Neutrino Energy Spectra from Nuclear Reactors  
Calculated from Nuclear Data Libraries  

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Abstract. Nuclear reactors generate a highly intense flux of electron-antineutrinos from fission products through $\beta^-$ decay, and produce a slight number of electron-neutrinos through either $\beta^+$ decay or electron capture. Neutrino energy spectra are usually calculated by the $\beta$ decay theory. Since the reactor neutrinos are emitted from a great number of fission products, the calculation requires many level schemes 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).  

In this study, 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 for estimating the reactor neutrino spectra without complicated computation.  

INTRODUCTION  

In nature, there exist a great number of neutrinos, and their fluxes are $10^{11}$ to $10^{12}$ [s$^{-1}$cm$^{-2}$] [1]. The neutrino measurement and evaluation may become useful in engineering fields in the future.  

Neutrinos have no electric charge and make only a weak interaction with very small cross sections. It is an important theme to experimentally prove whether or not the neutrino is massless. 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 in search of neutrino oscillations as in KamLAND [2], Chooze [3], and Burgey [4]. The spectra of neutrinos are required for these experiments.  

The neutrinos are emitted from reactors by $\beta$ transition of fission products (FPs). The $\beta$ transitions generate radiations of either antineutrinos or neutrinos together with $\beta$-rays of electrons or positrons. 

$$^{\hat{A}}X \rightarrow ^{\hat{A}}X' + e^- + \bar{\nu}_e,$$  

(1) 

$$^{\hat{A}}X \rightarrow ^{\hat{A}}X' + e^+ + \nu_e.$$  

(2) 

These neutrinos have continuous energy spectra. To obtain these spectra theoretically, we should make the calculation by the $\beta$ decay theory with information on a level scheme of a great number of nuclides [5]. Nuclear data files, however, are available these days.  

JENDL-FP-Decay-Data-File-2000 is a data file evaluated in Japan [6]. 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 $\beta^-$, $\gamma$, and $\alpha$-rays. In addition, spectral data on individual radiations including conversion electrons and X-rays are separately given in the file. For computing neutrino spectra, the $\beta$-ray spectra of this data file are usable. Unlike the case of antineutrinos, electron-neutrinos often have mono-chromatic spectra due to electron captures (E.C.). We calculate these spectra with the Q values of E.C. In order to know FP yields in light-water reactors (LWRs), we select cumulative FP yield data in JENDL-3.3 [7]. Use of these spectra and yield data enables us to readily compute the neutrino and antineutrino spectra from a reactor.
NEUTRINO ENERGY SPECTRA

Neutrino Spectra from a Reactor

Electron-antineutrinos from the $\beta^-$ decay of FPs form a major flux of reactor neutrinos. In contrast, electron-neutrinos from the $\beta^+$ decay and E.C. of FPs have much smaller yields than electron-antineutrinos. In fact, the FP yields of these nuclides are as small as the order of $10^{-7}$ [fission$^{-1}$]. Structural and fuel elements are radioactivated by neutron reactions, and the radioactive nuclides either emit neutrinos by the $\beta$ decay or E.C. The neutrino spectra are not supposed to be ignored in the calculation.

In this study, we compute neutrino spectra for a LWR from two types of origins. One is neutrino spectra from the decay of FPs, and the other is from the decay of radioactivated constituent elements.

Neutrino Spectra by Decay of FPs

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

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

Electron-neutrinos are often produced through E.C.:

$$X^+_N + e^- \rightarrow X^+_{N-1} + \nu_e. \tag{4}$$

The neutrinos have a monochromatic energy, being equal to the $Q$ value of decay.

To obtain $\beta$-ray spectra theoretically, we should usually make the calculation by the $\beta$ decay theory. Because hundreds of FP nuclides are present in a reactor, the calculation requires a great number of detailed information on these FPs [5]. In this study, we simply use the $\beta$-ray spectra and $Q$ value of the $\beta$ transition in JENDL-FP-Decay-Data-File-2000. Then the neutrino and antineutrino energy spectra from FPs are calculated by Eq. (3).

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

$$S_{\text{fission}}(E) = \sum_{fp} Y_{fp} S_{\beta}(E), \tag{5}$$

where $Y_{fp}$ is the 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. (5), we used the cumulative FP yield data for thermal neutrons (0.025 eV) in JENDL-3.3 except for the case of $^{238}$U. For $^{235}$U, we simply utilized the fission yield for a fast-neutron energy of 1 MeV. The burning in LWR gives a typical fission fraction of individual fissionable nuclides as follows [8]:

$$^{235}\text{U}_{\text{fission}} : 58\%, \quad ^{239}\text{Pu}_{\text{fission}} : 30\%, \quad ^{238}\text{U}_{\text{fission}} : 7\%, \quad ^{241}\text{Pu}_{\text{fission}} : 5\%. \tag{6}$$

The neutrino spectra from reactors caused by FPs are obtained by summing individual spectra $S_{\text{fission}}$ multiplied by the fraction in Eq. (6).

Neutrino Spectra Generated 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]. These neutrons produce activation reactions such as $(n,\gamma)$, $(n,2n)$, $(n,p)$, and $(n,\alpha)$ with structural elements X. Nuclides generated by these reactions often emit neutrinos by the $\beta^+$ decay or E.C. To compute the neutrino spectra, we considered the activation reactions 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 activation reactions take place in this region, the coolant outside the core was not considered.

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

$$R_N = N_X/N_U, \tag{7}$$

where $N_X$ and $N_U$ are the number of X and $^{235}$U nuclides per unit volume, respectively. A cross section ratio $R_\sigma$ is defined as

$$R_\sigma = \sigma_X/\sigma_U, \tag{8}$$

where $\sigma_X$ is the cross section of the activation reaction and $\sigma_U$ is that of $^{235}$U fission. The yield of
radioactivated nuclide per fission of $^{235}$U, $Y_A$ is given as

$$Y_A = R_{\chi} \cdot R_{\sigma}.$$  \hfill (9)

The spectrum of neutrinos from structural elements $S_{str}$ is expressed by

$$S_{str}(E) = \sum Y_j S_j(E),$$  \hfill (10)

where $S_j$ is the neutrino spectrum for the decay of radioactivated nuclide.

We computed the electron-neutrino spectra by Eq. (10). For $\sigma_X$ in Eq. (8), we took cross sections at 300 K averaged over the neutron spectrum in the reactor [10]. Neutrino spectra of nuclides for which data were not included in JENDL-FP-Decay-Data-File-2000 were obtained from theoretical calculation [5].

**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, which was evaluated from $\beta$-ray spectra measured by Feilitzsch et al. [11] Figure 1 also presents the spectrum calculated by Ishimoto et al. [5] by a dotted line, which was theoretically evaluated by use of the $\beta$ decay theory with individual $\beta$ 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. For $^{235}$U, $^{239}$Pu, and $^{241}$Pu fissions, we calculated the electron-antineutrino and -neutrino energy spectra $S_{\text{fission}}$ with the same method. These spectra $S_{\text{fission}}$ and the fission fraction of Eq. (5) gave neutrino spectra for LWR in Fig. 2. The electron-antineutrino spectrum is shown by a bold solid line. Kopeikin et al. [8] measured the neutrino spectrum above 2 MeV, and it is plotted by a dash-dotted line. The same line in the region below 2 MeV indicates neutrinos from allowed $\beta$ decays of all FPs by Vogel et al. [12]. The agreement in Figs. 1 and 2 between the present calculation and measured spectra shows the validity of $\beta$-ray spectra of nuclear data files. Figures 3 and 4 show spectra of electron-antineutrinos and -neutinos, respectively. Solid lines indicate neutrinos from FPs, while dashed ones stand for those from constituents. Sharp peaks in Fig. 4 are ascribed to the monochromatic neutrinos from E.C. One can see in Fig. 4 that most of the electron-neutrinos from reactors are produced by the $\beta^+$ decay and E.C. of constituents. The total neutrino spectra from LWR are shown in Fig. 5. The electron-neutrinos from LWR have energies below 4 MeV, and their intensity is lower than the electron-antineutrino by about five orders of magnitude. For a typical reactor of 3 GWt, the electron-neutrino flux is estimated to be about $10^7$ [cm$^{-2}$s$^{-1}$] at a 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 [1,13]. The flux of electron-neutrinos from LWR is at a similar level to that from the sun.
CONCLUSIONS

We calculated electron-antineutrino and -neutrino spectra for LWR by a simple method on the basis of the nuclear data files. The computed electron-antineutrino spectra from $^{235}$U fission as well as light water reactor were in good agreement with experimental data. The agreement shows the validity of $\beta$-ray spectra of the nuclear data files. We calculated the neutrino spectra from $\beta^-$ decays and E.C. of radioactive structural elements. The neutrino flux is lower by about five orders of magnitudes than that of antineutrinos.

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