Journal of NUCLEAR SCIENCE and TECHNOLOGY, Supplement 4, p. 522–525 (March 2004)

# Brief Calculation of Neutrino Energy Spectra by the Use of Nuclear Data Files

T. NISHIMURA[1]*, S. ISHIMOTO[1], H.ARIMA[1], K.ISHIBASHI[1], J. KATAKURA[2]
[1]*Department of Applied Quantum Physics and Nuclear Engineering, Kyushu University, Fukuoka 812-8581, Japan*
[2]*Nuclear Data Center, Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki, 319-1195, Japan*

**Abstract**

Nuclear reactors generate a highly intense flux of electron-antineutrinos from fission products through $\beta^-$ decay, and a slight amount of electron-neutrinos through either $\beta^+$ decay or electron capture. Neutrino energy spectra are usually calculated by the β decay theory. Since the reactor neutrinos are emitted from a great number of nuclides, the calculation requires a lot of level scheme of these nuclides. Nuclear data files, however, are available these days. It is possible to evaluate the electron-antineutrino and -neutrino spectra for a nuclear reactor on the basis of nuclear data files (JENDL-FP-Decay-Data-File-2000, JENDL-3.3)[1,2].

In the study, we consider β transition of 420 nuclides for electron-antineutrino spectra and 120 nuclides for electron-neutrinos. We derive electron-neutrino and -antineutrino spectra in the energy range of 10 keV to 8 MeV from nuclear data files. The method gives good agreement with other studies for electron-antineutrino spectra. We show a simple method to estimate the reactor neutrino spectra without complicated computation.

***KEYWORDS: nuclear reactor, nuclear-data-library, JENDL-FP-Decay-Data-File-2000, JENDL-3.3, neutrino***

## I Introduction

Typical radiations are gamma rays, neutrons, and other charged particles. Neutrinos are also included in radiations. There exist a great number of neutrinos, and their fluxes are $10^{11}$~$10^{12}$[$s^{-1}cm^{-2}$][3]. The neutrinos measurement and evaluation may become useful in engineering fields in future.

Neutrinos have no electric charge and make only weak interaction with quite small cross sections. It is an important theme to experimentally prove whether neutrino is massless or not. The evidence of the rest mass of neutrinos is being obtained through the neutrino oscillation phenomenon. Nuclear reactors serve as intense sources of electron -antineutrinos in such experiments on search for neutrino oscillations as in KamLAND[4], Chooze[5] and Burgey[6]. The spectra of neutrinos are required for these experiments. The neutrinos are emitted from reactors by β transition of fission products (FPs).

The β transitions emit radiations of either antineutrinos or neutrinos together with β-rays i.e. electrons or positrons.

$$X_N^A \rightarrow X'^A_{N+1} + e^- + \overline{\nu}_e , \tag{1}$$

$$X_N^A \rightarrow X'^A_{N-1} + e^+ + \nu_e . \tag{2}$$

These neutrinos have continuous energy spectra. For obtaining these spectra theoretically, we should make the calculation by the β decay theory with information on a level scheme of a great number of nuclides[7]. Nuclear data files, however, are available these days.

*Corresponding author, Tel.+91-92-642-3765 Fax.+91-92-642-3769
E-Mail; nisimura@kune2a.nucl.kyushu-u.ac.jp

JENDL-FP-Decay-Data-File-2000 is a data file evaluated in Japan.[1] The file contains the decay data of 1229 FP nuclides from A=60 to 178, and includes decay data of half-lives, decay modes, Q values, branching ratios and average energy values of such radiations as β-rays, gamma-rays and alpha-rays. In addition, spectral data on individual radiations including conversion electrons and X-rays are separately given in the file. To compute neutrino spectra, we used the β-rays spectra of this data file. Unlike the case of antineutrinos, electron-neutrinos often have monochromatic spectra caused by electron captures (E.C.). We calculated these spectra with the Q values of E.C. The main fissile nuclides to yield FPs in a reactor are $^{235}$U, $^{238}$U, $^{239}$Pu and $^{241}$Pu. For FP yields of these nuclides, cumulative FP yield data for the thermal neutron (0.025eV) fission are selected in JENDL-3.3. These spectrum-data and yield-data enable us to readily compute the neutrino and antineutrino spectra from a reactor.

## II Neutrino Energy Spectra

### 1 Neutrino Spectra from a Reactor

In light water reactors (LWRs), electron-antineutrinos and -neutrinos are emitted from $\beta^-$ and $\beta^+$ decay by FPs and radioactivated structural nuclides.

Electron-antineutrinos from the $\beta^-$ decay of FPs form a flux, and are the main constituents of reactor neutrinos. In addition, radioactivated nuclides by (n,γ) reaction either in structural or fuel elements emit electron-antineutrinos by the $\beta^-$ decay. The electron -antineutrinos from these elements have much lower fluxes than those from FPs, and they can be ignored. Electron-neutrinos from the $\beta^+$ decay or E.C. of FPs are considered to have a lower yield than electron -antineutrinos, because the fission yield of those unstable nuclides are very small of the order of $10^{-7}$ [fission$^{-1}$]. In contrast, electron-neutrinos are generated from $\beta^+$ decay and E.C. of nuclides produced by (n,2n) reactions in the structural elements, and their neutrinos spectra are not supposed to be ignored in calculation.

For these reasons, in the study, we computed two types of neutrino spectra. One is electron-antineutrino and -neutrino spectrum from the $\beta^-$ decay of FPs, and the other is electron-neutrino one from the $\beta^+$ decay and E.C. of FPs and structural elements.

## 2 Neutrino Spectra by Decay of FP

Neutrinos that are emitted from the β decay of FPs have continuous energy spectra. The energy sum of β-ray and electron-antineutrino or -neutrino is conserved, so that the neutrino energy $E_\nu$ is given by subtraction of β-ray energy $E_\beta$ from the maximum β-ray energy $E_{\beta MAX}$ :

$$E_\nu = E_{\beta MAX} - E_\beta \,. \tag{3}$$

Electron-neutrinos are emitted through E.C. as

$$X_N^A + e^- \to X'^A_{N-1} + \nu_e \,. \tag{4}$$

The electron-neutrinos from E.C. have monochromatic energy of

$$E_\nu = Q - 2m_0c^2 \,, \tag{5}$$

where $Q$ is the $Q$ value of the decay and $m_0$ the mass of electron.

The neutrino energy spectrum is obtained from the β-ray spectrum and the $Q$ value using Eqs. (3) and (5). For obtaining β-ray spectra theoretically, we should usually make the calculation by the β decay theory. Because hundreds of FPs nuclides are present in a reactor, the calculation requires a great number of detailed information on these FPs[7]. In this study, we simply use the β-ray spectra and $Q$ value of β transition in JENDL-FP-Decay-Data-File-2000. Then the neutrino and anti-neutrino energy spectra from FPs are calculated by Eqs. (3) and (5).

Calculating neutrino spectra in a nuclear reactor needs summation of neutrino spectra from all FP nuclides. Since the amount of yielded and decayed FPs are readily balanced, neutrino spectrum from FPs of a fissionable nuclide $S_{fission}$ is written as

$$S_{fission}(E) = \sum_{FP} Y_{fp} S_{fp}(E), \tag{6}$$

where $Y_{fp}$ is the fission yield of FPs.

In LWR, the main fissionable nuclides to yield FPs are $^{235}$U, $^{238}$U, $^{239}$Pu and $^{241}$Pu. We calculated the neutrino spectra for these nuclides. For $Y_{fp}$ in Eq. (6), we used the cumulative FP yield data for thermal neutrons (0.025 eV) in JENDL-3.3 except $^{238}$U. For $^{238}$U, we utilized the fission yield for neutron energy of 1 MeV.

The burning in LWR gives a typical fission fraction of individual fissionable nuclides as follows[8]:

$$\begin{aligned} &^{235}U_{fission}: 58\%, \quad ^{239}Pu_{fission}: 30\%, \\ &^{238}U_{fission}: 7\%, \quad ^{241}Pu_{fission}: 5\%. \end{aligned} \tag{7}$$

The neutrino spectra from reactors caused by FPs are obtained by summing individual spectra $S_{fission}$ multiplied by the fraction in Eq. (7)

## 3 Electron-Neutrino Spectra Caused by Structural Elements

A LWR consists of constituents such as a pressure vessel, control rods, coolants, and cladding tubes. The constituents are exposed to a high neutron flux of the order of $10^{13}$ [cm$^{-2}$s$^{-1}$] [9]. The $^{A}$X(n,2n)$^{A-1}$X reaction is produced by neutrons. Nuclides $^{A-1}$X generated by this reaction often emit electron-neutrinos by the $\beta^+$ decay. The (n,2n) reaction has energy thresholds of 6~14 MeV for structural elements [2]. Because neutrons emitted from fission are quickly moderated to thermal neutrons, the most of (n,2n) reactions take place near the fuel. To compute the electron-neutrino spectra, we considered the (n,2n) reaction at cladding tubes, fuel pellets and coolant. The number of atoms of coolant was estimated in the region around cladding tubes. Since most of the (n,2n) reaction takes place in this region, coolant outside the core was not considered.

For LWR such as boiling water reactor (BWR) and pressurized water reactor (PWR), the typical size of a pellet and a cladding tube are listed in **Table 1**, and the composition and density are shown in **Table 2**.

**Table 1** Typical sizes of a cladding tube and pellet.

| | | BWR | PWR |
|---|---|---|---|
| Cladding tube | Outside radius [mm] | 12.5 | 9.5 |
| | Thickness [mm] | 0.863 | 0.572 |
| | Tube distance [mm] | 16.25 | 12.6 |
| Pellet | Radius [mm] | 10.56 | 8.19 |

**Table 2** Composition and density of cladding tube and pellet.

| | Element | BWR | PWR |
|---|---|---|---|
| | | Zircaloy-2 | Zircaloy-4 |
| Cladding tube Composition [Weight%] | Sn | 1.5 | |
| | Ni | 0.05 | 0.00 |
| | Cr | 0.1 | 0.1 |
| | Fe | 0.12 | 0.21 |
| | Zr | 98.23 | 98.52 |
| Tube density [g/cm$^3$] | | 6.5 | |
| Pellet [Weight %] | U | 88.15 | |
| | O | 11.85 | |
| Pellet density [g/cm$^3$] | | 10.96 | |

The size, density and the composition of a cladding tube and fuel pellet give the number ratio $R_N$ of $^{A}X$ to $^{235}U$ as

$$R_N = N_X/N_U, \tag{8}$$

where $N_X$ and $N_U$ are the number of $^{A}X$ and $^{235}U$ nuclides per unit length, respectively. A value $R_S$ is defined as

$$R_\sigma = \sigma_X/\sigma_U, \tag{9}$$

where $\sigma_X$ is the cross section of the $^{A}X(n,2n)^{A-1}X$ reaction and $\sigma_U$ is that of $^{235}U$ fission. The yield of $^{A-1}X$ per fission of $^{235}U$, $Y_X$, is given as

$$Y_X = R_N \cdot R_\sigma, \tag{10}$$

The spectrum of electron-neutrinos from structural elements is expressed by

$$S_{str}(E)=\sum_X Y_X S_X(E), \tag{11}$$

where $S_X$ is the electron-neutrino spectrum for the decay of radioactive nuclide $^{A-1}X$.

We computed the electron-neutrino spectra by Eq. (11). For cross section in Eq. (9), we took cross sections at 300 K averaged over the neutron spectrum in the reactor[10]. The neutrino energy spectra for O, Fe, Cr and Ni were obtained from theoretical calculation[7] because JENDL-FP-Decay-Data-File-2000 has no data of these light nuclides.

## III Calculation Results

The calculated energy spectrum of electron-antineutrino for $^{235}U$ fission by thermal neutrons is shown in **Fig. 1** by a solid line. Circular marks indicate the antineutrino spectrum[11], which was evaluated from β-ray spectra measured by Feilitzsch *et al.*[11] **Figure 1** also presents the spectrum calculated by Ishimoto *et al.*[7] by a dotted line, which was theoretically evaluated by use of the β decay theory with individual β decay information such as Q values and branching ratios in nuclear data files. In Fig. 1, the present result is in good agreement with other studies. With the same method, we calculated the electron-antineutrino and -neutrino energy spectra $S_{fission}$ for $^{238}U$, $^{239}Pu$, and $^{241}Pu$ fission. The spectra $S_{fission}$ and the fission fraction of Eq. (6) gave neutrino spectra for LWR as shown in **Figs. 2** and **3**. The electron-antineutrino spectrum is plotted by a bold solid line. In Fig. 2, experimental spectrum by Kopeikin *et al.*[8] is plotted by the dash-dotted line which was obtained from measurement of the neutrino spectrum above 2 MeV, and from summation of the allowed β decays of all FPs below

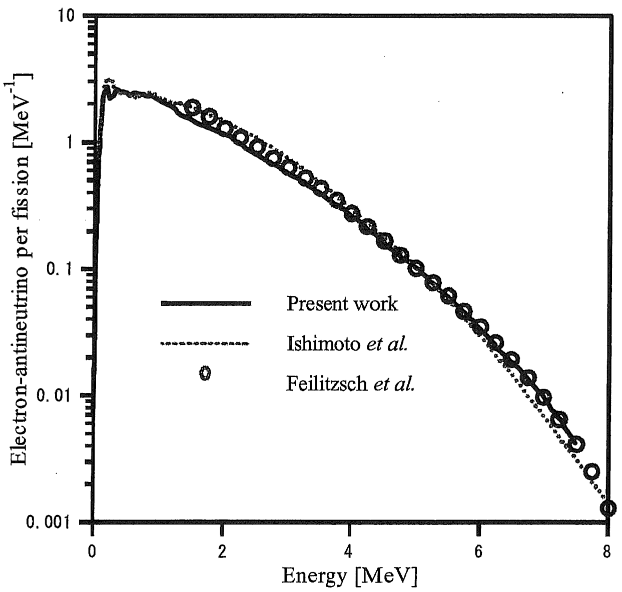


**Fig. 1** Electron-antineutrino spectra for $^{235}U$ fission

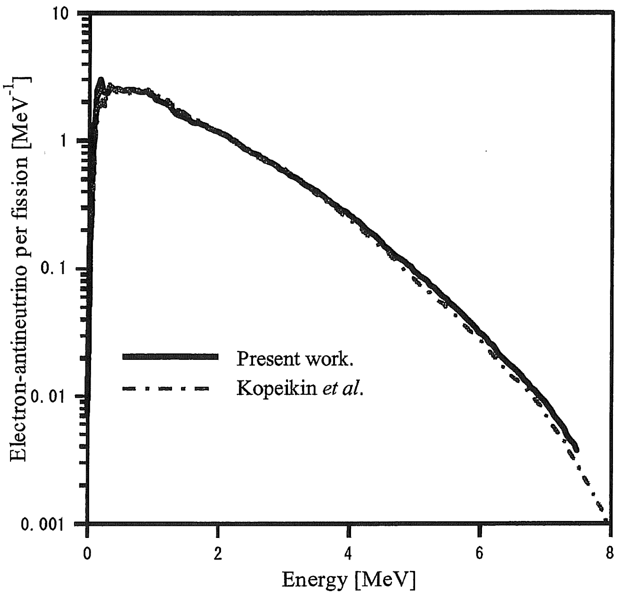


**Fig. 2** Electron-antineutrino spectra from LWR.

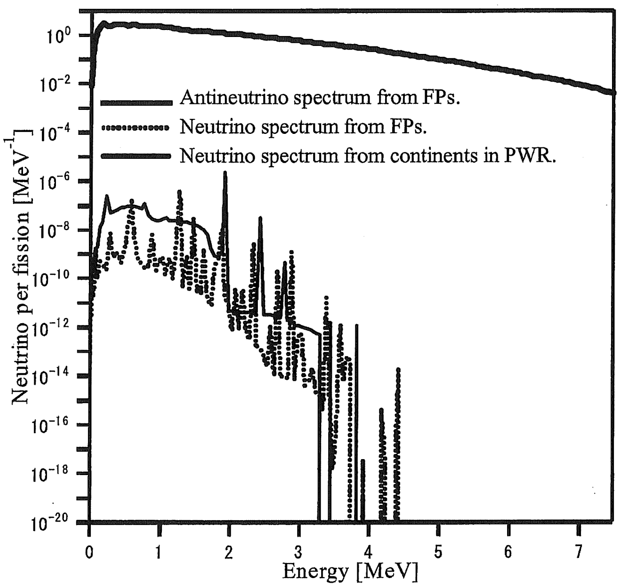


**Fig.3** Neutrino spectra from FPs and constituents elements in a LWR.

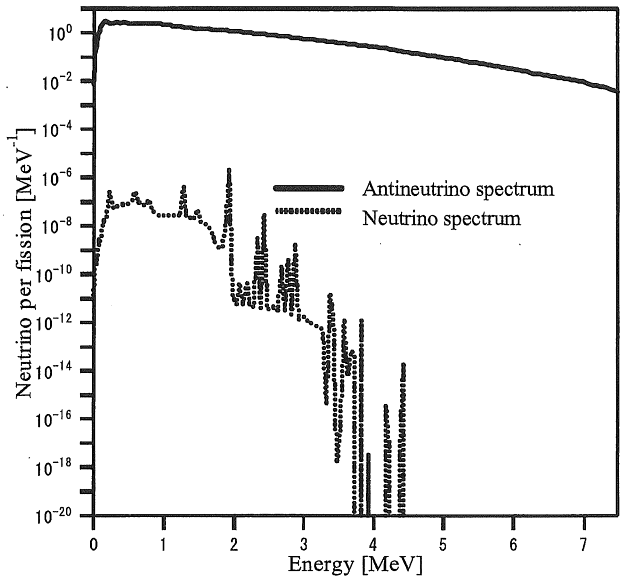


**Fig. 4** Neutrino spectra from PWR.

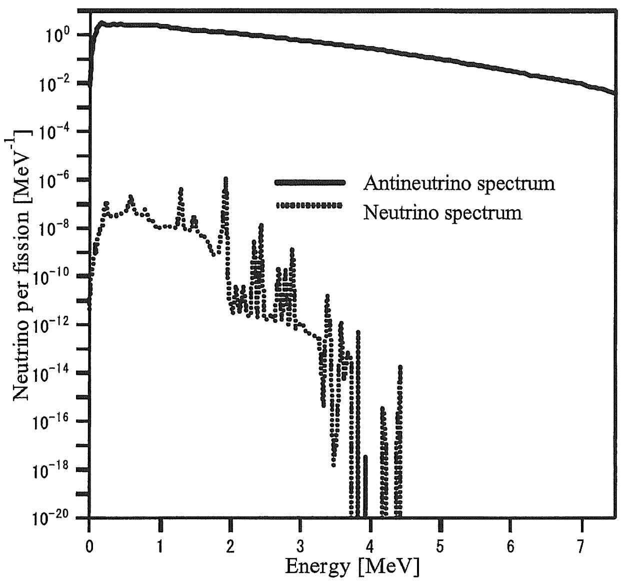


**Fig. 5** Neutrino spectra from BWR

2 MeV by Vogel *et al.*[12] The spectrum that we calculated is in good agreement with other studies. The agreement in Figs. 1 and 2 between the present calculation and measured spectra shows the validity of β-ray spectra of nuclear data files. In Fig. 3, the electron-neutrino spectrum is drawn by a dotted line. Sharp peaks in this spectrum are ascribed to monochromatic neutrinos from E.C. The electron-neutrino energy spectra from constituents for PWR and BWR were calculated by Eq. (3). The neutrino spectra from PWR are shown in Fig. 3 by a solid line. **Figure 3** indicates that most of the electron-neutrinos from reactors are produced by the $\beta^+$ decay and E.C. of constituents.

The total neutrino spectra from PWR are shown in **Fig. 4** and that from BWR are presented in **Fig. 5**. One can see from these figures that the electron-neutrino's energy from LWR is lower than 4 MeV, and that the intensity is lower than electron-antineutrino's one by about seven orders of magnitude. For a reactor of 3 GWt, the electron-neutrino flux is estimated to be about $10^5$ [cm$^{-2}$s$^{-1}$] at location 25 m apart from the core. The electron-neutrino flux from $\beta^+$ decay of $^8$B in the sun is $10^6$ [cm$^{-2}$s$^{-1}$] in the energy range of 0.5~8 MeV on the ground[3, 13]. The electron-neutrinos from LWR are in a similar level to that from the sun.

## IV Conclusions

We calculated electron-antineutrino and -neutrino spectra for BWR and PWR by a simple method on the basis of the nuclear data files. The computed electron-antineutrino spectrum from $^{235}$U fission is in good agreement with experimental data and other calculated spectra. The agreement shows the validity of β-ray spectra of nuclear data files. We computed the neutrino spectra from $\beta^+$ decays and E.C of radioactive structural elements. These neutrino fluxes are lower by about seven orders of magnitude than those of antineutrinos.


## Acknowledgement

The authors are grateful to staff of JAERI for supplying us the code to treat JENDL-FP-Decay-Data-File-2000 and advising for treatment of the code.


## References


1) J. Katakura, T. Yoshida, K. Oyamatsu, T. Tachibana: "JENDL FP Decay Data File2000," *JAERI* **1343** (2001).
2) K. Shibata, T. Kawano, *et al., J. Nucl. Sci. Technol.* **39**, 1125 (2002).
3) J. N. Bahcall, *Nucl. Phys. B (Proc. Suppl.)*, **77**, 64-72 (1999).
4) A. Piepke, *Nucl. Phys.* B (Proc. Suppl.), **91**, 90(2001).
5) M. Apollonio, A. Baldini, C. Bemporad, *et al., Phys. Lett. B*, **420**, 397 (1998).
6) B. Achkar, R. Aleksan, M. Avenier, *et al., Phys. Lett. B*, **374**, 243 (1996).
7) S. Ishimoto, T. Omori, H. Arima, K. Ishibashi, *J. Nucl. Sci. Tec.* **39**-6, 670-672 (2002).
8) V. I. Kopeikin, *Phys. Atom. Nucl.* **66**, 472-475 (2003).
9) L. A. Khan, N. Ahmad, M. S. Zafar, A. Ahmad, *Ann. Nucl. Energy* **27**, 873-885, (2000).
10) T. Nakagawa, "Curves and tables of neutron cross sections of fission product nuclei in JENDL-3", JAERI-M 92-077 (1992).
11) E. von Feilitzsch, A.A. Hahn. K. Shreckenbach, *Phys. Lett. B.* **118**, 162 (1982).
12) P. Vogel, J. Engel. *Phys. Rev. D* **29**, 3378 (1989).
13) J. N. Bahcall, "Observational Neutrino Astrophysics", Talk given at the David N. Schramm Memorial Symposium, *Inner Space/Outer Space II*, May 26-29, *Fermi National Accelerator Laboratory*. (1999).