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Atomic effects in antineutrino spectrum of ^{144}Pr

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Abstract. Pr-144 isotope is one of the most favorable antineutrino sources for short-baseline experiments aimed at sterile neutrino search. These experiments require precise theoretical knowledge of the antineutrino spectrum. We calculate antineutrino spectrum of Pr-144 taking into account various corrections with emphasis on corrections due to atomic effects.

Introduction

Prospective short-baseline neutrino experiments with intense radioactive sources aimed at sterile neutrino searches require precise knowledge of the emitted (anti)neutrino spectrum. One of the most promising antineutrino sources for such experiments (probing $\bar{\nu}_e$ disappearance) is ^{144}Ce-^{144}Pr [1].

Antineutrinos are usually detected via inverse beta decay (IBD) process

$$\bar{\nu}_e + p \rightarrow n + e^+ \tag{1}$$

with a threshold $E_{thr} = 1806$ keV. The cross section of IBD could be calculated with 1% accuracy (see [2] for more details). Since the effect of neutrino oscillations to sterile states is expected to be about several percent, the antineutrino spectrum has to be known with percent accuracy.

Let us now discuss the calculation of ^{144}Ce-^{144}Pr antineutrino spectra. Note that the actual antineutrino source is ^{144}Pr, because it has two decay branches with endpoint energies greater than the IBD threshold E_{thr} (see figure 1). The first (dominant) branch is a non-unique first-forbidden Gamow–Teller transition $0^- \rightarrow 0^+$ with endpoint energy 2998 keV and 97.9% branching ratio. The second one is a unique first-forbidden Gamow–Teller transition $0^- \rightarrow 2^+$ with endpoint energy 2301 keV and 1.04% branching ratio.

Previously we analyzed the accuracy of antineutrino spectrum calculation and presented the influence of several types of effects on the spectrum [3, 4]. A comparison of calculated electron spectrum with experimental data was also made [4, 5]. In this work, we consider additional corrections related to atomic excitations and atomic exchange. In our analysis, only the dominant decay branch of ^{144}Pr is considered.

Beta spectrum calculation

The spectrum of electrons from beta decay can be written in the following form:

$$\begin{aligned} N(E_e) = K p_e (E_e + m_e) (E_e - E_0)^2 F(Z, E_e) H(E_e) C(Z, E_e) \times \\ \times C_{\text{excitation}}(Z, E_e) C_{\text{exchange}}(Z, E_e). \end{aligned} \tag{2}$$

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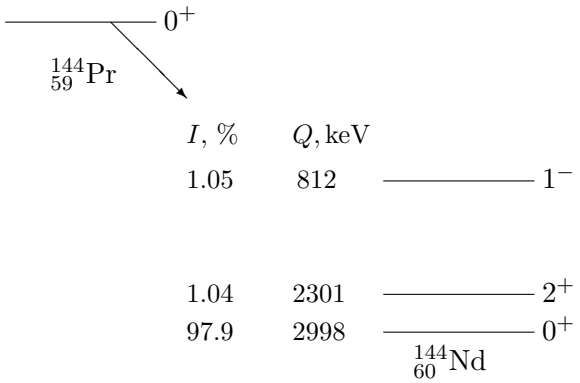

Figure 1. $^{144}_{59}$Pr ground state β-decay scheme.

Here E_e, m_e, p_e are the electron kinetic energy, mass and momentum, E_0 is the endpoint energy, K is a normalization constant. The antineutrino spectrum can be obtained by replacing E_e with $E_0 - E_e$.

The Fermi function $F(Z, E_e)$ describes the effect of nuclear Coulomb field on the outgoing electrons. In the case of forbidden decays one has to take into account the shape factor $H(E_e)$ depending on nuclear matrix elements. The factor $C(Z, E_e)$ includes electromagnetic and weak finite-size corrections, screening correction, radiative corrections and weak magnetism correction (see [3, 4] for more details). $C_{\text{excitations}}(Z, E_e)$ and $C_{\text{exchange}}(Z, E_e)$ are the corrections due to atomic excitations and atomic exchange effects. The relative effects of corrections on antineutrino spectrum for ^{144}Pr branch with endpoint energy 2998 keV are shown on figure 2. Let us discuss the corrections $C_{\text{excitations}}(Z, E_e)$ and $C_{\text{exchange}}(Z, E_e)$ in more detail.

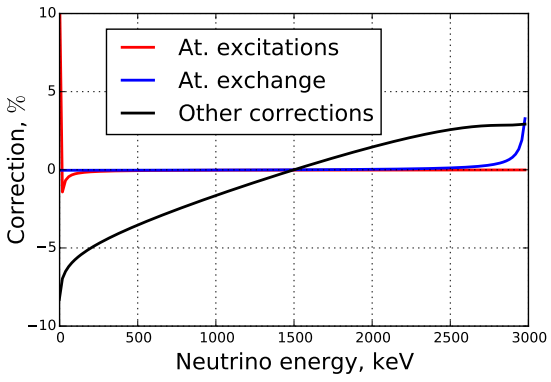

Figure 2. Relative effects of atomic excitations, atomic exchange and other corrections on antineutrino spectrum for ^{144}Pr branch with endpoint energy 2998 keV.

Atomic excitations

Imperfect overlap between atomic orbitals of the initial and final atom may cause transitions to excited states or into continuum. This effect, described by correction $C_{\text{excitations}}(Z, E_e)$ (we used the formulas from [6] for computation), increases the fraction of emitted electrons with kinetic energies in a narrow range near the endpoint (and, thus, neutrinos with near-zero energies) and can reach about 10% in the case of ^{144}Pr. Evidently, the effect is not substantial for neutrino experiments based on detection via IBD.

Atomic exchange

The atomic exchange effect, described by correction $C_{\text{exchange}}(Z, E_e)$, takes into account that the electron produced in β^--decay can be created not only in a continuous state, but also in a bound

state on atomic orbital with a simultaneous transition of an atomic electron into continuum. For our calculations we use the results from [7]. The effect is significant for low-energy electrons ($E_e < 100$ keV) and, hence, for neutrinos with energies near the endpoint. For ^{144}Pr, the correction can reach up to about 3%, which is comparable with other corrections. Therefore, this correction has to be taken into account in calculations related to neutrino experiments.

Conclusion

We showed the effects of atomic exchange and atomic excitations on ^{144}Pr beta spectrum and compared it to other corrections. The influence of atomic exchange can be significant for sterile neutrino searches with ^{144}Ce-^{144}Pr source.

Note that there are various approaches to calculate the corrections to beta spectrum (see, e.g., the review [8]). Corrections of any type are usually defined in the following manner. The spectrum is evaluated taking into account only one effect of interest (say, atomic exchange), and the ratio of the resulting spectrum to the spectrum calculated in the simplest approximation is called a "correction". This approach allows to figure out the influence of various effects on the spectrum. The corrections are usually given in a simple algebraic form so it is easy to apply them on practice and compare with other calculations. However, the approach also has a disadvantage, since it does not take into account possible interplay between different effects. Thus, it is desirable to develop a more consistent computation method.

Acknowledgments

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