SOX: short baseline neutrino oscillations with Borexino

Matthieu Vivier,
on behalf the Borexino/SOX collaboration
Two short baseline anomalies in $\bar{\nu}_e$ disappearance mode, each at the 3$\sigma$ level:

- Gallium anomalies: calibration of the radiochemical solar experiments Gallex and SAGE with $^{51}$Cr \& $^{37}$Ar $\nu_e$ sources, $<L> \approx 0.5 - 2 \text{ m}$ [C. Giunti et al. (2010)]
- Short baseline reactor $\bar{\nu}_e$ experiments, $<L> \approx O(100 \text{ m})$ [G. Mention et al. (2011)]

Rate deficits can be explained by the addition of $\geq 1$ sterile neutrino state

Combined fits using a (3+1) model point toward:

- $\Delta m^2_{\text{new}} \approx 0.1 - 5 \text{ eV}^2$
- $\sin^2 2\theta_{\text{new}} \approx 0.1$

Corresponds to meter scaled oscillation lengths for MeV $\nu_e$

A decisive test requires observation of oscillation patterns: “oscillometry” concept

see J. Link’s plenary talk this morning for further details and discussions
The Borexino detector at LNGS

- Ultra low background neutrino detector
- Various physics program:
  - solar $\nu$ [see G. Testera’s talk]
  - geo $\nu$ [see A. Ianni’s talk]
  - Neutrino oscillation
  - ...

**Water volume:**
Muon veto & radioactivity shielding

**Stainless steel sphere:**
Equipped with 2200 PMTs

**Stainless steel water tank:**
Equipped with 208 PMTs

**Detection volume:**
Pseudocumene + PPO – $R=4.25$ m – $M=270$ t

**Buffer volumes:**
PC + DMP (scintillation light quencher)
Shielding against external gamma-rays
The SOX experiment

- Deployment of an intense (anti)neutrino source in a pit underneath the detector

- Rail and trolley system for source deployment

- "T-shaped" pit

- Borexino detector at hall C
The SOX experiment

- Deployment of an intense (anti)neutrino source in a pit underneath the detector
- Two-phase experiment:

1. **CeSOX**: $^{144}$Ce-$^{144}$Pr $\bar{\nu}_e$ generator:
   - $\beta^-$ emitter: $\bar{\nu}_e$ up to 3 MeV
   - $^{144}$Ce $T_{1/2} = 285$ days
   - Extracted from spent nuclear fuel
   - Detection via IBD:
     - threshold of 1.8 MeV
     - time coincidence between $e^+$ & n
     - $\approx$ background free
   - Activity: $\approx 100$ kCi ($\approx 3.7 \times 10^{15}$ Bq)

2. **CrSOX**: $^{51}$Cr $\nu_e$ generator:
   - EC source, monoenergetic $\nu_e$: 753 KeV (90%) & 433 keV (10%)
   - $T_{1/2} = 27.7$ days
   - Produced by neutron irradiation of (stable) $^{50}$Cr
   - Detection via $e^-$ scattering
   - Backgrounds: $^{210}$Po, $^{210}$Bi and solar $\nu_e$
   - Activity: $\approx 10$ Mci

- Mostly CeSOX latest developments will be covered in the next slides.
CeSOX sterile neutrino signature

\[ \mathcal{P}(\theta, \Delta m^2, L, E) = 1 - \sin^2(2\theta) \sin^2(1.27\Delta m^2 \frac{L}{E}) \]

- \( \sin^2(2\theta) = 0.15 \)
- \( \Delta m^2 = 2\text{ eV}^2 \)

100 kCi \(^{144}\text{Ce}\) source in pit @ 8.5 m from detector center
- 1.5 years of data taking: \( \approx 10^4 \) events
- 5% energy resolution @ 1 MeV
- 15 cm spatial resolution
- Background free

IBD count rate as a function of L \& E in a (3+1) sterile neutrino model
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IBD count rate as a function of L/E in a (3+1) sterile neutrino model
CeSOX can potentially test most of the preferred parameter space in a really short time:

- **Shape-only measurement**
  - Smoking-gun signature
  - Sensitive to $\Delta m^2 \approx 0.5 - 5$ eV$^2$ region
  - Requires good energy and vertex resolution
  - Dominated by statistical unc.

- **Rate + shape measurement**
  - Overall sensitivity improvement with respect to shape-only analysis
  - Especially sensitive for $\Delta m^2 \geq 5$ eV$^2$
  - Need accurate activity measurement
    - Heat power measurement (calo.)
    - Power-to-activity conversion ($\beta$ spec.)
  - Need good detection systematics
    - Energy, vertex reconstruction
    - IBD efficiency
    - …
Source production

- Done @ FSUE Mayak PA (Russia)
- 9 to 12 months production process:
  1. Standard radiochemical re-processing of a few tons of SNF from research reactor:
      Purex process $\Rightarrow$ lanthanides and actinides concentrate
  2. Separation of Cerium (REE complex displacement chromatography)
  3. Calcination + pressing + encapsulation: $\approx 30$ g of $^{144}\text{Ce}$ in 5 kg of $\text{CeO}_2$
Source shielding

- Any gamma radiation escaping the source (reminder, activity \( \approx \) few PBq) must be shielded
  - Biological protection
  - Avoid source-induced backgrounds in the detector

- 19-cm thick high density tungsten alloy shielding (HDTAS)
- Dimensions mostly driven by \(^{144}\text{Pr} 2.185\) MeV deexcitation gamma-ray (0.7% intensity).
- Manufactured at Xiamen Honglu Inc., China. Biggest tungsten shielding ever built...
- Delivery end of 2015

- Cylindrical shape
- \( H \approx 60\) cm – \( \phi \approx 60\) cm
- Density \( \approx 18.5\) g cm\(^{-3}\)
- 2.3 tons

Aluminium mock-up
- Transportation cask identified: MTR from Areva TN (21 tons)
- Itinerary route identified: from Mayak to LNGS through France
- Train/dedicated boat/truck: 3 weeks travel (5% activity loss)
- **Source transport authorized ✔**
- Expected delivery date at LNGS < Dec. 2016
Calorimetric measurement

- Measure CeANG thermal power with ≤ 1.5% precision
  - P ≈ 216 W/PBq
  - 800 W @ beginning of data taking

- Measure flow and temperature in and out a water circulation loop
  \[ P_{\text{source}} = \frac{dM}{dt} \times C_p \times (T_{\text{out}} - T_{\text{in}}) + P_{\text{leak}} \]

- Calorimetric device designed to minimize leaks:
  - Conduction: suspension platform + insulation
  - Convection: vacuum vessel
  - Radiation: multilayer insulation + vacuum vessel thermalization

- Calibration with an electrical source
- Both source heat power and expected IBD interaction rate in Borexino depends on CeANG $\beta/\nu_e$ spectrum
- $^{144}\text{Ce}$ and $^{144}\text{Pr}$ beta spectra both present non-unique forbidden transitions, for which spectral shape is uncertain at the few % level
- Furthermore, past $\beta$ spectrum measurements don’t agree well: up to 10-15% differences, which makes 10% uncertainty in the predicted IBD rate
- Need for a new $\beta$ spectrum measurement to reach < 1% uncertainty on IBD rate

Past measurements of $^{144}\text{Pr}$ 1st branch beta spectra

Neutrino spectra from past measurements of $^{144}\text{Pr}$ 1st branch beta spectra (beta–branch level conversion)
Both source heat power and expected IBD interaction rate in Borexino depends on CeANG $\beta/\nu_e$ spectrum

$^{144}$Ce and $^{144}$Pr beta spectra both present non-unique forbidden transitions, for which spectral shape is uncertain at the few % level

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Two measurements on-going at Saclay, on Ce(NO$_3$)$_3$ samples received from PA Mayak:

- Chemical separation of $^{144}$Ce and $^{144}$Pr envisaged, to measure separately their corresponding spectra
- Other measurement techniques under consideration: Si-detector, magnetic spectrometer, …
Impact of source related systematics

Heat power measurement
- Necessary for rate+shape analysis
- Target precision: 1% (calorimetry)

\[ \Delta m^2_{\alpha \beta} [eV^2] \]

\[ \sin^2(2\theta_{14}) \]

\( ^{144}\text{Ce} - 100\text{kCi} - 1.5\text{y} - 4.25\text{m}, 95\% \text{ CL} \)

\( \sigma = 0\% \)
\( \sigma = 1\% \)
\( \sigma = 1.5\% \)
\( \sigma = 2\% \)
\( \sigma = \text{inf.} \)

\[ \text{PRELIMINARY} \]

\[ \text{Best Fit, 95\% CL} \]
\[ \text{Best Fit, 99\% CL} \]
\[ \text{Best Fit, PRD 88 073008 (2013)} \]

\[ \text{144Ce - 100kCi - 1.5y - 4.25m, 95% CL} \]

\( \sigma_{\alpha,\beta,\gamma} = 0\% \)
\( \sigma_{\alpha} = 0.5\%, \sigma_{\beta} = 5\% \)
\( \sigma_{\alpha} = 0.5\%, \sigma_{\beta} = 5\%, \sigma_{\gamma} = 1\% \)

\( \text{Best Fit, 95\% CL} \)
\( \text{Best Fit, 99\% CL} \)
\( \text{Best Fit, PRD 88 073008 (2013)} \)

\[ \text{PRELIMINARY} \]

\( \Delta m^2_{\alpha \beta} [eV^2] \]

\( \sin^2(2\theta_{14}) \)

\( ^{144}\text{Ce} - 100\text{kCi} - 1.5\text{y} - 4.25\text{m}, 95\% \text{ CL} \)

\[ \text{no uncert.} \]
\[ \text{s.f. (only)} \]
\[ \text{s.f + activity} \]
Conclusion

- SOX will test the Gallium and reactor anomalies and search for $\bar{\nu}_e / \nu_e$ very short baseline oscillations

- First SOX phase, namely CeSOX, is soon to be started:
  - Source shielding in production: delivery by end of 2015

- CeANG characterization on-going. Goal: benefit from an additional rate information for $\nu_s$ search and make sure source impurities are kept to sufficiently low levels
  - Calorimetry
  - $\beta$ spectrometry
  - $\gamma$, $\alpha$ and ICP-MS/AES spectrometry (not covered in this talk)

- Intense detector calibration campaign to achieve detection systematics at the 1-2 % level

- Future measurement with $^{51}$Cr under consideration (very relevant in case of a positive signal)

THANK YOU!