SENSITIVITY TO CNO CYCLE SOLAR NEUTRINOS IN BOREXINO

ÖMER PENEK
On behalf of the Borexino Collaboration

XIX International Workshop on Neutrino Telescopes
24th February 2021
CONTENTS

- Introduction and Motivation
- The Borexino Detector
- Sensitivity to CNO cycle solar neutrinos
- Summary and Conclusions
Introduction and Motivation
SOLAR NEUTRINOS → THE STANDARD SOLAR MODEL

Usage of current physics and input parameters with best fit observations

**SSM Inputs:**

- Photon luminosity $L_\odot$, the solar mass $M_\odot$, the solar radius $R_\odot$,
  
  the oblateness $O_\odot = \frac{R_{\text{equator}}}{R_{\text{polar}}} - 1$, and the solar age $A_\odot$

- Abundances of Elements (Metallicity, High=HZ or Low=LZ)

  → Solar Surface Metal-to-Hydrogen Ratio $\left(\frac{Z}{X}\right)_\odot$ (Metal = Elements above He)

**SSM Outputs:**

- Neutrinos Fluxes (HZ-SSM or LZ-SSM)
- Sound speed profiles → Discrepancy in HZ-SSM and LZ-SSM

**Helioseismology (Accustic waves, Sun’s oscillation):**

- Excellent Description of Sun’s interior structure for > 2 decades
- Consistent with older HZ (1D description) but in tension with newer LZ (3D description) → SSM should be consistent with both!!!
- A measurement of CNO can unravel this “solar metallicity problem“
HOW IS THE SUN FUELED?  FUSION  SOLAR NEUTRINOS

Production in the Core of the Sun  vs on Earth in ~8 minutes

Standard Solar Model (SSM)

~ 99 %  pp chain

~ 1 %  CNO cycle

assumed to be the main mechanism in heavier stars

Slide 5
<table>
<thead>
<tr>
<th>Species</th>
<th>Flux [cm(^{-2}\cdot s(^{-1})]</th>
<th>Flux [cm(^{-2}\cdot s(^{-1})]</th>
<th>Difference (HZ-LZ)/HZ %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GS98 (HZ-SSM)</td>
<td>AGSS09met (LZ-SSM)</td>
<td></td>
</tr>
<tr>
<td>pp</td>
<td>5.98(1 ± 0.006)\times10^{10}</td>
<td>6.03(1 ± 0.005)\times10^{10}</td>
<td>−0.8 %</td>
</tr>
<tr>
<td>pep</td>
<td>1.44(1 ± 0.01)\times10^{8}</td>
<td>1.46(1 ± 0.009)\times10^{8}</td>
<td>−1.4 %</td>
</tr>
<tr>
<td>hep</td>
<td>7.98(1 ± 0.30)\times10^{3}</td>
<td>8.25(1 ± 0.30)\times10^{3}</td>
<td>−3.4 %</td>
</tr>
<tr>
<td>(^7)Be</td>
<td>4.93(1 ± 0.06)\times10^{9}</td>
<td>4.50(1 ± 0.06)\times10^{9}</td>
<td>8.9 %</td>
</tr>
<tr>
<td>(^8)B</td>
<td>5.46(1 ± 0.12)\times10^{6}</td>
<td>4.50(1 ± 0.12)\times10^{6}</td>
<td>17.6 %</td>
</tr>
<tr>
<td>(^{13})N</td>
<td>2.78(1 ± 0.15)\times10^{8}</td>
<td>2.04(1 ± 0.14)\times10^{8}</td>
<td>26.6 %</td>
</tr>
<tr>
<td>(^{15})O</td>
<td>2.05(1 ± 0.17)\times10^{8}</td>
<td>1.44(1 ± 0.16)\times10^{8}</td>
<td>29.7 %</td>
</tr>
<tr>
<td>(^{17})F</td>
<td>5.29(1 ± 0.20)\times10^{6}</td>
<td>3.26(1 ± 0.18)\times10^{6}</td>
<td>38.3 %</td>
</tr>
</tbody>
</table>
## METALLICITY: SOLAR NEUTRINOS FLUXES

<table>
<thead>
<tr>
<th>Species</th>
<th>Flux [cm(^{-2})s(^{-1})] GS98 (HZ-SSM)</th>
<th>Flux [cm(^{-2})s(^{-1})] AGSS09met (LZ-SSM)</th>
<th>Difference (HZ-LZ)/HZ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>5.98(1 ± 0.006)×10(^{10})</td>
<td>6.03(1 ± 0.005)×10(^{10})</td>
<td>-0.8 %</td>
</tr>
<tr>
<td>pep</td>
<td>1.44(1 ± 0.01)×10(^{8})</td>
<td>1.46(1 ± 0.009)×10(^{8})</td>
<td>-1.4 %</td>
</tr>
<tr>
<td>hep</td>
<td>7.98(1 ± 0.30)×10(^{3})</td>
<td>8.25(1 ± 0.30)×10(^{3})</td>
<td>-3.4 %</td>
</tr>
<tr>
<td>(^7)Be</td>
<td>4.93(1 ± 0.06)×10(^{9})</td>
<td>4.50(1 ± 0.06)×10(^{9})</td>
<td>8.9 %</td>
</tr>
<tr>
<td>(^8)B</td>
<td>5.46(1 ± 0.12)×10(^{6})</td>
<td>4.50(1 ± 0.12)×10(^{6})</td>
<td>17.6 %</td>
</tr>
<tr>
<td>(^{13})N</td>
<td></td>
<td></td>
<td>26.6 %</td>
</tr>
<tr>
<td>(^{15})O</td>
<td></td>
<td></td>
<td>29.7 %</td>
</tr>
<tr>
<td>(^{17})F</td>
<td></td>
<td></td>
<td>38.3 %</td>
</tr>
</tbody>
</table>

**CNO-\(\nu\) Flux**

→ HZ and LZ separation is high

~30%
EXPECTED SOLAR NEUTRINO SPECTRA

Difference in endpoint energies and shapes gives possibility to distinguish them
The Borexino Detector
**HOW TO “DETECT” THE SUN?**

The Borexino Detector located at LNGS in Italy

- **2212 inward-facing PMTs**
- **Nylon Outer Vessel**
  - $R = 5.5 \text{ m}$
  - *Barrier for Rn from steel, PMTs etc.*
- **Nylon Inner Vessel**
  - $R = 4.25 \text{ m}$
  - ~300 tons of liquid scintillator: (PC/PPO solution)
- **Fiducial volume:**
  - ~100 tons (software cut)

**Detection principle:**
- elastic scattering on electrons

**Technique advantages:**
- high light-yield

**Technique disadvantages:**
- no directional information

**Water tank:**
- $R = 9 \text{ m}$, 2.1 kt of water
  - *Shielding*
  - *Cherenkov muon veto*

**Stainless Steel Sphere:**
- $R = 6.85 \text{ m}$
- Scintillator container
- PMTs support
- 208 Outer Detector PMTs

- **Hardware Threshold ~ 50 keV**
- $\frac{\Delta E}{E} \approx 5 \%$
  
- **Ph. Yield ~ 500 p.e./MeV in 2000 PMTs**
- **Position Reconstruction ~10 cm @1MeV**

MITGLIED DER HELMHOLTZ-GEMEINSCHAFT

Forschungszentrum
Sensitivity to CNO cycle solar neutrinos in Borexino
CHALLENGES I: CORRELATIONS

- Shown here: recoiled $e^{-}$ spectra for CNO-$\nu$, pep-$\nu$, and $^{210}$Bi $\beta^{-}$ decay electrons
- High Spectral Correlation with $^{210}$Bi and solar pep neutrino signal
**CHALLENGES I: SOLUTIONS**

**pep-ν constraint**

- $p + e^- + p \rightarrow d + \nu_e$ and $p + p \rightarrow d + e^+ + \nu_e$ maximal correlated (same matrix element in nuclear physics)
- $\Phi_{pp}/\Phi_{pep}$ robust prediction without latest data $\Rightarrow \sigma(\text{pep}) \sim 10\%$
- Global Analysis on all Solar-ν experiments applying luminosity constraint $\Rightarrow \sigma(\text{pep}) \sim 1.4\%$ (Here, 1\% CNO contribution negligible)

**$^{210}\text{Bi}$ constraint**

\[
\begin{align*}
^{210}\text{Pb} & \xrightarrow{\beta^-} ^{210}\text{Bi} & \xrightarrow{\beta^-} ^{210}\text{Po} & \xrightarrow{\alpha} ^{206}\text{Pb}
\end{align*}
\]

Lifetimes: 32 y, 7.23 d, 199.1 d

**Bi-Po-Tagging** (Unsupported Po, Migration Po, Supported Po):
In secular equilibrium $\text{Rate}(^{210}\text{Bi}, \beta^-) = \text{Rate}(^{210}\text{Po}, \alpha)$ (Supported Po)

**$^{210}\text{Po}$ identification:**
Monoenergetic Decay (“Gaussian“) + $\alpha$-decay in Borexino $\Leftrightarrow$ Event-by-Event Pulse Shape Discrimination $\Rightarrow$ Multilayer Perceptron (MLP variable)
CHALLENGES II: $^{11}$C

RECIPE $\rightarrow$ THREEEFOLD COINCIDENCE (TFC)

$\rightarrow$ We have recipe for that Muon interactions with $^{12}$C ($\sim$ 4000 muons per day)

$\mu + ^{12}$C $\rightarrow$ n + $^{11}$C + $\mu$

TFC Algorithm

- Calculate for each event the probability to be $^{11}$C (using a Likelihood)
- Divide Total Exposure in TFC-subtracted and TFC-tagged spectra (also called $^{11}$C depleted and $^{11}$C enriched spectra, respectively)
PSEUDO DATASETS

- Fiducial Volume Cut: $R < 2.8 \text{ m}, -1.8 \text{ m} < z < 2.2 \text{ m}$
- Exposure: $1000 \text{ days} \times 71.3 \text{ tonnes}$
- $^{11}\text{C}$ depleted spectrum (TFC)

Two Methods: Counting vs. Fit
COUNTING ANALYSIS I

- **Counting Analysis**: Count the number of events in a region of interest (ROI), dominated by $^{210}\text{Bi}$, CNO, and $\text{pep}$

$$N_{\text{total}} = N_{\text{Bi}}^{\text{ROI}} + N_{\text{CNO}}^{\text{ROI}} + N_{\text{pep}}^{\text{ROI}} + N_{\text{others}}^{\text{ROI}}$$

---

**Region of Interest (ROI)** for Counting Analysis

**ROI**: $\sim$0.8 to 1.0 MeV
Number of events in ROI (~0.8..1.0 MeV) is:

\[ N_{model} = \sum_{k=\text{Bi,CNO,pep,others}} \varepsilon_k N_k \]

Here, the efficiency of each species is important:

\[ \varepsilon_k = \int_{0.8 \text{ MeV}}^{1.0 \text{ MeV}} \text{PDF}_k(E) \, dE \]

<table>
<thead>
<tr>
<th>Component</th>
<th>Efficiency in ROI $\varepsilon_k$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNO-$\nu$</td>
<td>7.37</td>
</tr>
<tr>
<td>pep-$\nu$</td>
<td>15.98</td>
</tr>
<tr>
<td>$^{210}\text{Bi}$</td>
<td>4.55</td>
</tr>
<tr>
<td>$^{11}\text{C}$</td>
<td>4.91</td>
</tr>
</tbody>
</table>

Other species efficiencies are less than 1.5%

Robust against systematics
MULTIVARIATE FITTING $\rightarrow$ ENERGY + RADIAL

- $\mathcal{L}^{2D}_{MV} (\hat{\theta}) = \mathcal{L}^{TFC}_{sub} (\hat{\theta}) \mathcal{L}^{TFC}_{tag} (\hat{\theta}) \mathcal{L}_{radial} (\hat{\theta})$
  (complementary 2D poisson with fit in Energy = TFC subtracted + TFC tagged fit + Radial fit)

- Constraints on $pp$ and $^{210}$Bi are considered as gaussian or semi-gaussian (= upper limit) pull terms
  $\rightarrow$ Upper Limit only only applied on $^{210}$Bi

Radial Fit: $\sim 1.2$ to $2.5$ MeV
INJECTED RATES FOR TOY MC STUDY

Exposure 1000 days times 71.3 tonnes

Injected Rates for HZ- and LZ-SSM predictions

<table>
<thead>
<tr>
<th>Component</th>
<th>Injected Rates HZ [cpd/100t]</th>
<th>Injected Rates LZ [cpd/100t]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNO-ν</td>
<td>4.92</td>
<td>3.52</td>
</tr>
<tr>
<td>pep-ν</td>
<td>2.74</td>
<td>2.78</td>
</tr>
<tr>
<td>⁷Be-ν</td>
<td>47.9</td>
<td>43.7</td>
</tr>
<tr>
<td>²¹⁰Bi</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>¹¹C</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Ext. ⁴⁰K</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ext. ²⁰⁸Tl</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Ext. ²¹⁴Bi</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>⁸⁵Kr</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>²¹⁰Po</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

→ Constrained

→ Constrained
CNO PRECISION: COUNTING VS. FIT

- $^{210}$Bi and pep rates → symmetric gaussian pull term

Multivariate Fit has overall better performance if $^{210}$Bi precision is getting weaker.

- $\sigma_{\text{pep}} = 0.28 \text{ cpd/100 t}$
  - $\text{pep} @ \sim 10\%$ precision

- $\sigma_{\text{pep}} = 0.04 \text{ cpd/100 t}$
  - $\text{pep} @ \sim 1.4\%$ precision

4.92 cpd/100t HZ-SSM
3.52 cpd/100t LZ-SSM
SENSITIVITY STUDIES I: DISCOVERY POTENTIAL

I. Fit Pseudo Datasets w/ CNO injected and w/o CNO injected twice:
   1. CNO leaving free and 2. CNO fixed to 0

II. Define test statistics \( q(\theta) = -2 \times \log \frac{L(\theta=CNO=\text{free})}{L(CNO=0)} \)
    (log-likelihood-ratio on each dataset)

III. Evaluate \( p \)-value:
    \[ p = \int_{q_{\text{med}}}^{\infty} f(q|\text{no CNO injected}) \, dq \]
    \( q_{\text{med}} \): Median of \( q \)

Asymptotic Limit Case:
\[
f(q|\mu) = \left(1 - \Phi \left( \frac{\mu}{\sigma} \right) \right) \delta(q) + \frac{1}{2} \cdot \frac{1}{\sqrt{2\pi q}} \exp \left( -\frac{1}{2} \left( \sqrt{q} - \frac{\mu}{\sigma} \right)^2 \right)
\]

- Blue Distribution: \( f(q|\mu) \Leftrightarrow \text{CNO injected} \)
- Red Distribution: \( f(q|0) \Leftrightarrow \text{No CNO injected} \)
Using an exposure of 1000 days times 71.3 tonnes

- Counting Analysis in ROI
- **HZ-SSM Multivariate fit**
  - done with $^{210}$Bi symmetric Gaussian constraint
- **HZ-SSM Multivariate fit (Bi limit)**
  - $^{210}$Bi Semi-Gaussian constraint
- $^{210}$Bi constraint: for sensitivity precision is important rather than central value
Using an exposure of 1000 days times 71.3 tonnes

- Counting Analysis in ROI
- **HZ-SSM Multivariate fit** done with $^{210}\text{Bi}$ symmetric Gaussian constraint
- **HZ-SSM Multivariate fit (Bi limit)** $^{210}\text{Bi}$ Semi-Gaussian constraint
- $^{210}\text{Bi}$ constraint: for sensitivity precision is important rather than central value
CATCHING THE RAYS
Neutrino detector secures evidence of the Sun's secondary fusion cycle

The international journal of science / 26 November 2020

nature
The international journal of science
Explore our content ➜ | Journal information ➜ | Subscribe ➜

nature | Published: 26 November 2020
Article
Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun
The Borexino Collaboration
Nature 587, 577–582 (2020) | Cite this article
10.1038/s41586-020-2413-2

Abstract
For most of their existence, stars are fueled by the fusion of hydrogen into helium. Fusion proceeds via two processes that are well understood theoretically: the proton–proton (p–p) chain and the carbon–nitrogen–oxygen (CNO) cycle. Neutrinos that are emitted along such fusion processes in the solar core are the only direct probe of the deep interior of the Sun. A complete spectroscopic study of neutrinos from the p–p chain, which produces about 99 percent of the solar energy, has been performed previously. However, there has been no reported experimental evidence of the CNO cycle. Here we report the direct observation of neutrinos produced in the CNO cycle in the Sun. This experimental evidence was obtained using the highly radiopure, large-volume, liquid-scintillator detector of Borexino, an experiment located at the underground Laboratori Nazionali del Gran Sasso in Italy. The main experimental challenge was to identify the excess signal — only a few counts per day above the background per 100 tonnes of target — that is attributed to interactions of the CNO neutrinos. Advances in the thermal stabilization of the detector over the last five years enabled us to develop a method to constrain the rate of bismuth-201 contaminating the scintillator. In the CNO cycle, the fusion of hydrogen is catalysed by carbon, nitrogen and oxygen, and so its rate is a strong function of the CNO neutrinos — depends directly on the abundance of the CNO neutrinos. Our findings quantify the number of CNO neutrinos at the Sun with a high statistical significance, of neutrinos produced in the CNO cycle in the Sun. This experimental evidence was obtained using the highly radiopure, large-volume, liquid-scintillator detector of Borexino, an experiment located at the underground Laboratori Nazionali del Gran Sasso in Italy. The main experimental challenge was to identify the excess signal — only a few counts per day above the background per 100 tonnes of target — that is attributed to interactions of the CNO neutrinos. Advances in the thermal stabilization of the detector over the last five years enabled us to develop a method to constrain the rate of bismuth-201 contaminating the scintillator. In the CNO cycle, the fusion of hydrogen is catalysed by carbon, nitrogen and oxygen, and so its rate is a strong function of the CNO neutrinos — depends directly on the abundance of the CNO neutrinos. Our findings quantify the number of CNO neutrinos at the Sun with a high statistical significance.

physics world
TOP 10 BREAKTHROUGH 2020

Alessandra Re‘s talk – A successful strategy for the CNO measurement

Alex Goettel‘s talk – Data analysis of a low-Po field for the CNO discovery

Davide Basilico‘s talk – How the CNO neutrinos detection can unravel the solar metallicity problem

(All 3 talks, Friday 19/02/2021)
It has been proven through the sensitivity studies that Borexino has sensitivity to CNO cycle solar neutrinos.

5σ are clearly reached when constraining the pep-ν rate to 0.04 cpd/100t precision and 210Bi to 1 cpd/100t precision. This case is comparable to the observation on data.

There is 3σ sensitivity to CNO without 210Bi constraint when doubling the statistics (while keeping the pep constraint).
Grazie Infinite

Thanks a lot

Questions?
Discussion
Backup
### BOREXINO RESULTS OVERVIEW

<table>
<thead>
<tr>
<th>Year</th>
<th>Bx Phase I</th>
<th>Bx Phase II</th>
<th>Bx Phase III</th>
</tr>
</thead>
</table>
| 2007 | 7Be, pep, 8B Geo-Nu Calibrations | Scintillator Purification | Improved Measurement of I
| 2010 | Improved Radiopurity: 85Kr ~ 4.6, 210Bi ~ 2.3 | pp Discovery (5σ) | Improved Thermal stability CNO analysis |
| 2012 | Measurement of geo-neutrinos from 1353 days of Borexino, 7Be seasonal modulation | Seasonal modulation of the 7Be solar neutrino rate in Borexino | Comprehensive measurement of pp-chain solar neutrinos (Nature 562, 505–510 (2018)) |
| 2016 | Spectroscopy of geoneutrinos from 2056 days of Borexino Data | Simultaneous Precision Spectroscopy of pp, 7Be, and pep Solar Neutrinos with Borexino Phase-II | Comprehensive geoneutrino analysis with Borexino (Phys. Rev. D 101, 012009 (2020)) |

**Final results of Borexino Phase-I on low-energy solar neutrino spectroscopy** (Phys. Rev. D 89, 112007 (2014))

**Measurement of the solar 8B neutrino rate with a liquid scintillator target and 3 MeV energy threshold in the Borexino detector** (Phys. Rev. D 82, 033006 (2010))


**Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun** (Nature 587, 577-582 (2020))

**Sensitivity to neutrinos from the solar CNO cycle in Borexino** (Eur. Phys. J. C 80, 1091 (2020))
BISMUTH-210 FROM POLONIUM-210

- Two components: $^{210}\text{Po}$ in sec. Equilibrium with $^{210}\text{Bi}$ in the FV (supported Po) and $^{210}\text{Po}$ from the $^{210}\text{Pb}$ in inner vessel leaking inside the active liquid (via diffusion or convection) (unsupported Po)

Minimum $^{210}\text{Po}$ Rate $\Leftrightarrow$ Upper Limit of $^{210}\text{Bi}$ Rate:

$$R(Po_{min}) = R(Bi) + R(Po^U) \geq R(Bi)$$

- Identification of the low polonium field (LPoF)

20 tonnes $\varepsilon_{\text{Ene}}, \varepsilon_{\text{MLP}}$ efficiency Energy and MLP ($\alpha$s)

$$R_\beta \text{ beta rate after } \alpha \text{ selection}$$

$$\frac{d^2 R(Po_{min})}{d (\rho^2) dz} = [R(Po_{min}) \varepsilon_{\text{Ene}} \varepsilon_{\text{MLP}} + R_\beta]$$

$$\times \left( 1 + \frac{\rho^2}{a^2} + \frac{(z - z_0)^2}{b^2} \right).$$

Mitglied der Helmholtz-Gemeinschaft  

Seite 30
Minimum $^{210}$Po Rate $\Leftrightarrow$ Upper Limit of $^{210}$Bi Rate:

$$R(\text{Po}_{\text{min}}) = R(\text{Bi}) + R(\text{Po}^U) \geq R(\text{Bi})$$

Two methods:
1) Cubic Spline Fit
2) Paraboloidal Fit

Binning 1 or 2 months
Question: $^{210}$Bi in 20 tonnes. But FV is 71.3 tonnes. So, is the $^{210}$Bi rate homogenous? ➔ Compare the angular and radial distribution of events with homogeneous distribution.

Angular:

$$L^2C_l$$ vs. $l$

Radial:

$$\beta$$ rate [cpd/100t]

$$\pm 0.52 \text{ cpd/100t}$$

$$\pm 0.59 \text{ cpd/100t}$$

Answer: YES!
What do we get?

<table>
<thead>
<tr>
<th>$R(Po_{\text{min}})$</th>
<th>$\sigma_{\text{fit}}$</th>
<th>$\sigma_{\text{mass}}$</th>
<th>$\sigma_{\text{bin}}$</th>
<th>$\sigma^{\text{hom. angular}}$</th>
<th>$\sigma^{\text{hom. radial}}$</th>
<th>$\sigma^{\text{leak}}_\beta$</th>
<th>$\sigma_{\text{tot}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.5</td>
<td>0.88</td>
<td>0.36</td>
<td>0.31</td>
<td>0.59</td>
<td>0.52</td>
<td>0.30</td>
<td>1.30</td>
</tr>
</tbody>
</table>

- $\sigma_{\text{fit}}$: paraboloidal/spline fit uncertainty
- $\sigma_{\text{mass}}$: LPoF mass uncertainty
- $\sigma_{\text{bin}}$: Uncertainty due to data binning (10 – 30 cm)
- $\sigma^{\text{hom. angular}}$ and $\sigma^{\text{hom. radial}}$: see previous slide
- $\sigma^{\text{leak}}_\beta$: $R_\beta$ uncertainty ($\beta$ leakage)
- $\sigma_{\text{tot}}$: add all these uncertainties in quadrature $\Rightarrow$ total

$$R_{\text{Bi}} \leq (11.5 \pm 1.3) \text{ cpd/100t}$$
SPECTRAL FIT

Multivariate Fit: $\mathcal{L}_{MV}(\tilde{\theta}) = \mathcal{L}_{sub}^TFC(\tilde{\theta}) \mathcal{L}_{Tag}^TFC(\tilde{\theta}) \mathcal{L}_{Radial}(\tilde{\theta})$

Fit Conditions:
Monte Carlo Fit
Fit Range: 320 to 2640 keV

$R_{\text{pep}} = (2.74 \pm 0.04) \text{ cpd/100t} \rightarrow \text{symmetric gaussian penalty}$

$R_{\text{Bi}} \leq (11.5 \pm 1.3) \text{ cpd/100t upper limit}!$
CNO MEASUREMENT \(\rightarrow\) FIT

Counting Analysis \(\rightarrow\) Pick Ene. window where FOM is maximal

\[ q_{\text{data}} = 30.05 \]

\[ R_{\text{CNO}} = (7.2^{+3.0}_{-1.7}) \text{ cpd/100t} \]

\[ \Phi_{\text{CNO}} = (7.0^{+3.0}_{-2.0}) \times 10^8 \text{ cm}^{-2}\text{s}^{-1} \]

\( \Leftrightarrow \) 5.1\( \sigma \) from profiling w/ systematics
DISCOVERY POTENTIAL ➔ TOY MC APPROACH

Inject all systematics in a toy study based on non-linearity of the energy scale (0.4%), spatial non-uniformity z-axis (0.28%), light yield (0.32%), $^{11}$C peak position, other $^{210}$Bi spectral shapes (18%) (area of $^{210}$Bi is constrained by the upper limit)

- Create pseudo datasets w/ CNO ($H_1$) injected and w/o CNO injected ($H_0$)
- Fit both datasets leaving CNO free $\ln_{0,1} CNO=free$ and CNO fixed to zero $\ln_{0,1} CNO=0$
- Evaluate Test Statistics:
  \[ q = -2 \ln \frac{\ln_{0,1} CNO=free}{\ln_{0,1} CNO=0} \]

- Gray function 13.8 million simulations
- Integral of gray from 30.05 to infinity gives the p-value: **5$\sigma$ at 99% C.L.**
SENSITIVITY HZ-SSM VS. LZ-SSM

Using an exposure of 1000 days times 71.3 tonnes

\[ \sigma_B = 3.5, \sigma_p = 0.28 \]

\[ \sigma_B = 3.5, \sigma_p = 0.04 \]

\[ \sigma_B = 2.5, \sigma_p = 0.28 \]

\[ \sigma_B = 2.5, \sigma_p = 0.04 \]

\[ \sigma_B = 1.5, \sigma_p = 0.28 \]

\[ \sigma_B = 1.5, \sigma_p = 0.04 \]

\[ \sigma_B = 1, \sigma_p = 0.28 \]

\[ \sigma_B = 1, \sigma_p = 0.04 \]