Measurement of the cosmogenic ^{11}C background with the Borexino Counting Test Facility

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Abstract.

Within next year, two organic liquid scintillator detectors, Borexino [1] and KamLAND [2], will start the measurement of the mono-energetic ^{7}Be solar neutrino flux in real time. Besides this objective, both of them have the potential to detect neutrinos from the *pep* fusion reaction and the CNO cycle in the Sun.

For this purpose, two conditions are required: an extremely low radioactive contamination level and the efficient identification of the ^{11}C background, produced in reactions induced by the residual cosmic muon flux on ^{12}C. In the process, a free neutron is almost always produced. ^{11}C can be tagged on an event by event basis by looking at the three-fold coincidence with the parent muon track and the subsequent neutron capture on protons. We tested successfully this coincidence method with the Borexino Counting Test Facility. The results are reported here.

Moreover, we discuss on the effective potential of Borexino and KamLAND in detecting *pep*+CNO neutrinos compared to SNO+ [3], a detector specifically designed for measuring the *pep*+CNO ν flux and that will take data from 2009.

Keywords: Muon-induced nuclear reactions; Photonuclear reactions; pep fusion reaction, CNO cycle, Solar neutrinos, Low background experiments; Borexino

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1. INTRODUCTION

The next step in solar neutrino physics, after the evidences [2, 4, 5, 6, 7, 8] for neutrino oscillations as the explanation of the long-standing solar neutrino problem [9], is the real-time detection of the low energy ($<$ 2 MeV) component of the solar neutrino spectrum. In fact, only a tiny fraction (less than 0.01%) of the predicted solar neutrino spectrum has been studied in real time. The detection of neutrinos from *pp* and *pep* nuclear fusion reactions, ^{7}Be electron capture and the CNO-cycle will allow to investigate sub-dominant effects in the standard large mixing angle (LMA) solution [10], to look for new physics such as a non-zero neutrino magnetic moment, non-standard neutrino interactions [11], and to improve our knowledge of the Solar Standard Model (SSM) [12].

Particularly, *pep* and CNO neutrinos are an ideal source for probing the energy region, between 1 and 3 MeV, at which the transition between matter and vacuum dominated oscillations is supposed to occur, according to the MSW-LMA oscillation solution [12].

Deep underground organic liquid scintillator detectors, like Borexino and KamLAND, can detect *pep* and CNO solar neutrinos by the characteristic Compton-like electron recoil spectrum they produce.

If extremely low radioactive contamination level are reached (10^{-17}g/g of scintillator for ^{238}U and ^{232}Th and 10^{-15}g/g for ^{nat}K), the main challenge they have to face is the identification and suppression of the ^{11}C background.

^{11}C is produced deep underground by residual cosmic muons interacting with ^{12}C atoms in the scintillator. In 95% of the cases [13], the reaction can be summarized as follows:

$$\mu\ (+\ secondaries) + {}^{12}C \rightarrow \mu\ (+\ secondaries) + {}^{11}C + n. \tag{1}$$

^{11}C decays (τ = 29.4 min) can be thus detected and subtracted exploiting the neutron emission in the reaction. If ^{11}C is produced in association with a neutron emission, the three-fold coincidence (TFC) among the parent muon, the neutron capture on protons, and the ^{11}C decay, can be extremely efficient in tagging ^{11}C event by event. Once tagged, in order to suppress ^{11}C events, a cut in space and time is applied around each capture point of neutron created by the muon-induced shower in scintillator. All the events within a time Δt from the double muon+neutron coincidence and inside a sphere of radius r from the neutron capture point are rejected. Note that the information carried by the neutron capture is independent on the position of the ^{11}C birthplace. Therefore, the radius r of the spherical cut must be equal to a few times the average neutron range and Δt equal to a few times the the ^{11}C mean life.

The goal is then the suppression of ^{11}C events, minimizing the data loss.

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TABLE 1. Depth, residual muon flux, average muon energy, and neutrons capture rate (N) at KamLAND, Borexino, and SNO+. This table is taken from [13]

	Depth $[m.w.e.]$	Φ_μ $[\mu/\mathrm{m}^2/\mathrm{h}]$	$< \mathrm{E}_\mu >$ $[GeV]$	**N** $[cts/d/100tons]$
KamLAND	2700	9.6	285	300
Borexino	3800	1.2	320	40
SNO+	6000	0.012	350	0.43

TABLE 2. Total expected ^{11}C decay rate and ^{11}C-induced raw background rate (B_0) in the pep window [0.8-1.3 MeV] at KamLAND, Borexino, and SNO+. This table is taken from [13].

	^{11}**C rate** $[cts/d/100tons]$	^{11}**C rate** $[10^{-4}/\mu/\mathrm{m}]$	$\mathbf{B_0}$ $[cts/d/100tons]$
KamLAND	107	48	37
Borexino	15	52	5.1
SNO+	0.15	55	0.056

2. A DIRECT COMPARISON AMONG BOREXINO, KAMLAND AND SNO+

The ^{11}C production rate depends on the location and depth of the experiment. In Table 1, the expected muon fluxes are quoted for KamLAND, Borexino and SNO+. The flux ratio among the three experiments, 800:100:1, and the neutron rates (only 0.43 cts/d/100 tons for SNO+) make SNO+ the best candidate for measuring the *pep* and CNO ν flux. Nevertheless, waiting for SNO+, both KamLAND and Borexino can provide some information.

If Borexino is favored by the lower neutron production rate, KamLAND is advantaged by the bigger active mass, about 3 times the Borexino one. The energy region of observation is defined between 0.8 MeV, due to the presence of ^{7}Be νs, and 1.3 MeV, beyond which the signal to background ratio is disfavored as shown in figure 1 for the Borexino case. The expected rate for *pep* and CNO neutrinos in Borexino between [0.8,1.3] MeV is 0.015 day^{-1} ton^{-1}. In such energy window, the expected ^{11}C production rates (table 2) are evaluated by scaling the results obtained by the CERN experiment NA54 performed with a muon beam on a scintillator target [14].

We evaluated that background from ^{11}C is negligible in SNO+ [13]. *Vice versa*, it can not be neglected both in Borexino and KamLAND. In an ideal condition, with a perfectly cleaned scintillator and detection efficiency equal to 1, *pep*+CNO ν signal to background ratio can be reduced to 1 with the TFC technique in Borexino, loosing only 0.3% of the data. In KamLAND, accepting a data loss of 50%, the signal to background ratio is equal only to 0.3. The only way for KamLAND to improve it, is to reduce the mass×time detector fraction loss by intersecting the spherical volume around the neutron capture position with a cylindrical volume around the muon track. In fact, we observe with the Monte Carlo, that ^{11}C is produced mainly in proximity of the muon track.

In order to test the TFC technique, we apply it to data from the Borexino Counting Test Facility (CTF). This is, to the best of our knowledge, the first *in situ* event by event detection of ^{11}C production deep underground.

3. EXPERIMENTAL SETUP

CTF [1] (figure 2) is the Borexino prototype detector installed at the Gran Sasso underground laboratory. It was designed to test the required radiopurity of the Borexino liquid scintillator and its purification strategy. The active detector consists of 3.73 tons of the Borexino-like PC+PPO (1.5 g/l) scintillator in a 1 m radius transparent nylon vessel. A 7 m diameter stainless steel open structure supports 100 8"-PMTs equipped with light concentrators which provide an optical coverage of 21%.

The detector is housed within a cylindrical tank (11 m diameter and 10 m height) containing 1000 tons of pure water, which provides 4.5 m shielding against neutrons from the rock and external γ-rays from the rock and from the PMTs themselves. 16 upward-looking PMTs mounted on the bottom of the tank veto muons by detecting the Čerenkov light in water (muon veto system). The veto efficiency is larger than 99.7% for muon shower events with energy $>$ 4 MeV.

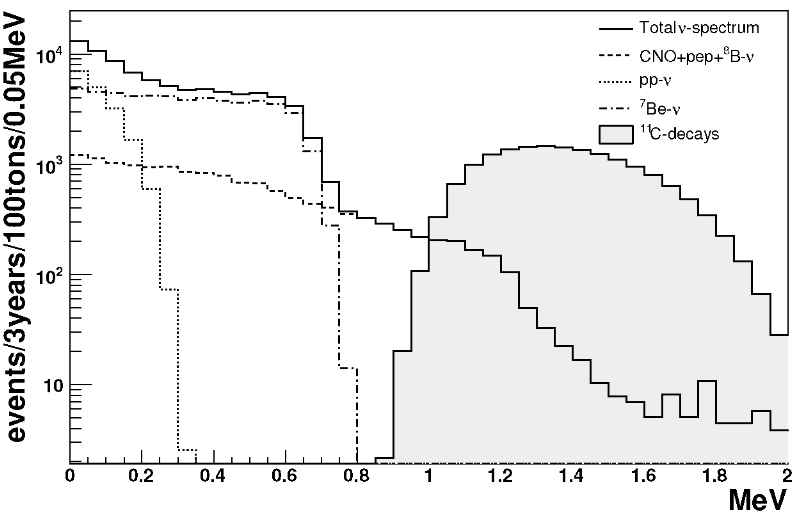

FIGURE 1. Expected recoil electron energy for different solar neutrinos interacting in Borexino assuming 3 year live time exposure, 100 tons fiducial volume and a detector energy resolution of $5\%/\sqrt{E_{[MeV]}}$. Neutrino fluxes are derived assuming the Standard Solar Model BP2004+LUNA [15, 16] and the LMA oscillation scenario [17]. The shaded superimposed area is the expected ^{11}C background [14].

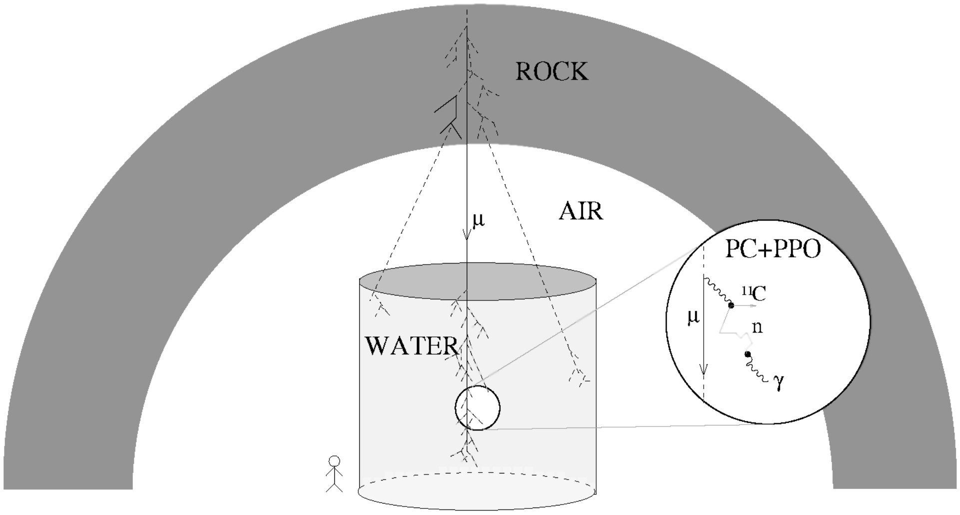

FIGURE 2. Overview of the CTF detector and of the physical processes included in the simulation.

A set of ADCs and TDCs records the charge and time information of the PMT pulses for each event. During the acquisition, a second identical electronic chain is sensitive to the next event occurring within the following 8.3 ms. The electronics can therefore detect pairs of fast time-correlated events. The coincidence time between the two chains is measured by means of a long range TDC. Further events are ignored until the first chain is "re-armed" ($\sim$ 20 ms). For longer delays the computer clock is used providing an accuracy of $\sim$ 50 ms.

The energy response of the detector is calibrated run-by-run by using the energy spectrum of ^{14}C decays, naturally present in the scintillator. The measured light yield is $\sim$ 3.6 photoelectrons per PMT for 1 MeV electrons. The electronics saturate at about 6 MeV.

TABLE 3. Efficiencies for the ^{11}C production rate measurement in CTF. This table is taken from [19].

	Efficiency	Value
ε_{vis}	visible channels	0.955
ε_{end}	end of run	0.990
ε_t	μ-2.2$MeV\,\gamma$ coincidence	0.925
ε_{escape}	contained neutrons	0.732
ε_c	^{11}C energy E $\in$ [1.15, 2.25] MeV 2.2$MeV\,\gamma$ energy E $>$ 0.2 MeV ^{11}C-2.2$MeV\,\gamma$ distance d $<$ 0.35 m	0.563
Total		0.360

4. MEASUREMENT OF THE μ-INDUCED ^{11}C PRODUCTION RATE IN CTF

At a depth of 3800 mwe, where the CTF detector is located, cosmic muons have a mean energy of 320 GeV and they produce enough light to fire the detector. Cosmic muons in CTF are then selected among those events tagged by the muon veto and saturating the electronics (detection efficiency 1). The characteristic γ of 2.2MeV following the muon-induced neutron capture on hydrogen is tagged by opening a gate (10 μs - 1 ms) after the detection of a cosmic muon. The ^{11}C decay is finally selected by opening a time gate of 300 min ($10\times\tau_{11C}$) after each $\mu-\gamma$ coincidence.

The time profile of the events selected by the TFC is fitted with:

$$F(t) = \frac{A}{\tau}e^{-\frac{t}{\tau}} + B \tag{2}$$

where A is the number of ^{11}C events, τ the ^{11}C mean life and B is the background activity due to random coincidence, which has been measured to be constant (as expected) by opening the time window independently on the $\mu-\gamma$ coincidence. The measured mean life time is compatible (27 $\pm$ 11 min) with the expected one.

Performing the fit with τ fixed to the nominal value, the ^{11}C production rate is computed from:

$$\begin{aligned} R(^{11}C) &= \frac{A}{\frac{4}{3}\pi r^3 \rho T} \cdot \frac{1}{\varepsilon_{vis}\cdot\varepsilon_{end}\cdot\varepsilon_t\cdot\varepsilon_{escape}\cdot\varepsilon_c} \\ &= 0.130 \pm 0.026(stat) \pm 0.014(syst)day^{-1}ton^{-1} \end{aligned} \tag{3}$$

(A = 54 $\pm$ 11, b$\times$T$_w$ = 164 $\pm$ 15 and χ^2/d.o.f = 9.7/13) where r is the selected volume radius (0.8 m), ρ the scintillator density (0.88 g/cm^3) and T the detector live time (611 days). All the efficiencies in Eq 3 are reported in Table 3.The fit is shown in figure 3.

The main systematic sources are due to the reconstruction position and of the light yield uncertainties. The analysis measured rate is in good agreement with the expected one from the CERN experiment: 0.146 ± 0.015 day^{-1} ton^{-1}. A complete description of the Monte Carlo simulation and of the data analysis can be found in [19].

5. DISCUSSION

The success of the three-fold coincidence technique in selecting ^{11}C events and in evaluating correctly their production rate is promising in prospective of deep underground liquid scintillator detectors.

In the Borexino case, including in the analysis also the background contribution due to the trace contaminants in the scintillator mixture, ^{238}U and ^{232}Th at 10^{-17}g/g and ^{nat}K at 10^{-15}g/g, the non-cosmogenic contaminants, B$_{n.c.}$, contribute to the *pep*+CNO window with 0.006 day^{-1} ton^{-1}.

In order to reach signal-to-background ratio equal to 1:

$$\frac{S_\nu}{(1-\varepsilon_{rej})\times B_{11C} + B_{n.c.}} = 1, \tag{4}$$

the ^{11}C rejection efficiency, ε_{rej}, must be equal to 0.88.

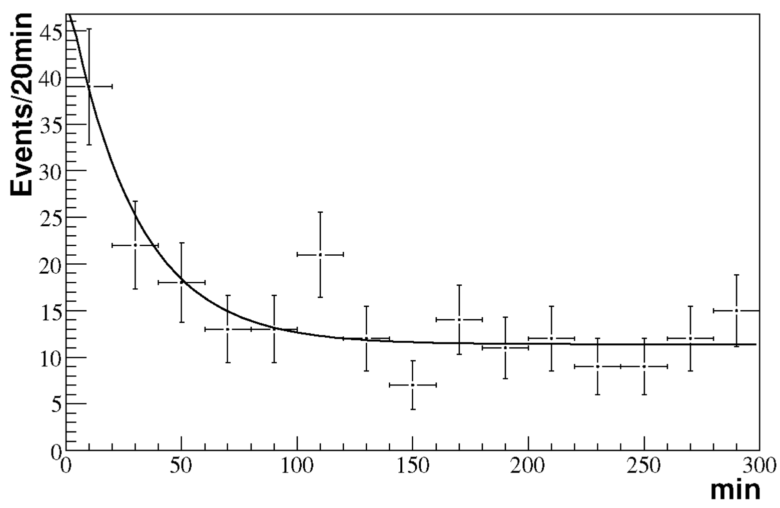

FIGURE 3. Fit of the data sample time profile selected by the three-fold coincidence (χ^2/ndf = 9.7/13) with free parameters A and b (see Eq 2).

TABLE 4. Predicted ^{11}C decay rejection efficiency for the Borexino detector in order to reach a signal (*pep*+CNO νs) to background (^{11}C decays) ratio equal to 1. The trace contamination is assumed at the level of 10^{-17}g/g for ^{238}U and ^{232}Th and 10^{-15}g/g for ^{nat}K.

	Efficiency	Value
ε_{vis}	visible channels	0.955
ε_t	μ-2.2$MeV\gamma$ coincidence	0.989
ε_c	2.2$MeV\gamma$ energy E > 0.2 MeV	0.954
ε_d	^{11}C-2.2$MeV\gamma$ distance d < 1 m	0.984
ε_t	^{11}C-2.2$MeV\gamma$ coincidence time T < $5\times\tau_{^{11}C}$	0.993
Total		0.880

The rejection efficiency is limited by the physics (^{12}C(X,Y)^{11}C invisible channels), by the detector itself (energy threshold and dead time) and by the software cuts in time and space around the neutron capture γ's.

Assuming a neutron rate of $1.5\times10^{-2}\ \mu^{-1}\ \mathrm{m}^{-1}$ [13, 21], we estimate that, even including the trace contamination, Borexino can reach a signal-to-background ratio equals to 1, loosing only 14% of the data [13, 22]. The optimal cuts and the relative efficiencies expected for Borexino are quoted in Table 4.

Furthermore, the Borexino collaboration is investigating the possibility to improve the TFC technique by reconstructing the muon track.

6. CONCLUDING REMARKS

The agreement between the measured ^{11}C production rate observed in CTF and the value extrapolated from the measurement performed at the NA54 CERN facility in a muon on target experiment [14], demonstrated that the three-fold coincidence technique is a powerful tool for tagging and suppressing the ^{11}C background. The results also indicate an agreement with the theoretical calculation in [13].

Waiting for SNO+, KamLAND can be challenging if a precise muon-tracker will be developed. Even without the muon-tracker, however, on the basis of the last promising CTF measurements of trace contaminants, Borexino has the potential for a first estimation of the *pep*+CNO ν flux from 2007, when data taking will start.

REFERENCES

1. Borexino Collaboration, G. Alimonti *et al.*, Nucl. Instr. Meth. A **406** (1998) 411.
2. KamLAND Collaboration, K. Eguchi *et al.*, Phys. Rev. Lett. **90** (2003) 21802.
3. C. Kraus for the SNO+ Collaboration, Prog. Part. Nucl. Phys. **57** (2006) 150.
4. SNO Collaboration, Q. R. Ahmad *et al.*, Phys. Rev. Lett. **89** (2002) 011301.
5. Homestake Collaboration, B. T. Cleveland *et al.*, Astrophys. J. **496**(1998) 505.
6. SAGE Collaboration, J. N. Abdurashitov*et al.*, J. Exp. Theor. Phys. **95**(2002) 181.
7. GNO Collaboration, M. Altmann *et al.*, Phys. Lett. B **616** (2005) 174.
8. T. Nakaya [Super-Kamiokande Collaboration], eConf C020620, SAAT01 (2002).
9. J. N. Bahcall and M. H. Pinsonneault, Rev. Mod. Phys. **64** (1992) 885.
10. G. L. Fogli *et al*, Prog. Part. Nucl. Phys. **57** (2006) 742.
11. A. de Gouvea and C. Pena-Garay, Phys. Rev. D **71** (2006) 093002.
12. J. N. Bahcall and C. Pena-Garay, New J. Phys. **6** (2004) 63.
13. C. Galbiati *et al.*, Phys. Rev. C **71** (2005) 055805.
14. T. Hagner *et al.*,Astropart. Phys. **14** (2000) 33.
15. J. N. Bahcall and M. H. Pinsonneault, Phys. Rev. Lett. **92** (2004) 121301.
16. A. Formicola *et al.*, Phys. Lett. B **591** (2004) 61.
17. J. N. Bahcall and C. Peña-Garay, J. High Energy Phys. **11** (2003) 004 .
18. Borexino Collaboration, G. Alimonti *et al.*,Astropart. Phys., **8** (1998) 141 .
19. H. Back *et al.*, Phys. Rev.C **74** (2006) 045805.
20. D. Franco *The Borexino Experiment: Test of the Purification Systems and Data Analysis in the Counting Test Facility.*, Ph.D. Thesis, Università degli Studi di Milano and University of Heidelberg, 2005, http://www.ub.uni-heidelberg.de/archiv/5403.
21. LVD Collaboration, M. Aglietta *et al.*, 26th International Cosmic Ray Conference, Salt Lake City, UT, 17-25 Aug 1999, Salt Lake City 1999, Cosmic ray, **2** (1999) 44.
22. D. Franco for the Borexino Collaboration, Nucl. Phys. Proc. Suppl. **145** (2005) 29.