The anisotropy of inverse beta decay and antineutrino detection

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The anisotropy of the positrons emitted in the reaction $\nu_e + p \rightarrow n + e^+$ has to be taken into account for extracting an antineutrino signal in Superkamiokande. For the Sun, this effect allows a sensitivity to $\nu_e \rightarrow \bar{\nu}_e$ transition probability at the 3% level already with the statistics collected in the first hundred days. For a supernova in the Galaxy, the effect is crucial for extracting the correct ratio of $\nu - e$ to $\bar{\nu}_e - p$ events.

As well known, the specific signature of antineutrinos in hydrogen containing materials is through the inverse beta decay ($I\beta D$), $\nu_e + p \rightarrow n + e^+$, which produces almost isotropically distributed monoenergetic positrons ($E_{e^+} = E_\nu - \Delta m; \Delta m = m_n - m_p$). For energy above a few MeV, the differential cross section is:

$$\frac{d\sigma}{d\cos \theta} = \frac{1}{2} \sigma_0(E_\nu) (1 - a \cos \theta)$$

where:

$$a = \left( \frac{g_A}{g_V} \right)^2 - \frac{1}{3(\frac{g_A}{g_V})^2 + 1} \simeq 0.1 ,$$

$g_V$ ($g_A$) is the vector (axial) coupling of the neutron and $\sigma_0(E_\nu)$ is the total cross section for antineutrino energy $E_\nu$.

The goal of this paper is to assess the importance of the angular dependence of the cross section in two situations of practical interest:

- The search for solar antineutrinos\(^1\)
- the detection of a supernova in the Galaxy.

1. Solar Antineutrinos

In the absence of a solar antineutrino flux, the Superkamiokande (SK) background is expected to be isotropic. In the presence of solar antineutrinos, positrons emitted by $I\beta D$ contribute to the background, which, due to the angular dependence of $I\beta D$ cross section, should have a non-zero angular slope proportional to the antineutrino flux. A linear fit to the counting yield, $C = C_0 - C_1 \cos \theta$ (in the angular region where events from the $\nu - e$ interactions can be neglected, see Fig. 1), provides the antineutrino flux $\Phi_\nu$ through the relation:

$$\Phi_\nu(E_\nu > E_0) = \frac{C_1}{T N_p \sigma_0(a)}$$

where $N_p$ is the number of free protons, $T$ is the exposure time, $\epsilon$ is the (assumed constant) detection efficiency, $E_0$ the minimal detectable antineutrino energy and $\sigma_0$ the cross section averaged over the antineutrino spectrum for $E_\nu > E_0$.

In order to provide a quantitative illustration of the previous points we used data from the first 101.9 operational days of SK, as reported in fig.3 of [2], corresponding to $E_0 = 8.3 MeV$. The reported background does not show an angular dependence. According to equation (3), to extract an upper limit on the solar antineutrino flux, we must know the average cross section $\sigma_0$, which can be determined within two approaches:

1) Assuming that the antineutrino spectrum has the same shape as that of $^8$B solar neutrinos, one has $\sigma_0 = 7.1 \cdot 10^{-42} cm^2$. This gives, as a final result, $\Phi_\nu(E_\nu > 8.3 MeV) < 6 \cdot 10^4 cm^{-2}s^{-1}$, to the 95% C.L. This bound corresponds to a fraction $x = 3.5\%$ of the solar neutrino flux (in the energy range $E_\nu > 8.3 MeV$) predicted by the SSM [3].

2) As $\sigma_0$ is an increasing function of $E_\nu$, one has $\sigma_0(E_0) \geq \sigma_0(E_0) = 4.5 \cdot 10^{-42} cm^2$. This lower limit

\(^1\)This signal is of interest since it might be a signature of $\nu$ decay or magnetic moment. see [2] for details and references.
to \( \sigma_0 \) gives a model independent bound \( \Phi_{\nu}(E_{\nu} > 8.3 \, MeV) < 9 \cdot 10^4 \, cm^{-2}s^{-1} \) to the 95% C.L.

We remark two points of the method just presented:

- The sensitivity to antineutrinos increases as statistics accumulates. Within three years of data taking, the sensitivity to \( \nu_e \rightarrow \nu_e \) transition probability will reach the 1% level, thus allowing for a definite test of several theoretical models.

- The determination of the angular slope \( C_1 \) provides a mean for detecting antineutrinos from the Sun (and not only for deriving upper bounds). A non vanishing slope for SK background would be, in fact, a clear signature of a solar antineutrino flux.

2. Supernova detection

If a type–II supernova explosion occurs near the center of our galaxy about 4000 \( \nu_e + p \rightarrow n + e^+ \) events and 300 \( \nu - e^- \rightarrow \nu - e^- \) events will be produced in the Superkamiokande detector. The detection of supernova neutrinos and antineutrinos will provide important information on the supernova mechanism. In particular we remark that:

- from the strong correlation of the elastic scattering events one can reconstruct the supernova direction with an accuracy of about four degrees;

- from a fit to experimental data one can determine the number of neutrinos and antineutrinos events, thus providing important inputs to check supernova modelling.

The anisotropy of I3D is so small that it looks reasonable to neglect it when discussing the detector sensitivity. However, let us investigate how it can affect the data analysis. With this aim we have simulated a supernova explosion in the galactic plane, assuming that it produces \( N_{e+} = 4000 \) and \( N_{e-} = 300 \) events in the detector. We took into account a 30° angular resolution and repeated the simulation two-hundred times. We analysed the data looking for the galactic longitude \( \phi \) of the supernova and the ratio \( f = N_{e-}/N_{e+} \) of reconstructed events, see fig.2.

If the analysis is performed neglecting the anisotropy (i.e. \( a = 0 \)) the supernova direction is correctly determined within the predicted accuracy, however the reconstructed \( f \) is badly underestimated (\( f = 0.057 \pm 0.009 \), the correct value being \( f = 0.075 \)) and the fit is poor (\( \chi^2/DOF = 24/18 \) on the average of the 200 simulations, using 20 angular bin). We checked that when the anisotropy is included, both the supernova direction and the ratio \( f \) are correctly reconstructed, and the quality of the fit improves significantly. These features are clearly understood:

- as the positron angular distribution is symmetrical around the supernova direction, it does not alter its reconstruction.

- The depleted forward positron production mimics a reduced number of \( \nu - e \) events.

In conclusion, we remark that inclusion of the anisotropy of I3D is essential for extracting the correct ratio of \( \nu - e \) to \( \nu_e - p \) events.
Figure 2. The simulated counts as a function of the galactic longitude for a supernova at the galactic center (dots), with their statistical errors (bars), the best fit for $a = 0$ (dotted curve) and that for $a = 0.1$ (full curve)

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