Investigation of antineutrino spectral anomaly with neutron spectrum

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Abstract

Recently, three successful antineutrino experiments (Daya Bay, Double Chooz, and RENO) measured the neutrino mixing angle $\theta_{13}$ using nuclear reactor power plant. However, significant discrepancies were found, both in the absolute flux and spectral shape. In reactor, the neutron have many kinds of energy, and different neutron energy will cause different fission yield. Different fission yield may be the reason for the antineutrino spectrum discrepancies. In this study, neutron spectrum has been expended investigating the possible reasons for the discrepancies. We found that there are no obvious excess from 5 $\sim$ 7 MeV for these isotopes. However, the neutron flux will make the antineutron spectrum decrease in the 7 $\sim$ 8 MeV, and therefore, it will affect the distribution of the antineutrino spectrum, especially at the high energy region.

Keywords: reactor neutrino experiment, uncertainties analysis, fission fraction, spectral anomaly

1. Introduction

Recently, three successful antineutrino experiments (Daya Bay, Double Chooz, and RENO) measured the neutrino mixing angle $\theta_{13}$; however, significant discrepancies were found, both in the absolute flux and spectral shape. The discrepancies of the absolute flux was called "reactor neutrino ...
anomaly”, which first appeared in a publication by Mention et al. [4]. For the antineutrino spectral shape, a 2.9σ deviation was found in the measured inverse beta decay position energy spectrum compared to predictions. In particular, an excess of events at energies of 4 – 6 MeV was found in the measured spectrum [5, 6, 7], with a local significance of 4.4σ. These results have brought home the notion that neutrino fluxes are not as well understood as had been thought. At present, it is not clear what physical processes give rise to the neutrino spectra bump. Much effort has been focused on the reactor antineutrino anomaly, which arose from improved calculations of the antineutrino spectra derived from a combination of information from nuclear databases with reference β spectra [8, 9, 10, 11]. In general, there are two approaches which were applied to estimate antineutrino spectral. One is called ”β− conversion”. The energy spectra of the β− from beta decay were measured to estimate the corresponding ν_e emission for the fissile isotopes 235U, 239Pu, 241Pu from ILL reactor in the 1980s [9, 10, 11]. More recently, a similar measurement was made for 238U [12]. For a single measured β− decay spectrum, the corresponding ν_e spectrum can be predicted with high precision. An other method was called ”ab initio method”. Using the measured β− decay parameters and fission yields of the nuclear library, the antineutrino spectra of each isotopes can be evaluated by summing each measured β− spectra of the fission daughters [13, 14, 15]. This introduces uncertainties of a few percent in the corresponding predictions of such calculation.

In this study, we discuss an calculation of ν_e spectrum from the updated nuclear structure data JENDL3.1 library, which combined the nuclear data from JENDL3.1 library [16] and JEFF4.0 library [17]. Beside the nuclear structure data library, the fission yield of each isotopes are also needed. The fission yield data are taken from ENDF/B-VII.1 library. The ab initio approach was applied and more than 1100 isotopes nuclear data were used which cause large uncertainties. Despite these uncertainties, we find that ab initio calculation predicting an excess ν_e’s with E_{ν_e} = 5-7 MeV relative to the β− conversion method. We also find that the beta n and beta α decay mode are important for the bump in the energy of 5-7 MeV.

2. Neutron spectrum

The Daya Bay nuclear power complex is situated at Daya Bay in southern China, approximately 55 kilometers northeast of Hong Kong. The Daya Bay use the French Framatome Advanced Nuclear Power 990 MW_e (electric
power) three cooling design. There are 157 fuel assemblies in the reactor core and each assembly is a $17 \times 17$ design, a total of 289 fuel rods. The enrichment of $^{235}\text{U}$ in the fuel for one and half year refueling cycle is 4.45%. There are many kind of neutron with different energy in the reactor core, and the neutron spectra for Pressure Water Reactor (PWR), Sodium Fast Reactor (SFR) and Lead cooled Fast Reactor (LFR) are shown in Fig. 1. It can be seen that most neutrons have high energy in sodium fast reactor and lead cooled fast reactor. However, there are also many fast neutrons in the Pressure Water Reactor which come from fission. The fission in the PWR core manly come from four isotopes, $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$ and $^{241}\text{Pu}$, and the total fission fraction of the four isotopes is more than 99%. At the same time, the total fission fraction of $^{235}\text{U}$, and $^{239}\text{Pu}$ is usually more than 80%. The fission yields will be different because of different neutron energy induced fission. The difference of thermal and fast neutron for $^{235}\text{U}$ and $^{239}\text{Pu}$ are shown in Fig.2 and Fig.3. It can be seen that the difference appears at the atomic number from 105 to 130, and the trend of $^{235}\text{U}$ is the same as $^{239}\text{Pu}$.

3. Calculation of isotope antineutrino spectrum

The \textit{ab initio} method of calculating the isotope antineutrino spectrum that presented in Refs.[13,16,17]. For a system in equilibrium, the total
Fig. 2: Comparing cumulative fission yield difference with thermal and fast neutron for $^{235}\text{U}$

Fig. 3: Comparing cumulative fission yield difference with thermal and fast neutron for $^{239}\text{Pu}$
The antineutrino spectra is given by

\[ S(E_\bar{\nu}) = \sum_{i=1}^{N} Y_i \sum_{j=1}^{M} f_{ij} S_{ij}(E_\bar{\nu}) \]  

(1)

where \( Y_i \) is the cumulative fission yield and \( f_{ij} \) is the branching ratio to the daughter level with energy \( E_e \) and \( S_{ij}(E_\bar{\nu}) \) is the antineutrino spectra for a single transition with endpoint energy \( E_\bar{\nu} = E_0 - E_e \). The beta-decay spectrum \( S_{ij}(E_\bar{\nu}) \) for a single transition in nucleus \((Z,A)\) with end-point energy \( E_0 \) is

\[ S(E_e, Z, A) = S_0(E_e) F(E_e, Z, A) C(E_e) [1 + \delta(E_e, Z, A)] \]  

(2)

where \( S_0(E_e) = G_F^2 p_e E_e (E_0 - E_e) / 2\pi^3 \), \( E_e(p_e) \) is the electron total energy (momentum), \( F(E_e, Z, A) \) is the Fermi function needed to account for the Coulomb interaction of the outgoing electron with the charge of the daughter nucleus, and \( C(E_e) \) is a shape factor for forbidden transitions due to additional lepton momentum terms. For allowed transitions \( C(E_e) = 1 \). The term \( \delta(E_e, Z, A) \) represents fractional corrections to the spectrum. The primary corrections to beta decay are radiative \( \delta_{rad} \), finite size \( \delta_{FS} \), and weak magnetism \( \delta_{WM} \). In the present work, the cumulative fission yields are taken from the ENDF/B-VII.1 library\[18\]. The decay data are mainly taken from an version of JENDL-3.1\[16\]. However some important isotopes which are important for the bump and is not included in the JENDL-3.1 are taken from JEFF-3.1\[17\].

4. Average cumulative fission yield calculation method

Fission products yield libraries based on evaluated nuclear data in the endf-6 format can be compiled for particular regions of a core with a local neutron spectrum or an entire core with an average neutron spectrum. Data on the yield of the \( i \)th fission products \( FP_i(E_k) \) for a prescribed neutron energy range \( E_k \) are chosen for each actinide from a base set. The total number of nuclide- fission products in the initial, standard, nuclear data files- ranges from 800 to 1700. In ENDF/B, the fission products yield is usually presented for the thermal point \( E_1 = 2.53 \times 10^{-8} \text{MeV} \), the average point of the neutron fission spectrum \( E_2 = 0.4 \text{ MeV} \) or \( E_2 = 0.5 \text{ MeV} \), and the energy \( E_{max} \sim 14 \text{ MeV} \). Such a three group representation gives a non-unique representation of the yield in a neutron energy range which is important for the antineutrino
spectrum calculation\textsuperscript{[19]}. In this study, the average cumulative fission products yield in prescribed energy intervals of the spectrum is calculated for a selected nuclide as

\[
<F_P_i> = \sum_k C_k F_P_i(E_k)
\]  

where the coefficients \(C_k\) reflect the distribution of the number of fissions of a prescribed nuclide in the spectrum of the region under study. Here

\[
C_{\text{thermal}} = \frac{\int_{E_1}^{E_{\text{max}}} dE \phi(E) \sigma_f(E)}{\int_{0}^{E_{\text{max}}} dE \phi(E) \sigma_f(E)} 
\]  

\[
C_{\text{fast}} = \frac{\int_{E_1}^{E_{\text{max}}} dE \phi(E) \sigma_f(E)}{\int_{0}^{E_{\text{max}}} dE \phi(E) \sigma_f(E)}
\]

where \(E_1\) is the boundary energy between thermal group neutron and fast group neutron. Using equation (4) and (5), the average fission products yields, equation (3), is written as

\[
<F_P_i> = C_{\text{thermal}} F_P_i(E_1) + C_{\text{fast}} F_P_i(E_2)
\]

In order to calculate the coefficients \(C_{\text{thermal}}\) and \(C_{\text{fast}}\) for each isotopes, the fission fraction of the four isotopes with thermal and fast neutron were calculated for a typical PWR using SCIENCE code system\textsuperscript{[20]}. Fig.4 shows the thermal neutron and fast neutron fission fraction as a function of cycle burnup. It can be seen that the thermal neutron fission fraction is larger than that of fast neutron for the \(^{235}\text{U}, ^{239}\text{Pu}\) and \(^{241}\text{Pu}\), however, for the \(^{238}\text{U}\) the results is on the contrary. According to Fig.4, the average thermal and fast fission fraction and the thermal and fast coefficients were obtained as shown in table \textsuperscript{[1]}. It can be seen that the fast neutron fission yield will have important for the \(^{235}\text{U}\) and \(^{241}\text{Pu}\), and its contribution is about 23.18\% for the \(^{235}\text{U}\). Applying the thermal and fast neutron coefficients, the average fission products yields of \(^{235}\text{U}, ^{239}\text{Pu}\) and \(^{241}\text{Pu}\) were obtained and they were compared with the thermal fission products yields as shown in Fig.5, Fig.6 and Fig.7. It can seen that there are large difference in the atomic number region low, middle and high. However, in these large different region, the fission products yield are always small. In this calculation, we did not take into account with \(^{238}\text{U}\), because its fast neutron coefficients is 100\%, and will not contribution to the bump because of neutron spectrum.
Fig. 4: Thermal and fast neutron fission fraction vs cycle burnup

Table 1: The average fission fraction of the four isotopes(%)

|        | $^{235}$U | $^{238}$U | $^{239}$Pu | $^{241}$Pu |
|--------|-----------|-----------|------------|------------|
| fast   | 13.4      | 7.5       | 2.84       | 0.91       |
| thermal| 44.38     | 0.0       | 26.32      | 4.46       |
| total  | 57.78     | 7.5       | 29.17      | 5.37       |
| $C_{fast}$ | 23.18 | 100.0     | 9.75       | 16.89      |
| $C_{thermal}$ | 76.82 | 0.0       | 90.25      | 83.11      |
Fig. 5: The average fission yield distribution of $^{235}\text{U}$

Fig. 6: The average fission yield distribution of $^{239}\text{Pu}$
5. Bump analysis with neutron spectrum

Recent measurements of the position energy spectra from $\bar{\nu}_e$ inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$) show excess from 4 to 6 MeV, which corresponding to an excess of $\bar{\nu}_e$ spectra from 5 to 7 MeV because of the kinematic relationship $E_{\bar{\nu}_e} \sim E_{e^+} + 0.8$ MeV. Using the average fission yield, the antineutrino spectra of $^{235}\text{U}$, $^{239}\text{Pu}$ and $^{241}\text{Pu}$ were calculated and they were compared with that of thermal neutron fission yield. The spectra ratio of average fission yield to thermal fission yield of $^{235}\text{U}$, $^{239}\text{Pu}$ and $^{241}\text{Pu}$ were shown in Fig. 8, Fig. 9 and Fig. 10, respectively. It can be seen that there are no obvious excess from 5 $\sim$ 7 MeV for these isotopes. However, the ratio of average to thermal of $^{235}\text{U}$ will decrease with antineutrino energy increasing, and the ratio is about 0.925 at energy 8.0 MeV. Therefore, the neutron flux can not be responsibility for the bump, but it will affect the distribution of the antineutrino spectrum, especially at the high energy region.

6. Conclusion

At present, it is not clear what physical processes give rise to the neutrino spectra bump. Much effort has been focused on the reactor antineutrino anomaly, which arose from improved calculations of the antineutrino spectra derived from a combination of information from nuclear databases. In this
Fig. 8: Antineutrino spectrum of $^{235}$U and the average to thermal ratio

Fig. 9: Antineutrino spectrum of $^{239}$Pu and the average to thermal ratio
Fig. 10: Antineutrino spectrum of $^{241}$Pu and the average to thermal ratio

Fig. 11: Total antineutrino spectrum and the ratio of average spectrum to thermal spectrum
study, the question of whether the bump were cause by the neutron spectrum was studied, and the \textit{ab initio} method was applied to calculated the antineutrino spectrum based on the updated nuclear database library. In order to calculate the average fission yield, the fission rate was used as a weight function. It is shown that there are no obvious excess from $5 \sim 7$ MeV for these isotopes and the neutron flux can not be responsibility for the bump. However, the neutron flux will affect the total antineutrino spectrum distribution, especially in the high energy region.

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