Detection of $^8$B solar neutrinos in liquid scintillators

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Abstract. We show that liquid organic scintillator detectors (e.g., KamLAND and Borexino) can measure the $^8$B solar neutrino flux by means of the $\nu_e$ charged current interaction with the $^{13}$C nuclei naturally contained in the scintillators. The neutrino events can be identified by exploiting the time and space coincidence with the subsequent decay of the produced $^{13}$N nuclei.

1. Introduction
In the next future, liquid organic scintillator detectors (KamLAND, Borexino, SNO+, LENA) will be operating with the goal of measuring the low energy solar neutrino fluxes, in particular $^7$Be, CNO and pep solar neutrinos. We show that these detectors can also measure the $^8$B solar neutrino flux by means of the $\nu_e$ charged current interaction with the $^{13}$C nuclei naturally contained in the scintillators. The possibility to use $^{13}$C as a target for $^8$B neutrinos was pointed out in the past by [2, 3, 4]. Here, we propose a technique to tag the solar neutrino events. Namely, we propose to identify the signal by looking at the time and space coincidence with the decay of the produced $^{13}$N nuclei. By using this technique, which does not involve any modification of the experimental setup, one expects a background-to-signal ratio of the order of 1 or less even assuming the natural isotopic abundance of $^{13}$C ($\sim$ 1%) and the contamination levels already reached in the KamLAND detector.

2. The $^8$B solar neutrino signal
The $^{13}$C is a stable isotope of carbon with a natural isotopic abundance $I = 1.07\%$. A small amount of $^{13}$C is, thus, naturally present in organic liquid scintillators and can be used as a target for neutrino detection. The relevant detection process in our discussion is the charged current (CC) transition to $^{13}$N ground state:

$$\nu_e + ^{13}\text{C} \rightarrow ^{13}\text{N(gnd)} + e^-.$$  \hspace{1cm} (1)

The reaction threshold is $Q = 2.22$ MeV and, thus, only $^8$B solar neutrinos are detectable (with a negligible contribution from hep neutrinos). The cross section of reaction (1) is known with great accuracy, since it can be deduced from the mean life of $^{13}$N. One has [3]...
Table 1. Prompt neutrino event rates, delayed energy window efficiency and observed signal event rates for KamLAND and Borexino liquid scintillators.

|                  | Prompt event rate$^1$ [2.8, 16] MeV | Delayed energy windows$^2$ [1.02, 2.22] MeV | Signal event rate$^{1,3,4}$ [2.8, 16] MeV |
|------------------|-------------------------------------|---------------------------------------------|------------------------------------------|
| KamLAND          | 23.6                                | 0.77                                        | 12.4                                     |
| Borexino         | 24.7                                | 1.0                                         | 16.8                                     |

1 Counts kTy$^{-1}$.
2 Fraction of $^{13}$N decay events in the delayed energy window.
3 Space cut: $\Delta r = 3\sigma$, where $\sigma = 10$ cm is the typical detector spatial resolution.
4 Time cut: $\Delta t = 2\tau$, where $\tau = 862.6$ s is the $^{13}$N mean life.

\[
\sigma(E_\nu) = 0.2167 \times 10^{-43} \text{cm}^2 \frac{p_e E_e}{\text{MeV}^2} F(Z, E_e),
\]

\[
\text{where } E_e = E_\nu - Q + m_e \text{ is the electron energy.}
\]

\[
p_e \text{ is the electron momentum and } F(Z = 7, E_e) \text{ is the Fermi factor.}
\]

\[
\text{The peculiarity of process (1) is that it can be monitored by looking for the delayed coincidence with the positron emitted in the }^{13}\text{N decay:}
\]

\[
^{13}\text{N} \to ^{13}\text{C} + \nu_e + e^+,
\]

which occurs with $\sim 99.8\%$ branching ratio (0.2\% of $^{13}\text{N}$ nuclei undergo electron capture) and a mean life $\tau = 862.6$ s. In this case, the visible energy is the sum of the positron kinetic energy and the energy released in $e^+e^- \text{ annihilation}$, so that the delayed events have a continuous energy spectrum in the range [1.02, 2.22] MeV. Moreover, in the absence of macroscopic motions in the detector, the $^{13}\text{N}$ nucleus essentially does not move from its original position. The expected displacement due to recoil and diffusion during the decay is, indeed, smaller than the typical detector spatial resolution, $\sigma \sim 10$ cm. This means that the prompt event produced by the reaction (1) and the delayed event produced by the decay (2) have to be observed essentially in the same position. This condition is extremely effective in reducing the background.

In the first two columns of table I, we show the neutrino event rates (given in counts-kTy$^{-1}$) expected in KamLAND and Borexino scintillators in the energy windows [2.8, 16] MeV and [2.8, 5.5] MeV, assuming the mass and mixing parameters for the large mixing angle solution of the solar neutrino problem. The prompt event rates are further reduced by the cuts, essential to reduce the background. In the last two columns, we show the signal event rates after space and time cuts are applied. For KamLand detector we have also restricted the delayed energy window to [1.3, 2.2] MeV in order to reduce the background from $^{210}\text{Bi}$. As a final result, the expected signal event rates are at the level of 10-20 counts-kTy$^{-1}$. In order to observe such low counting rates, one clearly needs detectors with sufficiently low background levels. Present detectors already satisfy this requirement.

3. Expected sensitivity
There are three main sources of background for the proposed measure. These are: internal background; cosmogenic background due to muon-induced production of radioactive nuclides; elastic $\nu-e$ scattering by solar neutrinos. These background sources are well known, so that it is possible to perform a detailed analysis of their relevance. In reference [1] a complete description of all the relevant background sources is provided. Moreover, a conservative analysis of the background levels expected in KamLand, Borexino and for a possible liquid scintillator experiment at SNOLab (SNO+) is performed. It is shown that, despite the large number of background events (several thousands per kTy) in the prompt and delayed windows, the fake coincidences are rare (tenth per kTy in KamLAND, few per kTy in Borexino or almost absent in SNO+) and comparable or lower than the expected signal.

\[
\text{We neglected the small recoil energy of the }^{13}\text{N nucleus (of the order of few keV).}
\]
Table 2. Background-to-signal ratio and expected sensitivity for KamLAND, Borexino and SNO+ for 1kTy of exposure.

| Detector     | Background-to-signal ratio$^1$ | Expected sensitivity$^1$ | Expected sensitivity (optimized)$^2$ |
|--------------|-------------------------------|--------------------------|--------------------------------------|
|              | [2.8, 16] MeV                 | [2.8, 5.5] MeV           | [2.8, 16] MeV                        |
| KamLAND$^3$  | 2.35                          | 6.73                     | 51.9%                                |
|              |                               |                          | 152.2%                               |
|              |                               |                          | 51.2%                                |
|              |                               |                          | 145.4%                               |
| Borexino$^4$ | 0.100                         | 0.291                    | 25.6%                                |
|              |                               |                          | 53.6%                                |
|              |                               |                          | 23.7%                                |
|              |                               |                          | 52.2%                                |
| SNO+=$^4$    | 0.005                         | 0.014                    | 24.4%                                |
|              |                               |                          | 47.5%                                |
|              |                               |                          | 20.6%                                |
|              |                               |                          | 40.9%                                |

$^1$Space cut Δ$R = 3\sigma$ and time cut Δ$t = 2\tau$, see the text.

$^2$Space and time cuts are optimized to minimize $\delta S$ in each detector, see the text.

$^3$Delayed energy window: [1.3, 2.22] MeV.

$^4$Delayed energy window: [1.02, 2.22] MeV.

It is important to remark that, being the background event rates much larger than the signal event rate both in the prompt and delayed energy window (before space and time cuts are applied), the real background levels will be measured directly by the experiments with great accuracy. This means that the contribution of the background uncertainty to the total error budget will be negligible. The fractional uncertainty $\delta S$ of the extracted $^8$B solar neutrino signal is thus simply estimated:

$$\delta S \simeq \sqrt{1 + r \over S \cdot \mathcal{E}}.$$  (3)

where $\mathcal{E}$ is the total detector exposure and $r$ is the background-to-signal ratio. In table 2, we show the background-to-signal ratio $r$ for KamLAND, Borexino and SNO+ in the two energy windows [2.8, 16] MeV and [2.8, 5.5] MeV, assuming a space cut $\Delta R = 3\sigma$ (where $\sigma = 10$ cm) is the typical detector spatial resolution and a time cut $\Delta t = 2\tau$ (where $\tau = 862.6$ s is the $^{13}$N mean life). In the third and fourth columns, we show the corresponding sensitivity $\delta S$, calculated according to Eq. (3), assuming a total exposure $\mathcal{E} = 1$ kTy. In the last two columns, we give the minimal values for $\delta S$ obtained by choosing the optimal values of $R$ and $T$ which minimize the quantity $(1 + r)/S$ in each experiment.

4. Conclusions

Several important conclusions can be obtained from table 2 and eq. 3:

i) The background-to-signal ratio is $\sim 2$ in KamLAND (in the energy window [2.8, 16] MeV), while is much less than 1 in Borexino and SNO+, showing that, in these detectors, the proposed measure is only limited by the statistical error of the signal event rates.

ii) Assuming an exposure equal to $\mathcal{E} = 1$ kTy, the solar neutrino signal can be extracted with uncertainty of the order of $\sim 50\%$ in KamLAND and $\sim 20 - 25\%$ in Borexino and SNO+. The expected sensitivity scales as $\mathcal{E}^{-1/2}$, since background is directly measured by the experiments.

iii) KamLAND has already analyzed data for a total exposure $\mathcal{E} = 0.766$ kTy, corresponding to $\sim 18$ solar neutrino events in the window [2.8, 16] MeV which can be extracted with about 60% uncertainty. Despite the large uncertainty, this measure would, anyhow, represent a milestone, since it would be the first observation of solar neutrinos into liquid scintillator detectors.

iv) We remark that gigantic (such as LENA) and/or enriched detectors, having a large statistics, will have the possibility to perform a very precise measurement of the $^8$B solar neutrino spectrum.

References

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