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Composition, decomposition and analysis of reactor antineutrino and electron spectra based on gross theory of β-decay and summation method

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ABSTRACT

We applied the gross theory of β-decay to compose and decompose the reactor electron and antineutrino spectra emitted from ^{235,238}U and ^{239,241}Pu by summing up all the contributions from a large number of decaying fission-products (FPs). We make it clear what kinds of transition types and FP nuclides are important to shape the lepton spectra. Important role of the odd(Z)-odd(N) nuclides is also argued from the view point of the gross theory of β-decay. After taking the ambiguity in the current data for fission yields and Q_β-values into account, we suggested a possibility that the high-energy part of the widely referred electron-spectra by Schreckenbach et al. might be too low. Our calculation supports the old experiment at University of Illinois.

1. Introduction

Recently increasing attention is paid to the technology of antineutrino-based monitoring of nuclear-reactor operation from the outside for non-proliferation purposes (Bernstein et al., 2008; Christensen et al., 2014). Precise determination of the antineutrino energy-spectra is one of the key issues there. Reliable knowledge of the reactor antineutrino spectra is also required for interpreting the neutrino oscillation experiments for basic research of physics (Gando et al., 2011; Abe et al., 2012), especially in the quest for *sterile neutrino* (Mention et al., 2011; Abazajian et al., 2012). One way to achieve this is to convert the measured electron spectra from fissionable samples into the antineutrino spectra using the energy conservation of leptons in the β-decay process. Another is to compose the spectrum by summing up all the contributions from a large number of decaying fission products (FPs). Even in the former method, information obtained from the systematic study based on the latter procedure is very useful and instructive.

In order to describe the aggregate behavior of FPs in a reactor core, we start with the calculation of the number density of each FP nuclide one by one considering its creation and destruction. By summing up the contributions from all the nuclides, we can calculate such important quantities as the FP decay heat, the delayed-neutron emission rate and also the antineutrino spectrum. This method, known as the summation calculation, was first applied to reactor-antineutrino energy spectra by Davis et al. (Davis et al., 1979) and Avignone et al. (Avignone et al., 1979). Summation method was also utilized during the process of obtaining the antineutrino spectra from the measured electron spectra in a precise way (Mueller et al., 2011) and has been revisited then in (Fallot et al., 2012; Sonzogni et al., 2015). Our present approach is to fully employ the generation 2 (Tachibana et al., 1990) of the gross theory of β-decay (Takahashi and Yamada, 1969) to the reactor antineutrino problem which has been successfully applied to predict and understand the aggregate behavior of the FPs in reactor cores, *e.g.*, the FP decay heat (Yoshida and Nakasima, 1981). Our methodology is independent of and complementary to the summation

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calculations based on the experimental decay data which may possibly be deficient, incomplete and/or suffering from the so-called 'pandemonium' problem (Hardy et al., 1977; Dimitriou and Nichols, 2015) in the far-off stability region of nuclides. Historically, there was a pioneering work in which Klapdor and Metzinger tried full use of a nuclear theory (QPRA method) in the reactor antineutrino-spectrum calculation (Klapdor and Metzinger, 1982), but it seems to be difficult to reproduce their results now because of unavailability the detailed documentation for it. In our case, the gross theory, the full description of which has already been published, is expected to provide us with a long-standing calculation basis independent of all the other method in predicting the reactor antineutrino spectra.

In Section 2 we describe the method of calculating the electron (more specifically, the β-particle) and the antineutrino spectra, and compare them with the measured and the converted spectra, respectively. Section 3 is devoted to analyze these spectra for the purpose of the improvement of the prediction accuracy of the reactor antineutrino spectra. Section 4 deals with a disagreement seen in the very high energy part of the antineutrino and the electron spectra. Section 5 concludes the paper.

2. Composition of electron and antineutrino spectra

2.1. Summation calculation of spectra

In the summation method, the aggregate electron- and antineutrino-spectra are written as a sum of the contributions from all the decaying FPs, namely,

$$I_e(E_e) = \sum N_i \lambda_i I_i^e(E_e) \tag{1}$$

$$I_{\overline{\nu}}(E_{\overline{\nu}}) = \sum N_i \lambda_i I_i^{\overline{\nu}}(E_{\overline{\nu}}), \tag{2}$$

where N_i and λ_i are the number density and the decay constant of the i-th FP. The point is how to obtain the spectra, $I_i^e(E_e)$ and $I_i^{\overline{\nu}}(E_{\overline{\nu}})$, characteristic of each nuclide i. Here E_e and $E_{\overline{\nu}}$ are the kinetic energies of the electron and the antineutrino.

2.2. Gross theory calculation

The electron spectrum of the i-th nuclide $I_i^e(E_e)$ (hereafter we drop the nuclide-index i for simplicity) is written by using the strength function of β-decay as,

$$I^e(E_e) = \frac{1}{D}\int_0^{Q_\beta - E_e}\left[\sum_\Omega G_\Omega^2 \left|M_\Omega(E_{\rm exc})\right|^2 F(Z,E) S_\Omega(Z,p)\right](Q_\beta - E_{\rm exc} - E_e)^2 pE dE_{\rm exc}, \tag{3}$$

where D is the normalization denominator introduced so as to give one electron per decay, namely, $\int_0^{Q_\beta} I^e(E_e)dE_e = 1.0$. Symbols G_Ω and $\left|M_\Omega(E_{\rm exc})\right|^2$ stand for the coupling constants and the strength functions, respectively, of type-Ω transition, which covers the Fermi, the Gamow-Teller, and the first-forbidden transitions. The variable E_e is the electron kinetic energy, $E\ (= E_e + mc^2)$ the electron total energy, $E_{\rm exc}$ the excitation energy of the daughter nucleus, p the momentum of the electron, m its rest mass, Q_β the Q-value of the β-decay in question. Symbols F and S_Ω indicate the Fermi function and the shape factor of the Ω-type transition, respectively.

The strength function $\left|M_\Omega(E_{\rm exc})\right|^2$ is essentially the absolute square of the transition matrix element multiplied by the final level-densities expressed as a continuous function of the excitation energy of the daughter nucleus $E_{\rm exc}$. For the calculation of $\left|M_\Omega(E_{\rm exc})\right|^2$, we fully utilize the gross theory of β-decay which was originally developed by Yamada and Takahashi (Takahashi and Yamada, 1969; Koyama et al., 1970; Takahashi, 1971). This theory was improved to take into account, on an average, the *UV*-factors of the BCS theory (Kondoh et al., 1985). Furthermore, the one-particle strength function of the model was modified to have a large peak corresponding to the giant resonance and a distribution spreading widely with a long tail. For this purpose, a modified-Lorentzian + Hyperbolic-secant type function is adopted (Tachibana et al., 1990). We call this modified model the 2nd generation of the gross theory which will be referred to as 'GT2' hereafter. By using GT2, the electron spectra is given as,

$$\begin{aligned} I^e(E_e) = \frac{1}{D}\int_0^{Q_\beta - E_e} \Bigg[& \left\{G_{\rm V}^2\left|M_{\rm F}(E_{\rm exc})\right|^2 + 3G_{\rm A}^2\left|M_{\rm GT}(E_{\rm exc})\right|^2\right\}F(Z,E) \\ & + \frac{3G_{\rm V}^2}{(\hbar/m_e c)^2}\left|M_{1\rm A}(E_{\rm exc})\right|^2 F_0 S_{10\rm A}(Z,p) \\ & + \frac{3}{(\hbar/m_e c)^2}\left\{G_{\rm V}^2\left|M_{1\rm V}(E_{\rm exc})\right|^2 F_0 S_{11\rm V}(Z,p) + 2G_{\rm A}^2\left|M_{1\rm A}(E_{\rm exc})\right|^2 F_0 S_{11\rm A}(Z,p)\right\} \\ & + \frac{20G_{\rm A}^2}{(\hbar/m_e c)^2}\left|M_{1\rm A}(E_{\rm exc})\right|^2 F_0 S_{12\rm A}(Z,p)\Bigg](Q - E_{\rm exc} - E_e)^2 pE dE_{\rm exc}. \end{aligned} \tag{4}$$