Calculation of antineutrino spectrum corrections for sterile neutrino experimental searches

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Abstract. For SOX experiment with intense $^{144}$Ce-$^{144}$Pr source, the antineutrino spectrum from two $^{144}$Pr decay branches should be calculated with high precision. We analyze the factors that affect beta- and antineutrino spectrum and give methods for their calculation.

Introduction
There are discrepancies between the data from recent neutrino experiments and the theoretical expectations. One of such discrepancies is the "reactor anomaly": a deficiency of antineutrino flux of about $5 - 6\%$ at small distances from the reactor [1]. The reactor anomaly could be explained either by lack of accuracy in reactor antineutrino spectra calculation or by manifestation of new physics such as neutrino transitions to sterile states.

Reactor antineutrinos are detected via inverse beta decay (IBD) reaction

$$\bar{\nu}_e + p \rightarrow n + e^+ \quad (1)$$

with threshold $E_{\text{thr}} = 1.806$ MeV. The cross section of (1) could be calculated with 1% accuracy [2]. The experimental cross section values are determined with less precision, mainly due to uncertainties in reactor antineutrino spectrum. For more precise measurements it was proposed to use an intense radioactive source with well known spectrum [3, 4]. The most promising source is $^{144}$Ce-$^{144}$Pr, which is intended to be used in SOX experiment [5].

In $^{144}$Ce-$^{144}$Pr source experiment the actual antineutrino source is $^{144}$Pr: it has two decay branches with endpoint energies greater than the IBD threshold $E_{\text{thr}}$. The first one is a non-unique first-forbidden Gamow–Teller transition $0^- \rightarrow 0^+$ with endpoint energy 2997.5 keV and 97.9% branching. The second one is a unique first-forbidden Gamow–Teller transition $0^- \rightarrow 2^+$ with endpoint energy 2301.0 keV and 1.040% branching.

To find possible effects of new physics in the SOX experiment one needs a precise calculation of the antineutrino spectrum from $^{144}$Pr. Here we estimate the accuracy of electron and antineutrino spectra calculation and discuss the factors that affect these spectra.

Accuracy of beta spectrum calculations
The beta spectrum could be described by equation

$$N(W) = K p^2 (W - W_0)^2 H(W) F(Z, W)L(Z, W)C(Z, W)S(Z, W)G(Z, W)B(W) \quad (2)$$
Here $W$ and $W_0$ are the total electron energy and the endpoint energy in units of $m_e c^2$, $p$ is the electron energy, $K$ is a normalization constant. The antineutrino spectrum is obtained from (2) by replacing $W$ with $W_0 - W$. The factors are [6]:

- shape factor $H(W)$;
- Fermi function $F(Z, W)$;
- electromagnetic finite-size correction $L(Z, W)$;
- weak finite-size corrections $C_V(Z, W)$ (for Fermi transitions), $C_A(Z, W)$ (for Gamow–Teller transitions);
- screening correction $S(Z, W)$;
- radiative corrections $G_{\beta}(Z, W)$ (for electrons), $G_\nu(Z, W)$ (for antineutrinos);
- weak magnetism correction $B(W)$. 

**Figure 1.** Corrections to $\bar{\nu}_e$ spectrum for $^{144}$Pr branch with endpoint energy 2997.5 keV.

**Figure 2.** Corrections to $\bar{\nu}_e$ spectrum for $^{144}$Pr branch with endpoint energy 2301.0 keV.
In forbidden decays, one must take into account the shape factor. For the transitions of our interest, the theoretical shape factor values are [7]:

\[ H(W) = p_e^2 + E_\nu^2 + 2\beta^2 E_\nu E_e \quad (1\text{st forbidden non-unique Gamow–Teller } 0^- \rightarrow 0^+) \]  
\[ H(W) = p_e^2 + E_\nu^2 \quad (1\text{st forbidden unique Gamow–Teller } 0^- \rightarrow 2^+) \]  (3)  

In general, the shape factor depends on the nuclear structure, so the theoretical values are not always reliable. For \(^{144}\text{Ce}\) and \(^{144}\text{Pr}\) the theoretical values differ from experiment, so additional measurements are required [8].

Fermi function describes the effect of Coulomb field of the daughter nucleus on beta particles. The general formula for Fermi function is

\[ F(Z, W) = 4(2pR)^2(\gamma - 1)e^{\alpha Zw/p} \frac{\Gamma(\gamma + i\alpha Zw/p)^2}{\Gamma(2\gamma + 1)^2}. \]  (5)

There are different calculation methods for the gamma function \(\Gamma\) of complex argument that agree with each other within a few % [9, 10, 11]. The most accurate method which gives reliable results for high neutrino energies is given in [11].

The electromagnetic and weak finite-size corrections \(L(Z, W)\) and \(C_A(Z, W)\) are calculated as prescribed in [12]. The correction for screening from atomic electrons \(S(Z, W)\) was taken from [6] (the method is in agreement with [10]). Radiative corrections \(G_\nu(Z, W)\) were calculated by Sirlin [13]. The weak magnetism correction \(B(W)\) depends on the transition type [7]; it is zero for the main decay branch of \(^{144}\text{Pr}\). Figures 1, 2 show the corrections values to antineutrino spectrum for two decay branches of \(^{144}\text{Pr}\).

Conclusion
We discussed the influence of different factors on antineutrino spectrum calculation. The corrections for two decay branches of \(^{144}\text{Pr}\) (with endpoint energies higher than the IBD threshold) are calculated.

Acknowledgments
The work was partially supported by the Russian Foundation for Basic Research under grant 16-02-00616.

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