

The inverse beta decay: a study of cross section

A Oralbaev¹, M Skorokhvatov^{1,2} and O Titov¹

¹ NRC "Kurchatov Institute", 123182, Moscow, Russia

² National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe highway 31, Moscow, 115409, Russia

E-mail: oralbaev_ay@nrcki.ru, skorokhvatov_md@nrcki.ru, titov-o@mail.ru

Abstract. Knowledge of antineutrino interaction cross-sections is an important and necessary ingredient in many measurements. With the advent of new precision experiments, the demands on better understanding of neutrino interactions is becoming even greater. The purpose of this report is to survey our current knowledge of the inverse beta decay cross-sections and to do a comparison the theoretical analysis with experimental data.

The inverse beta decay (IBD) reaction

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

has played an important role in the first observation of free antineutrinos and up to now the reaction (1) is used in the most of reactor antineutrino experiments. It also provides the detection of geo-neutrinos and the search for sterile neutrino.

The energy threshold of IBD, $E = 1.806$ MeV, is low enough to observe antineutrino from different sources. The neutrino energy $E_{\bar{\nu}}$ and the observable positron energy E_e are related by the formula $E_{\bar{\nu}} \rightarrow E_e + 1.3$ MeV, neglecting the small neutron recoil.

Compared to other neutrino interactions, the reaction (1) has relatively large cross section and its "naive" theoretical description at the low energy (< 10 MeV) is rather simple. The vector and the axial weak formfactors, g_V and g_A respectively, make the main contribution to the cross section. Neglecting all the other formfactors one derives the cross section:

$$\sigma_0(E_\nu) = \frac{1}{\pi} (G_V^2 + 3G_A^2) \bar{p} \bar{E}, \quad (2)$$

where E and p are the positron energy and momentum, the "effective" beta decay constants G_V and G_A were defined through the Fermi constant, G_F , and the Cabibbo angle, V_{ud} , by means of the relation:

$$(G_V^2 + 3G_A^2) = (G_F V_{ud})^2 (g_V^2 + 3g_A^2). \quad (3)$$

Under the fixed constants the formula (2) provides the accuracy of few percent for prediction of the IBD cross section. In the early 1980s, the experimental technique had been developed, and the problem of more precise calculations emerged. In order to provide accurate calculation of the cross section, one must take into account the following corrections:

- (i) "Outer" and "inner" radiative corrections δ_{rad} and Δ_{rad} [1, 2, 3, 4];
- (ii) Nucleon recoil and weak magnetism δ_{rec+WM} [2, 3];



(iii) Threshold correction δ_{thr} [1].

Thus, the overall IBD cross section takes form:

$$\sigma = \sigma_0(1 + \delta_{rad})(1 + \Delta_{rad})(1 + \delta_{rec+WM})(1 + \delta_{thr}). \quad (4)$$

Since the middle of the 80s these corrections were repeatedly calculated using different methods. In the most of works the coinciding results were received that gives us confidence to consider these calculations very reliable. Figures 1,2 present the correction functions (the inner radiative correction $\Delta_{rad} = 0.0238(4)$ [5] is omitted because it does not depend on energy). It is evident that corrections vary within several percent depending on energy. It is necessary to pay attention to the threshold correction which is important for the description of IBD cross section round the energy of 1.8 MeV. Thus it is possible to draw a conclusion that applying corrections, its precision at relevant energies for antineutrino observation (< 10 MeV) is better than 0.2 %. Of course, again it is fair at the fixed values of beta decay constants and to determine the total precision of IBD cross section we have to consider the experimental data on the combination $(G_V^2 + 3G_A^2)$ of beta decay constants.

There is a direct way to measure $(G_V^2 + 3G_A^2)$ from experimental study of free neutron lifetime τ . The neutron lifetime has been measured in the two sets of experiments — with neutron beams by decay-in-flight method and with storage of ultracold neutrons by a neutron confinement method. Unfortunately, there is a significant discrepancy between the measurements of τ in the beam and the storage experiments. Given disagreement [6] is essential to having a reliable $(G_V^2 + 3G_A^2)$ value. The beam measurements yield the value 888.0 ± 2.1 s for the lifetime, higher than the average of 879.6 ± 0.8 s for storage experiments [6]. From these data the numerical values of factors $(G_V^2 + 3G_A^2)$ are:

$$(G_V^2 + 3G_A^2)_{beam} = 7.516(18) \cdot 10^{-10} \text{ GeV}^{-4}; \quad (5)$$

$$(G_V^2 + 3G_A^2)_{storage} = 7.59(8) \cdot 10^{-10} \text{ GeV}^{-4}; \quad (6)$$

This discrepancy of 1% is large enough that is the dominant uncertainty now in the prediction of the IBD cross section.

It should be noted that there is also another way (but not direct) of definition of the constants, using data from nuclear superallowed transitions and from angular correlation coefficient measurements in neutron β -decay (measuring G_V^2 and a ratio $\lambda = G_A/G_V$, respectively). Using the recommended values for $G_V^2 = 1.29106(57) \cdot 10^{-10} \text{ GeV}^{-4}$ [7] and $\lambda = -1.2748(13)$ [8], the factor $(G_V^2 + 3G_A^2)$ is equal to $(G_V^2(1 + 3\lambda^2))_{corr.} = 7.583(15) \cdot 10^{-10} \text{ GeV}^{-4}$, that is close to data from storage experiments.

The IBD cross section has been measured in the reactor-based short-baseline experiments. Nuclear reactors are an intense source of 0-10 MeV antineutrinos, resulting from many fission products of nuclear fuel. Despite many studies let us consider the two most reliable measurements with the largest statistics that were carried out in the BUGEY-4 [9] and the Daya Bay [10] experiments. The measured cross section averaged over energy spectrum of antineutrinos (in units of cm^2 per fission):

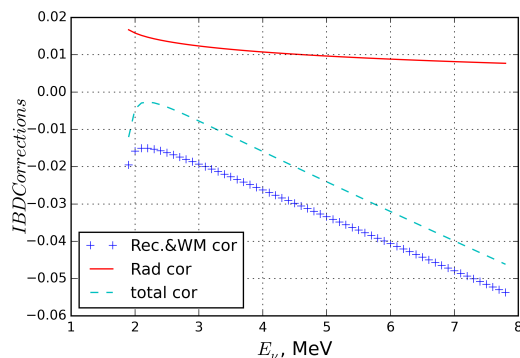
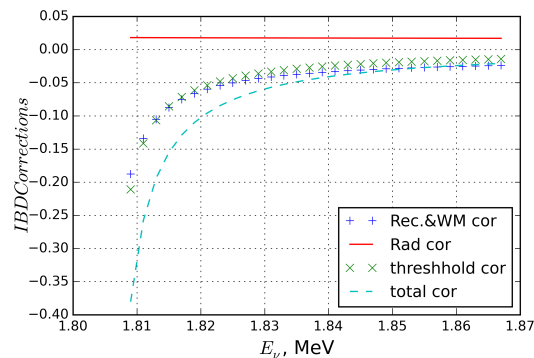
$$\sigma_{exp} (\text{Bugea-4}) = (5.75 \pm 0.08) \cdot 10^{-43} \text{ cm}^2/\text{fission} \quad (7)$$

$$\sigma_{exp} (\text{Daya Bay}) = (5.92 \pm 0.14) \cdot 10^{-43} \text{ cm}^2/\text{fission} \quad (8)$$

The energy spectrum of reactor antineutrinos depends on the composition of the main fuel isotopes: ^{235}U , ^{238}U , ^{239}Pu and ^{241}Pu . Corresponding contributions of fissile isotopes to antineutrino flux in considered experiments were:

$$^{235}\text{U} : ^{238}\text{U} : ^{239}\text{Pu} : ^{241}\text{Pu} (\text{Bugey-4}) \rightarrow 0.538 : 0.078 : 0.328 : 0.056 \quad (9)$$

$$^{235}\text{U} : ^{238}\text{U} : ^{239}\text{Pu} : ^{241}\text{Pu} (\text{Daya Bay}) \rightarrow 0.586 : 0.076 : 0.288 : 0.050 \quad (10)$$

**Figure 1.** IBD corrections**Figure 2.** IBD correction (near threshold)

The measured IBD cross sections are consistent for both experiments after correcting for the difference of fission fractions.

The expected cross section σ_{expect} can be calculated by means of the integration of the formula (4) under the antineutrino spectra. The energy spectrum of reactor antineutrinos was predicted in 80-s, using conversion procedure based on the beta spectra of fuel isotopes, measured at ILL [11]. The value of σ_{expect} for this case is in agreement with measurements within 3% uncertainty: $\sigma_{meas}/\sigma_{expect} \approx 0.99 \pm 0.03$. Recently improved treatments of reactor antineutrinos flux and spectrum were presented [12] to be higher than the measurements: $\sigma_{meas}/\sigma_{expect} \approx 0.94 \pm 0.03$. Sometimes this discrepancy is considered as a manifestation of new physics. But the most likely explanation is a difficulty of fissile antineutrino modeling and an underestimation of contributions of unknown fission fragments to a generation of the antineutrino energy spectrum.

In summary, we have reviewed the accuracy of the IBD cross section. The expected IBD cross section value has uncertainty of about 1 percent connected with the current uncertainty in the values of the beta decay constants combination. The contributions of some corrections are rather small and they are calculated reliably. Exact comparison with experimental data of reactor-based experiments is complicated mainly due to incomplete antineutrino energy spectrum knowledge. Thus, it is desirable to conduct measurements with an intense source of well-known spectrum.

Acknowledgments

The work was partially supported by the Russian Foundation for Basic Research under grant 16-02-00616 and by MEPhI Academic Excellence Project (contract 02.a03.21.0005, 27.08.2013).

References

- [1] Vogel P 1984 *Phys. Rev. D* **29** 1918
- Fayans S A 1985 *Sov. J. Nucl. Phys.* **42** 590
- [2] Raha U, Myhrer F and Kubodera K 2012 *Phys. Rev. C* **85** 045502 (*arXiv:1112.2007*)
- [3] Ivanov A N *et al.* 2013 *Phys. Rev. C* **88** 055501 (*arXiv:1306.1995*)
- [4] Vogel P and Beacom J F 1999 *Phys. Rev. D* **60** 53003
- [5] Marciano W J and Sirlin A 2006 *Phys. Rev. Lett.* **96** 032002
- [6] Bowman J D *et al.* 2014 *arXiv:1410.5311* [nucl-ex]
- [7] Hardy J C and Towner I S 2014 *arXiv:1411.5987* [nucl-ex]
- [8] Mund D *et al.* 2013 *Phys. Rev. Lett.* **110** 172502 (*arXiv:1204.0013*)
- [9] Declais Y *et al.* 1994 *Phys. Lett. B* **338** 383
- [10] An F P *et al.* [Daya Bay Collaboration] 2015 *arXiv:1508.04233* [hep-ex]
- [11] Schreckenbach K *et al.* 1985 *Phys. Lett. B* **160** 325
- Von Feilitzsch F, Hahn A A and Schreckenbach K 1982 *Phys. Lett. B* **118** 162

Hahn A A *et al.* 1989 *Phys. Lett. B* **218** 365

Vogel P *et al.* 1981 *Phys. Rev. C* **24** 1543

[12] Mueller T A *et al.* 2011 *Phys. Rev. C* **83** 054615

Huber P 2011 *Phys. Rev. C* **84** 024617