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A method to extract the CNO solar neutrino signal in ultrapure liquid scintillator detectors

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Abstract. One of the main goals of the present and next generation ultrapure liquid scintillator detectors is the determination of the CNO solar neutrino fluxes. In this work, we discuss a method of analysis that allows to determine the background due to β decay of Bismuth-210 that represents the major limitation for CNO neutrino extraction in these detectors.

1. Introduction

The observation of CNO solar neutrinos in ultrapure liquid scintillator detectors, such as KamLAND, Borexino, SNO+ and LENA, is a very difficult task[1]. The neutrinos produced in the CNO cycle have a relatively low flux that corresponds to an expected event rate $n_{\rm CNO} \simeq 3-5\,{\rm cpd}/100$ ton (the exact value depends on the assumed solar metallicity). Moreover, they have continuous energy spectra with endpoints at $\sim$ 1.5 MeV that do not produce specific spectral features that permit to extract them unambiguously from the background event spectrum.

The detection of CNO neutrinos is limited, in particular, by the background produced by $^{210}{\rm Bi} \to {}^{210}{\rm Po} + e^- + \overline{\nu}_e$. In the Borexino detector, this corresponds to a counting rate at the level of $n_{\rm Bi} \simeq$ few $\times\, 10\,{\rm cpd}/100$ ton [2, 3]. The electrons produced by the β-decay ^{210}Bi have a continuous spectrum with an endpoint $E_{\rm max} = 1.16\,{\rm MeV}$ that lies over the event spectrum produced by CNO neutrinos, see Fig. 1. As a consequence, spectral fits are able to determine only combined "Bismuth+CNO" contribution with the consequence that the CNO signal is basically unconstrained. This can be appreciated in the left panel of Fig. 2 where we perform a fit to simulated data for a $M = 100$ ton detector, an observation period $\Delta t = 1$ year, assuming background levels and detector energy resolution comparable to that obtained by Borexino [2, 3].

In this paper, we review a method to determine the Bismuth-210 counting rate and, thus, to remove this degeneracy. Our approach is based on the relationship between the Bismuth-210 and Polonium-210 activities in the detector and it only requires that α particle detection efficiency is stable over the data acquisition period and external sources of Polonium-210 are negligible.

2. Determining Bismuth-210 with the help of Polonium-210

Bismuth-210 and Polonium-210 are both daughter of Uranium-238. Bismuth-210 is produced by the slow decay of Lead-210 which has a lifetime equal to $\tau_{\rm Pb} = 32.3$ y. It then undergoes a

[1] Due to space limitation, we provide a limited reference list. For a complete list of references see [1].

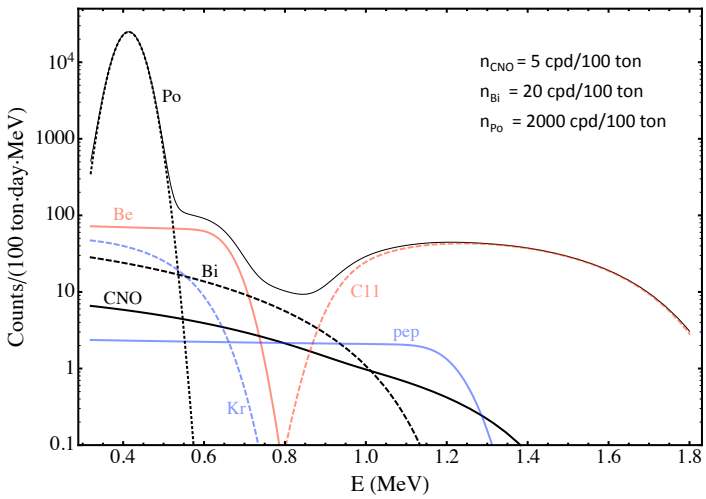

Figure 1. The expected event spectrum in solar neutrino liquid scintillator detectors. The continous lines correspond to the solar neutrino signals. The dotted lines are the various background sources. The sensitivity to CNO neutrinos arises from a narrow energy range at $E \sim 0.8\,\mathrm{MeV}$.

β^- decay to Polonium-210:

$$^{210}\mathrm{Bi} \rightarrow {}^{210}\mathrm{Po} + e^- + \overline{\nu}_e \tag{1}$$

with a lifetime $\tau_{\mathrm{Bi}} = 7.232$ d. Polonium-210 is also unstable and undergoes α decay to Lead-206:

$$^{210}\mathrm{Po} \rightarrow {}^{206}\mathrm{Pb} + \alpha \tag{2}$$

with a lifetime $\tau_{\mathrm{Po}} = 199.634$ d. The α particles produced in the decay have an energy $E_\alpha = 5.3$ MeV, but they are observed at a much lower effective energy, due to the large quenching factor of alpha particles in liquid scintillators. They produce a sharp peak superimposed to the low energy part of the ^{7}Be neutrino event rate at a visible energy $E_{\mathrm{vis}} \simeq 0.5\,\mathrm{MeV}$, see Fig. 1.

The relationship between the Polonium-210 and the Bismuth-210 abundances can be easily obtained. We have:

$$\frac{dN_{\mathrm{Po}}}{dt} = -\frac{N_{\mathrm{Po}}(t)}{\tau_{\mathrm{Po}}} + \frac{N_{\mathrm{Bi}}(t)}{\tau_{\mathrm{Bi}}} + S_{\mathrm{Po}}(t) \tag{3}$$

where $N_{\mathrm{Po}}(t)$ ($N_{\mathrm{Bi}}(t)$) is the number of Polonium-210 (Bismuth-210) nuclei per unit mass in the detector at a time t, and $S_{\mathrm{Po}}(t)$ indicates any possible external source of polonium-210 (i.e. not related to ^{238}U decay chain). The solution of Eq. (3) can be written as:

$$N_{\mathrm{Po}}(t) = N_{\mathrm{Po},0}\,\exp(-t/\tau_{\mathrm{Po}}) + \tau_{\mathrm{Po}} \left\langle \frac{N_{\mathrm{Bi}}(t)}{\tau_{\mathrm{Bi}}} + S_{\mathrm{Po}}(t) \right\rangle \tag{4}$$

where $N_{\mathrm{Po},0}$ is the number of Polonium-210 nuclei per unit mass at the time $t = 0$ and the symbol $\langle f(t) \rangle$ indicates the time "average":

$$\langle f(t) \rangle = \frac{1}{\tau_{\mathrm{Po}}} \int_0^t dt'\; f(t-t')\,\exp(-t'/\tau_{\mathrm{Po}}) \tag{5}$$

for the generic function $f(t)$. We assume that, during a data acquisition period, after liquid scintillator purification, external sources of Polonium can be neglected, i.e. $S_{\mathrm{Po}}(t) \simeq 0$. In this

Table 1. The absolute uncertainty $\Delta n_{\rm Bi}$ in the Bismuth-210 event rate determination, reconstructed by performing a fit over an observation period Δt to simulated data. All rates are expressed in cpd/100 ton.

	$M = 100\,$ton			$M = 1000\,$ton		
	0.5 year	1 year	1.5 year	0.5 year	1 year	1.5 year
$n_{\rm Po,0} = 2000$	10	2.9	1.3	3.3	0.9	0.4
$n_{\rm Po,0} = 4000$	15	4.1	1.8	4.6	1.3	0.6
$n_{\rm Po,0} = 8000$	> 20	5.7	2.5	5.6	1.8	0.8

assumption, the $\alpha-$decay rate of Polonium and the $\beta-$decay rate of Bismuth, given by:

$$\begin{aligned} n_{\rm Po}(t) &\equiv N_{\rm Po}(t)/\tau_{\rm Po} \\ n_{\rm Bi}(t) &\equiv N_{\rm Bi}(t)/\tau_{\rm Bi} \end{aligned} \tag{6}$$

respectively, follow the relation:

$$n_{\rm Po}(t) = n_{\rm Po,0}\, \exp(-t/\tau_{\rm Po}) + \langle n_{\rm Bi}(t)\rangle\,. \tag{7}$$

The above equation provides all the ingredients that are necessary for our analysis. It shows that, if we are able to measure $n_{\rm Po}(t)$ as a function of time with a high accuracy, we can provide an estimate for $n_{\rm Bi}(t)$, which is the main background for CNO neutrinos detection.

3. Perspectives for CNO signal extraction

The accuracy of the proposed method can be quantified with straightforward analytical considerations by making the following exercise. We assume that the Bismuth-210 event rate is constant[2], obtaining from Eq. (7):

$$n_{\rm Po}(t) = [n_{\rm Po,0} - n_{\rm Bi}]\, \exp(-t/\tau_{\rm Po}) + n_{\rm Bi}\,. \tag{8}$$

We imagine to collect the Polonium-210 events for a total period equal to Δt. We then divide this time interval into two large bins from $[0, \Delta t/2]$ and $[\Delta t/2, \Delta t]$. In the absence of the Bismuth-210 contribution, the ratio of events collected in the two bins is equal to $N_2/N_1 = \exp\left(-\Delta t/2\tau_{\rm Po}\right)$. The deviations of N_2/N_1 from this value can be used to measure the $\beta-$activity of Bismuth-210. We obtain, in fact:

$$N_2 - N_1\, e^{-\frac{\Delta t}{2\tau_{\rm Po}}} = \varepsilon\, M\, n_{\rm Bi}\, \frac{\Delta t}{2}\, \left(1 - e^{-\frac{\Delta t}{2\tau_{\rm Po}}}\right)\,. \tag{9}$$

where M indicates the detector mass and ε indicates the detection efficiency (averaged over the integration period) that we assumed not to vary significantly. By propagating the statistical errors $\Delta N_2 = \sqrt{N_2}$ and $\Delta N_1 = \sqrt{N_1}$, one is able to estimate the accuracy $\Delta n_{\rm Bi}$ of the determination of the Bismuth-210 decay rate. In the assumption that $n_{\rm Po,0} \gg n_{\rm Bi}$, we obtain

$$\Delta n_{\rm Bi} \simeq \sqrt{\frac{n_{\rm Po,0}}{\tau_{\rm Po}\, M}}\, f(\Delta t) \tag{10}$$

where we considered $\varepsilon \sim 1$. The function $f(\Delta t)$ is explicitly given as:

$$f(\Delta t) = \left(\frac{2\,\tau_{\rm Po}}{\Delta t}\right)\, e^{-\frac{\Delta t}{4\tau_{\rm Po}}}\, \sqrt{\frac{1 + e^{-\frac{\Delta t}{2\tau_{\rm Po}}}}{1 - e^{-\frac{\Delta t}{2\tau_{\rm Po}}}}}\,. \tag{11}$$

[2] We remark that, in the analysis of the experimental data, it is not necessary to make *a-priori* assumptions on the time evolution of $n_{\rm Bi}(t)$ since this can be determined from the experimental data themselves.

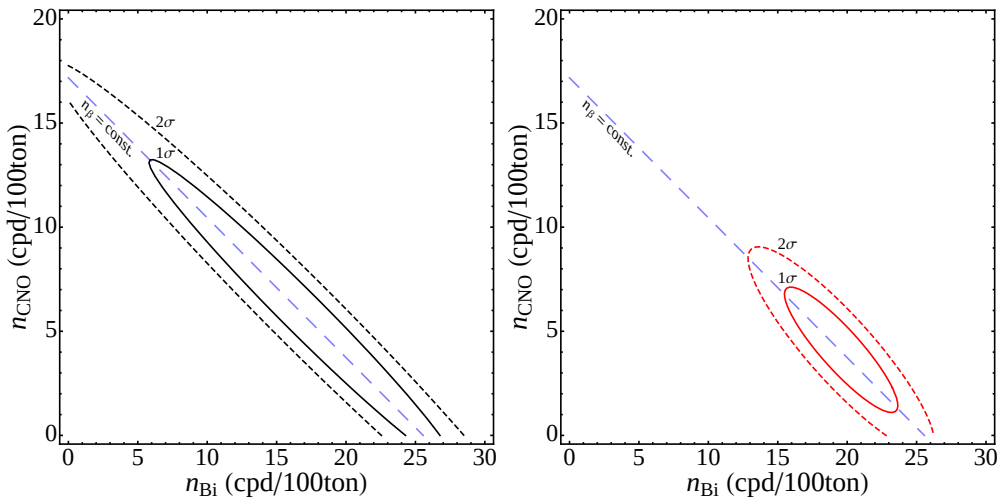

Figure 2. The 1σ and 2σ allowed regions obtained by a fit to simulated data, assuming a detector mass $M = 100$ ton and an observation period $\Delta t = 1$ yr. In the left panel, we consider only information contained in the energy distribution of the events. In the right panel, we perform a fit in the domain of energy and time, taking into account the relationship between Polonium-210 and Bismuth-210 expressed by Eq. (8).

The analytic estimates given above correspond within $\sim 15\%$ with the results of numerical simulations reported in tab. 1. These are obtained by assuming that the Bismuth-210 event rate is equal to $n_{\rm Bi} = 20$ cpd/100 ton, while the initial Polonium-210 event rate have been varied in the range $n_{\rm Po,0} = 2000 - 8000$ cpd/100 ton. We binned the data over five days and then extracted $n_{\rm Bi}$ and $n_{\rm Po,0}$ by fitting the data over an observation period Δt with the functional form in Eq. (8). For an initial Polonium activity equal to $n_{\rm Po,0} = 2000$ cpd/100 ton, we reach an accuracy comparable to the expected CNO signal, $n_{\rm CNO} \simeq 5$ cpd/100 ton, after a time $\Delta t \sim 300d$ ($\Delta t \sim 150d$) for a 100 ton (1000 ton) detector.

All this shows that the information contained in the time evolution of Polonium-210 can efficiently remove the degeneracy between Bismuth-210 background and CNO neutrinos signal. This can be better appreciated by comparing the left and the right panel of Fig. 2 that are obtained by using the same set of simulated data. In the right panel, we perform the fit *in the domain of energy and time* and we take advantage of Eq. (8) between Polonium-210 and Bismuth-210 rates. As a result of this, we obtain a considerable improvement in the CNO signal determination. The final uncertainty is $\Delta n_{\rm CNO} \simeq 2.1$ cpd/100 ton, showing that present generation liquid scintillator experiment, like e.g. Borexino, already have the potential to probe the CNO neutrino flux, provided that they are stable for sufficiently long time (~ 1 yr) and/or the initial Polonium-210 contamination can be made sufficiently low. Future kton-scale detectors, like e.g. SNO+, will be able to start discriminating between the predictions of high and low metallicity solar models.

References

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