Superkamiokande and solar antineutrinos

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Abstract

We propose to exploit the angular distribution of the positrons emitted in the reaction $\nu_e + p \rightarrow n + e^+$ to extract a possible antineutrino signal from the Superkamiokande background. From the statistics collected in just 101.9 days one obtains a model independent upper bound on the antineutrino flux $\Phi_{\bar{\nu}}(E_{\nu} > 8.3MeV) < 9 \times 10^4 cm^{-2}s^{-1}$ at the 95% C.L. By assuming the same energy spectrum as for the $^8$B neutrinos, the 95% C.L. bound is $\Phi_{\bar{\nu}}(E_{\nu} > 8.3MeV) < 6 \times 10^4 cm^{-2}s^{-1}$. Within three years of data taking, the sensitivity to $\nu_e \rightarrow \bar{\nu}_e$ transition probability will reach the 1% level, thus providing a stringent test of hybrid oscillation models.
We all believe that sun light is accompanied by an intense neutrino radiation \( \Phi_{\nu} \sim 10^{11} \text{cm}^{-2}\text{s}^{-1} \), i.e. about one neutrino per \( 10^7 \) photons. Since energy is produced by transforming hydrogen into helium, the conservation of electric charge and lepton number requires that this radiation consists of neutrinos and not of antineutrinos, see e.g. \[\text{1, 2, 3}\] for reviews on solar neutrinos. However, a fraction of the \( \nu_e \) formed in the core of the Sun could transform into \( \bar{\nu}_e \) during their trip from Sun to Earth; this transformation is predicted e.g. in the so called hybrid models \[\text{4, 5, 6}\] where a spin-flavour magnetic moment transition gives \( \nu_e^L \rightarrow \bar{\nu}_e^R \) and a mass oscillation yields \( \bar{\nu}_\mu^R \rightarrow \bar{\nu}_e^R \). Solar antineutrinos could also originate from neutrino decay \[\text{7}\] both in vacuum \[\text{8}\] and in matter \[\text{9}\]. All this shows that an experimental study of solar antineutrinos is important.

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

\[
\sigma_0(E_{\bar{\nu}}) = 9.2 \times 10^{-42} \text{cm}^2 \left[ \frac{(E_{\bar{\nu}} - \Delta m)}{10\text{MeV}} \right]^2
\]

Water Čerenkov detectors as Kamiokande \[\text{10, 11, 12, 13}\] and the recently operational Superkamiokande (SK) \[\text{14}\], which are sensible to the \( \nu_e - e \) interaction with a much smaller cross section, are clearly also capable of detecting I\(\beta\)D, which produces a number \( N_+ \) of events given by:

\[
N_+ = N_p T \epsilon \Phi_{\bar{\nu}}(E_{\bar{\nu}} > E_0) \sigma_0
\]

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

\[
\sigma_0 = \frac{\int_{E_0}^{\infty} dE_{\bar{\nu}} \sigma_0(E_{\bar{\nu}}) w(E_{\bar{\nu}})}{\int_{E_0}^{\infty} dE_{\bar{\nu}} w(E_{\bar{\nu}})}
\]

where \( w \) is the antineutrino probability distribution.

Antineutrino events contribute to the isotropic background \( B \). By requiring \( N_+ < B \), upper bounds on \( \Phi_{\bar{\nu}} \) have been derived from Kamiokande data \[\text{15}\]; for \( E_{\bar{\nu}} \geq 9.3\text{MeV} \) the antineutrino flux does not exceed \( 6 - 10\% \) of Standard Solar Model (SSM) predictions for the \( \nu_e \)-neutrino flux in the same energy range. A similar result can be obtained by SK, as the ratio \( B/N_pT \) is similar for the two
The aim of this letter is to show that a much better sensitivity can be achieved by exploiting the huge statistics of SK in conjunction with the (although weak) directionality of positrons from 1βD. In fact, a signature for the presence of positrons from antineutrinos is provided by the angular dependence of the cross section:

\[
\frac{d\sigma}{d\cos\theta} = \frac{\sigma_0}{2} (1 - a \cos\theta)
\]  \hspace{1cm} (4)

where

\[
a = \frac{(g_A/g_V)^2 - 1}{3(g_A/g_V)^2 + 1} \simeq 0.1
\]  \hspace{1cm} (5)

and \(g_{V,A}\) are respectively the vector and axial couplings of the neutrino.

In the angular region where events from the \(\nu - e\) interactions can be neglected (see fig.1), a linear fit to the counting yield, \(C = C_0 - C_1 \cos\theta\), gives the slope \(C_1\) and thus the antineutrino flux through the relation:

\[
\Phi_{\nu}(E_\nu > E_0) = \frac{C_1}{T N_p \epsilon \sigma_0 a}
\]  \hspace{1cm} (6)

We remark the advantages of this method with respect to the previous one:

- The isotropic background can be subtracted.
- The determination of \(C_1\) provides a mean for detecting antineutrinos from the Sun (and not only for deriving upper bounds).
- The sensitivity to antineutrinos increases as statistics accumulates. In fact the accuracy on the slope \(C_1\) is limited by statistical fluctuations, \(\Delta C_1 \sim \sqrt{B} \propto \sqrt{N_p T}\), and consequently \(\Delta \Phi_{\nu} \propto 1/\sqrt{N_p T}\). On the other hand, in the previous method there is no gain in increasing statistics as the ratio \(B/N_p T\) stays constant.

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 [16]. By considering the region \(-1 < \cos\theta < 0.5\) and taking into account the finite angular

\[\text{One should notice that the rough equality of } B/(N_p T) \text{ in the two detectors occurs although the SK energy threshold is significantly lower than that of Kamiokande. This is to say that the quality of SK data has neatly improved so that lower energies can now be explored [15].}\]
resolution, after subtracting the tail due the $\nu - e$ scattering, as a result of this exercise we obtain:

$$\frac{C_1}{T} = (-0.7 \pm 1.5) \text{day}^{-1}$$  \hspace{0.5cm} (7)

Let us remind that an antineutrino signal requires $C_1$ to be positive; with this constraint, following the prescription of [17] one has $C_1/T < 2.5 \text{day}^{-1}$ to the 95% C.L.

We now proceed to extract a bound on the antineutrino flux\(^2\). We assume $\epsilon = 0.95$\(^[16]\) for visible energy $E_{\text{vis}} \geq 7\text{MeV}$; since the visible energy can be identified with the total electron/positron energy, the minimal antineutrino energy is $E_0 = 8.3\text{MeV}$. In order to determine $\sigma_0$ we consider two approaches:

**a)** If one assumes that the antineutrino spectrum has the same shape as that of $^8\text{B}$ solar neutrinos, one has $\sigma_0 = 7.06 \cdot 10^{-42}\text{cm}^2$. This gives $\Phi_{\nu}(E_{\nu} > 8.3\text{MeV}) < 6 \cdot 10^4\text{cm}^{-2}\text{s}^{-1}$, to the 95% C.L. This bound corresponds to a fraction $x = 3.5\%$ of the solar neutrino flux (in the energy range $E_{\nu} > 8.3\text{MeV}$) predicted by the SSM\(^[18]\).

**b)** Alternatively one get a model independent bound by releasing the assumption on the antineutrino energy spectrum. As $\sigma_0$ increases with $E_{\nu}$, clearly $\sigma_0 \geq \sigma_0(E_0) = 4.5 \cdot 10^{-42}\text{cm}^2$. This gives a *model independent* bound $\Phi_{\nu}(E_{\nu} > 8.3\text{MeV}) < 9 \cdot 10^4\text{cm}^{-2}\text{s}^{-1}$ to the 95% C.L.

An additional way to discriminate a solar antineutrino signal from "true background" (which should be time independent) is provided by the study of seasonal effects, due to the variations of the Sun-Earth distance. The time distribution of positrons from $I\beta D$, to the first order in the eccentricity $e$ of the Earth orbit ($e = 0.0168$), is given by:

$$\frac{dN_+}{dt} = N_P\epsilon\sigma_0\Phi_{\nu}[1 + 2\epsilon\cos(\omega t)],$$  \hspace{0.5cm} (8)

where $\Phi_{\nu}$ is the yearly averaged antineutrino flux, $t$ is the time ($t = 0$ at the perihelion) and obviously $\omega = 2\pi$ years\(^{-1}\). As the amplitudes of the oscillating component in (8) and in (4) are comparable, also this method will allow, in due time, an accurate measurement of the solar antineutrino flux: quantitatively, the minimum detectable flux will be a 35% higher than that of the previous method. Both approaches – angular correlation and seasonal effects – clearly should be studied, as being independent from and complementary to each other.

\(^2\)For semplicity we neglect the finite energy resolution of the detector, which should be considered in a proper analysis.
In summary:

- The (although weak) directionality of inverse beta decay, combined with the huge statistics of SK allows for the search of the solar antineutrinos (and not only the derivation of upper bounds).

- By using this method and the first available data on SK one already improves on the information provided by Kamiokande [13] (where the statistics was too low for the new method to be useful).

- We would like to encourage our experimental colleagues to analyse in this spirit the available data and those which will be collected in the future. Within three years of data taking, the sensitivity to $\nu_e \rightarrow \bar{\nu}_e$ transition probability will reach the 1% level, thus allowing for a definite test of hybrid oscillation models. One could also detect galactic antineutrino sources with luminosities $L_{\nu} \geq 3 \cdot 10^{45}$ erg/s (i.e $L_{\nu} \sim 10^{12} L_\odot$), should they exist.

References

[1] J.N.Bahcall, Neutrino Astrophysics (Cambridge U.P., Cambridge, 1989).
[2] V.Berezinsky, Comments on Nuclear and Particle Physics, 21 (1994) 249.
[3] V.Castellani, S.Degl'Innocenti, G.Fiorentini, M.Lissia and B.Ricci, Physics Reports 281 (1997) 309.
[4] E.Kh.Akhmedov, Sov. Phys. JEPT 68 (1989) 690; H.Minakata and H.Nunokawa, Phys. Rev. Lett 63 (1989) 121; C.S.Lim and W.J.Marciano, Phys. Rev. D 37 (1988) 1368.
[5] E.Kh.Akhmedov, Phys. Lett. B 257 (1991) 163; E.Kh.Akhmedov, talk at the 4th International; Solar Neutrino Conference, Heidelberg, Germany, Apr (1997), [hep-ph/9705451]
[6] C.S.Lim, M.Mori, Y.Oyama and A.Suzuki, Phys. Lett. B 243 (1990) 389; E.Kh. Akhmedov, S.T. Petcov, A.Yu. Smirnov, Phys. Rev. D48 (1993) 2167 and Phys. Lett. B309 (1993) 95.
[7] J.N. Bahcall, N. Cabibbo and A. Yahill, Phys. Rev. Lett. 28 (1972) 316; J.N. Bahcall et al., Phys. Lett. B 181 (1986) 369.
[8] Z. Berezhiani, G. Fiorentini, M. Moretti and A. Rossi, Z. Phys. C 54 (1992) 581 and JETP Lett. 55 (1992) 151.

[9] Z. Berezhiani, M. Moretti, A. Rossi Z. Phys. C 58 (1993) 423; Z. Berezhiani and A. Rossi Proceedings of Fifth Int. Workshop on Neutrino Telescopes, M. Baldo Ceolin Ed. (Venice, 1993).

[10] K.S. Hirata et al., Phys. Rev. Lett. 65 (1990) 1297.

[11] K.S. Hirata et al., Phys. Rev. Lett. 66 (1991) 9.

[12] K.S. Hirata et al., Phys. Rev. Lett. D44 (1991) 2241, D45 (1992) 2170E.

[13] Y.Fukuda et al., Phys. Rev. Lett. 77 (1996) 1683.

[14] M.Takita, in “Frontiers of Neutrino Astrophysics”, Y.Suzuki and Nakamura eds., Universal Academy Press, Tokyo, 1993, p.135.

[15] R.Barbieri, G.Fiorentini, G.Mezzorani, M.Moretti, Phys. Lett. B 243 (1990) 389.

[16] Y.Totsuka, “First result from Super-Kamiokande”, presented at Texas Symposium (1996).

[17] Review of Particle Properties, Phys. Rev. D 54 (1996) 165.

[18] J.N.Bahcall and M.H.Pinsonneault, Rev. Mod. Phys. 61 (1992) 885.
Figure caption

Sketch of the expected angular distribution of events in the presence of a solar $\bar{\nu}_e$ flux.
