The $^{51}$Cr neutrino source and Borexino: a desirable marriage

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Abstract

Exposure to a $^{51}$Cr neutrino source as that used in Gallex will provide an excellent overall performance test of Borexino, which should collect about 1400 source induced events, with an initial rate of about 35 counts per day. This will be particularly important if MSW-small-angle turns out to be the solution of the solar neutrino problem. In addition, if an independent, accurate calibration is available, one will have an interesting experiment on neutrino properties: as an example, a neutrino magnetic moment of the order $5 \cdot 10^{-11} \mu_B$ could be detected/excluded at the 90% C.L.

Borexino at Gran Sasso [1] has a lot to tell about $^7$Be solar neutrinos: Standard Solar Models (SSMs) predict a rate $\lambda_\odot \simeq 50$ counts per day (c.p.d.), mostly from the $^7$Be neutrinos, over an estimated background $\lambda_b \simeq 10$ c.p.d. At such rates, seasonal modulations of $\lambda_\odot$, corresponding to variations in the earth-sun distance $R_{ES}$, should allow a clean discrimination of signal to background. In addition, the Just-So oscillation mechanism predicts large seasonal modulations of the signal, well in excess of the $1/R_{ES}^2$ law, which are clearly detectable with Borexino.

On the other hand, several scenarios predict much smaller event rates, comparable to or even smaller than the expected background: this is the case of the MSW-small-angle solutions, both for oscillations into active and sterile neutrinos. Also, if one insists on the massless neutrinos of the minimal electroweak theory, the available results (from Gallex [2], Sage [3] Chlorine [4] and Kamiokande [5]) together with the luminosity constraint imply

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an extreme reduction of the $^7$Be neutrino flux $\Phi_{^7\text{Be}}$ with respect to $\Phi_{^7\text{Be}}^{\text{SSM}}$, see e.g. [6,7]. A reasonable question is thus the following one:

- a) How to assess definitely the capability of Borexino to detect $\nu_e$ from $^7$Be, if the solar flux is low?

In this case, an overall performance test, with the exposure of Borexino to a man made neutrino source, is a must. We should like to demonstrate that the $^{51}$Cr source which was used by the Gallex collaboration in their pioneer experiment [8] looks ideal in this respect. In addition, we remark that if an independent, accurate calibration of Borexino is available, the neutrino source experiment is interesting for the study of neutrino properties: the $\nu_e - e$ cross section can be accurately measured, e.g. searching for the contribution of a neutrino magnetic moment. Also, neutrino oscillations along the path from the source to the interaction point can be investigated (disappearance experiment). We consider thus the following questions:

- b) What is the sensitivity to a neutrino magnetic moment?
- c) Which region in the oscillation plane can be investigated?

As a working hypothesis, we assume that the source is placed just outside the external wall of the detector, at a distance $D = 9$ m from the center (see fig.[1]), i.e. the easiest location. At the end of this note we shall consider the advantages/disadvantages of other possible configurations.

**a) The overall performance test**

The relevance of a $^{51}$Cr source as that which was used in Gallex, with activity at end of bombardment (EOB) $A_{\text{EOB}} = 61.9 \pm 1.2$ PBq, is immediately understood by observing that the corresponding neutrino flux at the centre of the detector, $\phi_{\text{EOB}} = (6.1 \pm 0.1) \cdot 10^9\text{cm}^{-2}\text{s}^{-1}$ is quite close to the solar $^7$Be neutrino flux predicted by SSMs: $\Phi_{^7\text{Be}}^{\text{SSM}}=5.1 \cdot 10^9\text{cm}^{-2}\text{s}^{-1}$, according to Ref. [9]. As well known [8], the spectrum of the $^{51}$Cr source (see table [2]) is quite similar to that of the $^7$Be electron capture, so that the source induced event rate $\lambda_s$ over its lifetime ($\tau = 39.97 \pm 0.01$ days) is well comparable to the event rate predicted by SSMs. More precisely, one has:

$$\lambda_s = N_e \langle \sigma_{\text{CC+NC}} \rangle \phi_s f ,$$

where full detection efficiency is assumed, $N_e = 3.2 \cdot 10^{31}$ is the number of electrons in the fiducial (100 tons) scintillator mass and $\langle \sigma_{\text{CC+NC}} \rangle$ is the electroweak cross section of $\nu_e - e$ scattering for kinetic energy of the recoiling electron $T_e \geq 250$ keV [4], averaged over the source components (see table [2]); $\phi_s$ is the neutrino flux at the detector center and $f(R/D)$ is the geometrical factor accounting for the finite distance $D$ from the (pointlike) source to the center of a spherical detector with radius $R$ (for the present case $R = 3$ m):

$$f(x) = \frac{3}{2x^3} \left[ x - \frac{1-x^2}{2} \ln \left( \frac{1+x}{1-x} \right) \right] .$$
All this gives, at EOB, $\lambda^{EOB}_s = 39$ c.p.d. Actually, it takes a few days to bring the source from the reactor to LNGS. Assuming that, as in Gallex, the exposure can start about 4 days after EOB and that it extends over a few lifetimes, one should collect a number of source induced events $N_s \simeq 90\% \lambda^{EOB}_s \tau = 1400$.

There are two main differences with respect to Gallex: i) a gain by an order of magnitude in statistics, originating mainly from the larger number of scattering centers. ii) As Borexino is a real time detector, the time dependence of source induced events can be accurately followed, so that background will be easily subtracted.

In the absence of background and/or solar neutrino events, $N_s$ could be ultimately determined to the level of its statistical accuracy. Here and in the following all uncertainties will be evaluated at the 90% Confidence Level (C.L.). In this way one has $\Delta N_s/N_s = 1.64/\sqrt{N_s} = 4.4\%$. Actually, from the background and/or the sun one expects a counting rate in the range (10–60) c.p.d. Correspondingly, we estimate an accuracy $\Delta N_s/N_s$ in the range (6–10)% from Monte Carlo simulations. We shall take $\Delta N_s/N_s = 8\%$ as an indicative value, corresponding to $(\lambda_\odot + \lambda_b) = 30$ c.p.d. By summing in quadratures this uncertainty with that on the source activity $(\Delta A/A = 3.1\%)$, the relative error in the comparison between expected and detected events will be, approximately:

$$\epsilon = \sqrt{(\Delta N_s/N_s)^2 + (\Delta A/A)^2} = 8.6\% \quad \text{at 90\% C.L.}$$

(3)

All this means that, as one cannot switch the Sun on and off, then it is best to switch another sun on.

b) The source experiment and the neutrino magnetic moment

If the detection efficiency is accurately determined, the source experiment provides a precise measurement of the $\nu_e - e$ elastic cross section and the possible contribution of a neutrino magnetic moment $(\sigma_{CC+NC} \rightarrow \sigma_{CC+NC} + \sigma_{mm})$ is detectable. The relative contribution to the cross section for $T_e > 250$ keV, $\xi = \langle \sigma_{mm}/\sigma_{CC+NC} \rangle$, is proportional to $\mu^2_\nu$ and one has $\xi = 0.39$ for $\mu_\nu = 10^{-10} \mu_B$. One can thus study a neutrino magnetic moment:

$$\mu_\nu/(10^{-10} \mu_B) = \sqrt{\epsilon/\xi} \simeq 0.5 \quad \text{at 90\% C.L. ,}$$

(4)

about an order of magnitude better than given from available experiments, close to the astrophysical upper-bounds (see fig. 2) and in the same range as planned in future experiments 11,12.

c) The source experiment and neutrino oscillations

Similar to the case of reactor experiments, one can perform a disappearance experiment 13, the main differences being: i) one is working with neutrinos (not antineutrinos); ii) the energy spectrum is precisely determined; iii) detection is through $\nu - e$ scattering.

Neutrino oscillation would result in a reduced number of detected events. For the case of oscillation into sterile neutrinos, the limiting (i.e. 90\% C.L.) detectable transition probability $P_{\nu_e \rightarrow \nu_s}$, averaged over neutrino paths and energies, is immediately obtained from the condition $P_{\nu_e \rightarrow \nu_s} = \epsilon$. The explorable region in the $(\sin^22\theta, \Delta m^2)$ plane, is shown in fig. 3.
The reader can immediately verify the intersections of the curve with the borders of the figure, since for large mass differences $\sin^22\theta = 2\epsilon$ whereas for maximal mixing $\delta m^2 = 4\sqrt{\epsilon}E/L$, where $L$ is the average of the squared path-lengths and $E$ is a suitable average neutrino energy, essentially the energy of the most intense line.

Due to the neutral current (NC) interaction, the experiment is somehow less sensitive to oscillations into active neutrinos, say $\nu_\tau$, see again fig. 3. With respect to the previous case, one has $\sin^22\theta \rightarrow \sin^22\theta(1 - \rho)$ where $\rho = \langle \sigma_{NC} \rangle/\langle \sigma_{CC+NC} \rangle = 0.2$, which results in a uniform shift to the right in the logarithmic plot.

From fig. 3 one sees that the region which can be accessed with the source experiment is already excluded. This result is not so bad, as it actually provides an additional test for Borexino: if the number of source events comes out smaller than expected, it cannot be due to neutrino oscillations.

d) The optimal location of the source

The source might be placed just outside the inner steel sphere, a distance $d = 6.5\,\text{m}$ from the detector center. With respect to the previous case, the event number $N_s$ increases by a factor 2; for $(\lambda_\odot + \lambda_b) = 30\,\text{c.p.d.}$ the uncertainty is $\Delta N_s/N_s = 4.5\%$, comparable to $\Delta A/A$. In place of eq. (3) one has now $\epsilon' = 5.5\%$. A small gain ($\sqrt{\epsilon'/\epsilon}$) is obtained for the limiting magnetic moment. Concerning neutrino oscillations, for $\Delta m^2 \geq 1\,\text{eV}^2$ one can reach $\sin^22\theta = 0.1$, a region not completely excluded. On the other hand, as a consequence of the shorter baseline, the lower limit for $\Delta m^2$ increases for a factor $D/d\sqrt{\epsilon'/\epsilon} \simeq 1.1$.

If the source is placed at the center of the detector (the hardest choice from the technical point of view), the expected rate for standard neutrinos $[\lambda_c = A\langle \sigma_{CC+NC} \rangle 3N_e/(4\pi R^2)]$ is a factor 27 larger than when the source is placed just outside the tank. However, with such a huge statistics, the error on the activity is now dominant.

In conclusion the easiest location (just outside the tank) looks as the most convenient one.

In the Borexino proposal, the exposure to an intense beta emitter such as $^{90}\text{Sr}$ was considered and the potential for the study of antineutrino properties, as the magnetic moment, was discussed [4]. The $^{51}\text{Cr}$ source has several advantages: i) neutrinos with almost the same spectrum as the solar ones will be detected; ii) the detection reaction is the same for solar and source neutrinos and iii) last not least, the source is there (it has to be reactivated, of course). We should like to encourage our colleagues to exploit its potential, when Borexino will be ready.

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TABLE I. For each of the four lines of the $^{51}$Cr spectrum we show the neutrino energy $E_{\nu}$, the relative intensity $P$, the $\nu_e - e$ cross section $\sigma_{CC+NC}$, that for $\nu_{\tau} - e$ scattering $\sigma_{NC}$ (both calculated following ref. [14]) and the contribution to the cross sections for a magnetic moment $\mu = 10^{-10} \mu_B$. All these have been integrated for electron kinetic energies higher than 250 keV. In the last row, the values averaged over the source spectrum are shown.

| $E_{\nu}$ [MeV] | P $[10^{-46} \text{cm}^2]$ | $\sigma_{CC+CN}$ $[10^{-46} \text{cm}^2]$ | $\sigma_{CN}$ $[10^{-46} \text{cm}^2]$ | $\sigma_{mm}$ $[10^{-46} \text{cm}^2]$ |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0.751 | 0.09 | 25.2 | 5.84 | 9.82 |
| 0.746 | 0.81 | 24.8 | 5.76 | 9.70 |
| 0.431 | 0.01 | 1.45 | 0.45 | 0.78 |
| 0.426 | 0.09 | 1.14 | 0.36 | 0.62 |
| **Average:** | | **22.5** | **5.23** | **8.81** |
FIGURES

FIG. 1. Schematic layout of Borexino and the $^{51}$Cr source.

FIG. 2. Upper bounds on $\mu_\nu$ from reactor [15–17] and accelerator experiments [18], at the 90% C.L. (arrows), sensitivity of Borexino at the same C.L. (dashed line). Astrophysical and cosmological arguments suggest $\mu_\nu \leq 3 \cdot 10^{-11} \mu_B$, see e.g. Ref. [19].

FIG. 3. The borders of the 90% C.L. regions explorable with the source at $D = 9$ m from the detector center for oscillations into sterile neutrinos (dot-dashed line) and into $\nu_\tau$ (dashed line). Available results from reactor [20,21] and accelerator [22] experiments are also shown (solid line).
INNER STEEL SPHERE

R = 3.0 m

INNER VESSEL

R.B. VOLUME

CR SOURCE

0.44 m

0.55 m

17.0 m

8.5 m

D = 9.0 m

17.0 m

8.5 m

8.5 m
Fig. 2
