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Antineutrino flux and spectrum calculation for spent nuclear fuel for the Daya Bay antineutrino experiment

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Abstract

The antineutrino flux from spent nuclear fuel (SNF) is an important source of uncertainty when making estimates of a reactor neutrino flux. However, to determine the contribution from SNF, sufficient data is needed such as the amount of spent fuel in the pool, the time after discharged from the reactor core, the burnup of each assembly, and the antineutrino spectrum of each isotope in the SNF. A method to calculate this contribution is proposed. A reactor simulation code verified against experimental data has been used to simulate fuel depletion by taking into account more than 2000 isotopes and fission products, the quantity of SNF in each of the six spent fuel pools, and the time variation of the antineutrino spectra after SNF discharging from the core. Results show that the SNF contribution to the total antineutrino flux is about 0.26%–0.34%, and the shutdown impact is about 20%. The SNF spectrum alters the softer part of the antineutrino spectra, and the maximum contribution from the SNF is about 3.0%. Nevertheless, there is an 18% difference between the line evaluate method and under evaluate method. In addition, non-equilibrium effects are also discussed, and the results are compatible considering the uncertainties.

Keywords: Reactor neutrino experiment; Uncertainties analysis; Spent fuel

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1. Introduction

Reactor antineutrinos are used in the study of neutrino oscillations and in the search for signatures of nonstandard neutrino interactions, as well as to monitor reactor conditions to safeguard operations. Antineutrino flux is an important source of uncertainty associated with measurements in reactor neutrino experiments. The time dependence of the antineutrino flux and spectrum of $\bar{\nu}_e$ from a reactor can be estimated using

$$\frac{d^2N(E,t)}{dEdt} = \sum_i \frac{W_{th}(t)}{\sum_j f_j(t)e_j} f_i(t)S_i(E)c_i^{ne}(E,t) + S_{SNF}(E,t), \tag{1}$$

where $W_{th}(t)$ is the reactor thermal power, $f_i(t)$ the fission fraction associated with each isotope, e_i the thermal energy release per fission for each isotope, $S_i(E)$ a function of the $\bar{\nu}_e$ energy E signifying the $\bar{\nu}_e$ yield per fission for each isotope, $c_i^{ne}(E,t)$ the non-equilibrium correction of the long-live fission fragment isotopes, and $S_{SNF}(E,t)$ the yield from the spent nuclear fuel (SNF). As a result, the antineutrino flux from the SNF and spectra from all its isotopes must be estimated more accurately to provide a precise estimate of the total antineutrino flux and energy spectrum. Antineutrinos emitted from the SNF contribute to the soft part of the energy spectrum [1] and introduce a non-negligible systematic uncertainty. Hence study was performed on the impact of the SNF on θ_{13} sensitivity for the Daya Bay antineutrino experiment [2].

In the range of 1.8–4.0 MeV, the contribution of the rate of antineutrino events from SNF was assessed [3] to be above 4%. This event rate differed largely from previous results [2] of below 0.2%.

However, the purpose of this study was to calculate the SNF rate and spectrum more precisely. Determining the contribution of SNF precisely is difficult because much data including the number of assemblies in each of the SNF pools, the amount of burnup in each assembly, the rate of discharge from each core, the antineutrino spectrum of each isotope, and accurate simulation data for each assembly, are needed. Previously, a simple model [3] was used to simulate fuel depletion in the reactor but did not consider the variation in neutron flux during reactor operation.

A method to calculate the SNF antineutrino rate and spectrum is proposed. In this method, a reactor simulation code verified using experimental data is used to simulate fuel depletion by taking into account more than 2000 isotopes and fission products, the amount of SNF in each of the storage pools, and the time variation of the antineutrino spectrum for SNF after each core discharge. The SNF rate is about 0.3% and the shutdown impact is found to be about 20%.

2. Neutrino spectrum after shutdown for one batch

The Daya Bay reactor is a pressurized water reactor (PWR) that uses 175 fuel assemblies in the core. At the end of an equilibrium cycle, about one third of the fuel is removed from the reactor core and sent to one of six SNF storage pools. The antineutrino spectrum of the SNF is calculated using

$$\rho_m^r(E_\nu,t) = \sum_i A_i(t)\rho_i(E_\nu), \tag{2}$$

where $\rho(E_\nu,t)$ is the total normalized antineutrino spectrum of the SNF of reactor number r and batch number m at time t; $A_i(t)$ and $\rho_i(E_\nu)$ are the activity and the normalized antineutrino spectrum of isotope i.

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