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CNO and *pep* neutrino spectroscopy in BOREXino: measurement of the cosmogenic ^{11}C background with the Counting Test Facility

Davide Franco for the BOREXino Collaboration

Dipartimento di Fisica - Università di Milano

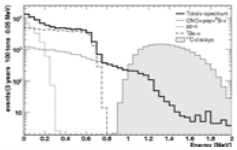
INFN – Sezione di Milano

Introduction

Borexino is an experiment for low energy neutrino spectroscopy at the Gran Sasso underground laboratories. It is designed to measure the mono-energetic ^{7}Be solar neutrino flux in real time, via neutrino-electron elastic scattering in ultra-pure organic liquid scintillator.

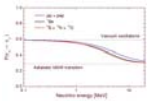
Borexino has the potential to also detect neutrinos from the *pep* fusion process and the CNO cycle. For this measurement to be possible, radioactive contamination in the detector must be kept extremely low. Once sufficiently clean conditions are met, the main background source is ^{11}C, produced in 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. This coincidence method has been implemented on the Borexino Counting Test Facility data.



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%/E$^{1/2}$. Neutrino fluxes are derived assuming the Standard Solar Model BP2004+LUNA [18, 19] and the LMA oscillation scenario [20]. The shaded superimposed area is the expected ^{11}C background [10].

Why *pep* and CNO neutrinos?



- Ideal source for probing the energy region, between 1 and 3 MeV, at which the transition between matter and vacuum dominated oscillations according to the MSW-LMA oscillation solution
- *pep* and *pp* solar neutrino rates are directly related, via the ratio of the cross section of the two reactions. Measuring the *pep* neutrino flux is hence a way to study the fundamental *pp* fusion reaction by which the Sun burns, and improves our knowledge of the solar neutrino luminosity
- CNO neutrinos play a key role on the age estimation of the Globular Clusters, pivotal in setting a lower limit for the age of the universe.

The goal

Expected ν-rate in Borexino (BP2004 + LUNA + LMA [BAH04,FOR04]) in the energy range [0.8 – 1.4] MeV:

pep-ν: 9×10^{-3} d^{-1} ton^{-1}
CNO-ν: 6×10^{-3} d^{-1} ton^{-1} → Signal Rate R_ν = 1.5×10^{-2} d^{-1} ton^{-1}

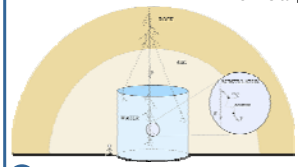
Internal background in [0.8 – 1.4] MeV: 6×10^{-3} d^{-1} ton^{-1} assuming a trace contamination of 10^{-17} g/g U and Th

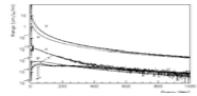
In situ production muon-induced ^{11}C Rate R_{11C} = 7.5×10^{-2} d^{-1} ton^{-1} in the range [0.8 – 1.4] MeV, R_{11C} = 14.6×10^{-2} d^{-1} ton^{-1} in the whole energy spectrum (measured by the NA54 CERN Facility Experiment [HAG00]).

To reach a signal-to-background ratio 1, the required reduction factor is

$f > R_{11C}/R_\nu = 5$

^{11}C in situ production: the Three-Fold Coincidence Technique (TFCT)





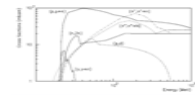
Cumulative range of secondaries generated in showers induced by negatively charged muons at 320 GeV. Results are quoted in cm of range per meter of μ track.

μ (+ secondaries) + ^{12}C → μ (+ secondaries) + ^{11}C + n (~ 250 μs) → + H → D + γ

^{11}C → ^{11}B + e^+ + ν_e (~ 30 min)

Coincidence among:

- **cosmic muon:**
  - rate at LNGS (3700 mwe): 1.16 hr^{-1} m^{-2}
  - average energy: 320 GeV
- **gamma from neutron capture:**
  - energy: 2.2 MeV
  - capture time: 250 μs
- **positron from ^{11}C decay:**
  - deposited energy between 1.022 and 1.982 MeV
  - mean life: 30 min



Cross sections for 11C production from ^{12}C as a function of energy.

Cosmic muon average energy measured at LNGS [GAL04]

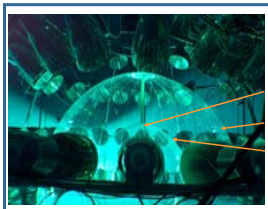
E_μ [GeV]	100	190	285	320	350
Process			Rate [10^{-4}/μ/m]		
$^{12}C(p,p+n)^{11}C$	1.8	3.2	4.9	5.5	5.6
$^{12}C(p,d)^{11}C$	0.2	0.4	0.5	0.6	0.6
$^{12}C(\gamma,n)^{11}C$	19.3	26.3	33.3	35.6	37.4
$^{12}C(n,2n)^{11}C$	2.6	4.7	7.0	8.0	8.2
$^{12}C(\pi^+,\pi+N)^{11}C$	1.0	1.8	2.8	3.2	3.3
$^{12}C(\pi^-,\pi^-+n)^{11}C$	1.3	2.3	3.6	4.1	4.2
$^{12}C(e,e+n)^{11}C$	0.2	0.3	0.4	0.4	0.4
$^{12}C(\mu,\mu+n)^{11}C$	2.0	2.3	2.4	2.4	2.4
Invisible channels	0.9	1.6	2.4	2.7	2.8
Total	28.3	41.3	54.8	59.9	62.2
1σ systematic	1.9	3.1	4.4	5.0	5.2
Measured	22.9	36.0			
1σ experimental	1.8	2.3			
Extrapolated			47.8	51.8	55.1

Production rates for ^{11}C in muon induced showers. The calculated total production rates are compared with the experimental values available at 100 and 190 GeV from Ref. [23], and with the extrapolated values at different mean muon energies.

Invisible channels: no neutron emitted. They account for 4.5% of the ^{11}C production rate.

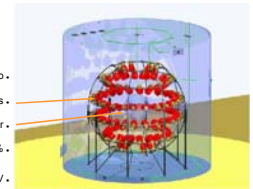
Test of the TFCT

the Counting Test Facility Detector (CTF)



Main properties of the detector [BOR98]

- 4 tons of scintillator PC ($C_6H_5(CH_3)_3$) + 1.5 g/l of PPO ($C_{15}H_{11}NO$)
- 2 m radius "shroud" against external radiation
- 1 m radius vessel housing the scintillator
- 3.6 photoelectron per PMT for 1 MeV electron



- Muon veto
- 100 photomultiplier tubes
- Buffer of water
- Optical coverage: 21%
- Energy saturation: 6 MeV

Event selection cuts

Muon selection

cut on the number of photoelectrons detected by the muon-veto

Neutron selection

For each detected μ, the following event in the time window Tn = [20, 2000] μs is selected as a candidate event for a neutron capture γ

E < 2.6 MeV

^{11}C selection

For each muon-gamma coincidence, ^{11}C candidates are selected in a subsequent time window Tw = 300 min, 10 times the ^{11}C mean life.

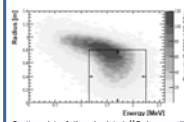
Optimal energy range: 1.15 < E < 2.25 MeV

Distance between ^{11}C event and gamma < 35 cm

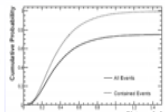
Test of the TFCT

Detection efficiency and results

FLUKA-based simulation results

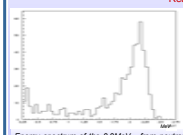


Scatter plot of the simulated ^{11}C-decay radial position vs energy. Solid lines represent the cuts applied in the analysis. Events with an energy lower than 1.022 MeV are due to the escaping positron annihilation γ γ.

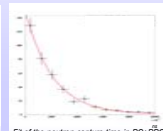


Cumulative probability to contain a ^{11}C event in a sphere of radius r centered on the 2.2MeV γ.

Real data



Energy spectrum of the 2.2MeV γ from neutron captures detected in CTF.



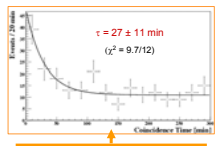
Fit of the neutron capture time in PC+PPO. τ = 257 ± 27 μs, as expected.

Fit of the time profile of the data sample selected by the TFCT [BAL06]. The fit function contains two terms:

- ^{11}C decay function
- constant component for the random coincidence

$$P(t) = \frac{A}{\tau} e^{-\frac{t}{\tau}} + b$$

A = number of ^{11}C events
τ = ^{11}C mean life
b = random coincidence rate



Goal reached!

$$R(^{11}C) = \frac{A}{\frac{4}{3}\pi r^3 \rho T} \cdot \frac{1}{\varepsilon_{vis} \cdot \varepsilon_{end} \cdot \varepsilon_t \cdot \varepsilon_{escape} \cdot \varepsilon_c}$$

r = fiducial volume radius (0.8 m)
ρ = scintillator density (0.88 g/cm^3)
T = detector live time (611days)

Efficiency in CTF		Value
ε_{vis}	Visible channels	0.955
ε_{end}	End of run during the time window T_w	0.990
ε_t	Time window T_n neutron selection	0.925
ε_{escape}	Neutrons contained in the vessel	0.732
ε_c	^{11}C energy cut Neutron capture gamma energy > 0.2 MeV ^{11}C-γ distance < 35 cm	0.563
Total		0.360

$R(^{11}C)$ = [13.0 ± 2.6(stat) ± 1.4(syst)]×10^{-2} d^{-1} ton^{-1}

$$\frac{\text{Measured Rate}}{\text{Expected Rate}} = 0.89 \pm 0.20$$

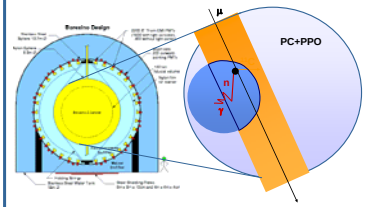
BOREXino potential

Goal in BOREXino: ^{11}C background reduction with efficiency larger than

$$\varepsilon_{required} = 1 - S_\nu/(R_{11C}+R_{t.c.}) = 0.81$$

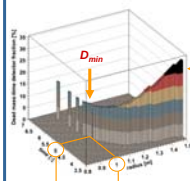
where S_ν is the neutrino signal rate, and R_{11C} and $R_{t.c.}$ the ^{11}C and the trace contaminant rates, respectively [BAH06,FRA04].

Howto: definition and blinding of a spherical volume of radius *r*, centered on the neutron capture gamma, for a time *t*.



The reconstruction of the μ-track (not yet implemented) will reduce the dead mass-time detector fraction (*D*) by intersecting the spherical volume with a cylindrical one around the μ-track.

The optimal parameters, *r* and *t*, are obtained by minimizing the dead mass-time detector fraction. We assume the neutron rate equal to 1.5×10^{-2} μ^{-1} m^{-1} [BAL06] and require the signal-to-background ratio equal to 1. Only the spherical volume is considered.



Efficiency in BOREXino		Value
ε_{vis}	Visible channels	0.955
ε_{end}	End of run during the time window T_w for ^{11}C selection	1.000
ε_t	Time window T_n for neutron selection	0.989
ε_{escape}	Neutrons contained in the vessel	1.000
ε_c	Neutron capture gamma energy > 0.2 MeV ^{11}C-γ distance < 1 m ^{11}C-γ coincidence time < 5×τ_{11C}	0.932
Total		0.880

$\varepsilon_{expected} > \varepsilon_{required}$

D = 14%

Conclusions

- The agreement between the ^{11}C production rate measured at LNGS by CTF and the one extrapolated from the NA54 CERN experiment results, demonstrated that the three-fold coincidence technique is a powerful tool for isolating and discriminating the ^{11}C background;
- BOREXino has the potential to minimize the ^{11}C background at a level compatible with the observation of *pep* and CNO neutrinos, loosing only 14% of the data.

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