**
Tc-102 (43,102)	5.28	4.53	3.01	1000	4.45
Tc-104 (43,104)	1098	5.6	4.27	1000	2.5
Rb-90 (37,90)	158	6.59	5.83	1000	1.38
Cs-140 (55,140)	63.7	6.22	5.77	100	7.87
Rb-90 (37,90)	158	6.59	5.83	100	4.51
Sr-94 (38,94)	75.3	3.51	2.97	100	4.12
Br-87 (35,87)	55.6	6.85	6.19	100	3.17
Nb-98 (41,98)	2.86	4.59	4.1	100	2.96
Sr-95 (38,95)	23.9	6.08	4.56	100	2.7
La-145 (57,145)	24.8	4.12	2.61	100	1.92
Cs-141 (55,141)	24.94	5.26	4.67	100	1.83
Nb-99m (41,99)	156	3.64	2.94	100	1.42
Ce-145 (58,145)	180	2.54	1.61	100	1.3
Ce-147 (58,147)	56.4	3.29	1.19	100	1.26
Tc-103 (43,103)	54.2	2.66	1.11	100	1.24
Zr-98 (40,98)	30.7	2.26	0	100	1.08
Te-135 (52,135)	19	5.96	4.77	100	1.04
Nb-100 (41,100)	1.5	6.25	3.13	10	6.25
Rb-92 (37,92)	4.492	8.11	7.36	10	5.53
Y-96 (39,96)	5.34	7.09	6.23	10	4.97
Nb-101 (41,101)	7.1	7.57	1.1	10	3.46
Zr-100 (40,100)	7.1	3.34	0.7	10	2.47
Nb-102 (41,102)	1.3	7.21	0	10	2.25
Te-135 (52,135)	19	5.96	4.78	10	2.25
Y-97 (39,97)	3.75	6.69	3.55	10	2.2
Br-89 (35,89)	4.4	8.16	4.71	10	1.97
Rb-94 (37,94)	2.702	10.31	6.06	10	1.79
Ba-144 (56,144)	11.5	3.12	1.24	10	1.65
Nb-98 (41,98)	2.86	4.59	4.1	10	1.56
Nb-99 (41,99)	15	3.64	2.94	10	1.56
La-146 (57,146)	6.27	6.55	4.69	10	1.36
La-145 (57,145)	24.8	4.12	2.61	10	1.18
Se-87 (34,87)	5.85	7.28	3.99	10	1.11

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