The SOX experiment

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**Scientific motivations**

The Standard Model of neutrino oscillations

\[
\begin{bmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{bmatrix} =
\begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{bmatrix}
\begin{bmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{bmatrix}
\]

\[\Delta m_{32}^2 \approx \Delta m_{31}^2 = 2.4 \times 10^{-3} \text{ eV}^2\]
\[\Delta m_{12}^2 = 8 \times 10^{-5} \text{ eV}^2\]

The anomalies

- **LSND** \(P(\bar{\nu}_\mu \rightarrow \nu_e)\) 30 m
- **MiniBoone** \(P(\bar{\nu}_\mu \rightarrow \nu_e)\) and \(P(\nu_\mu \rightarrow \nu_e)\) 540 m
- **GalleX, SAGE** \(^{51}\text{Cr} - ^{37}\text{Ar}\) 1.9 m - 0.6 m
- **Reactors** \(\bar{\nu}\) flux 10 - 100 m

cannot be explained by the same matrix

All of these hint to \(\Delta m^2 \approx 1\) - 10 eV\(^2\) mass scale
The hypothesis of the sterile neutrinos

Combined analysis: 3+1 scenario

**Sterile neutrino properties**
- no SM interactions
- no coupling with Z boson (LEP)
- mixing with active $\nu$'s

\[ E = 1 - 10 \text{ MeV} \rightarrow L = E/\Delta m^2 = 1 - 10 \text{ m} \]

\[ L_{\text{osc}} (m) = \frac{E(\text{MeV})}{1.27 \Delta m^2 (\text{eV}^2)} \]

**Experimental requirements:**
- Precision on $L$ (vertex reconstruction and compact source dimension)
- High sensitivity (low background, large scale detector)
Hunt the sterile neutrino

- **With accelerators** to test the MiniBooNE and LSND signal
  - T2K and MicroBooNE
  - MINOS-DayaBay $\nu_\mu$ disappearance $\Delta m^2_{14} < 0.8 \text{ eV}^2$ Arxiv:1607.01177 (2016)

- **With artificial source** to test the Gallium anomaly
  - RICOCHET $^{37}\text{Ar}$ $\nu_\text{e}$
  - SNO+ $^{53}\text{Cr (EC)}$ $\nu_\text{e}$
  - BOREXINO-SOX $^{144}\text{Ce-144Pr}$ $\bar{\nu}_\text{e}$ **in 2018!**

- **Others**
  - ICeCube: from sterile neutrino induced matter effect in atmospheric neutrino
    - IceCube 1605.01990 (2016)
The SOX idea

Short neutrino Oscillation with BoreXino

A $^{144}\text{Ce} - ^{144}\text{Pr} \bar{\nu}_e$ source (100-150 kCi)
under the Borexino detector at LNGS Laboratory

Signature signal of new sterile neutrinos:

• Deviation from $1/r^2$ behavior of count rates
  ("disappearance technique")
• Direct observation of oscillation pattern ("waves")
The radioactive source

$^{144}\text{Ce} \rightarrow ^{144}\text{Pr} + \text{e}^- + \bar{\nu}_\text{e}$ long lived with low Q

$^{144}\text{Pr} \rightarrow ^{144}\text{Nd} + \text{e}^- + \bar{\nu}_\text{e}$ short lived with high Q above the IBD threshold

Activity: 100 - 150 kCi  \( T_{1/2} = 285 \) days

$\bar{\nu}_\text{e}$ detected by Inverse beta Decay
Threshold 1.8 MeV

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The Borexino detector

Built mainly, for solar neutrino: \( \nu + e^- \rightarrow \nu + e^- \) in an organic liquid scintillator

Ultra-low radioactive background
- Spatial resolution: 12 cm @ 2 MeV
- Energy resolution: ~3.5% @ 2 MeV

Fiducial volume estimation: 0.7% for \(^{7}\)Be

See G. Bellini’s talk
The Borexino detector

The anti-neutrino detection by a coincidence measurement

\[ \bar{\nu} + p \rightarrow n + e^+ \]

- geo-\(\nu\): \(~5\) ev/y in 300 t
- distant reactors: \(~10\) ev/y in 300 t
- accidental background: \(\ll 1\) ev/y

SOX is background free

expected signal: \(> 10^4\) events in 1.5 y

New calibration with many radioactive sources (next October)
Two types of analysis

The rate analysis

We look for a deviation from $1/r^2$ behaviour

It depends mainly on $\theta_{ee}$

the amplitude of the oscillation

\[
N_0(l, T_1, T_2) = n_e \Phi(l) V(l) P_{ee}(l, E) \int_{T_1}^{T_2} \frac{d\sigma_{ee}(E, T)}{dT} dT
\]

The sensitivity depends on:

- Error on source activity
- Error on $\nu_e$ spectrum
- FV determination

\[
\Phi(l) = \frac{I_0}{4\pi l^2}
\]

\[
V(l) = 2\pi l^2 \left(1 - \frac{L^2}{2 l^2} + \frac{L^2}{2 l^2} - 1\right)
\]

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Two types of analysis

The shape analysis

The «waves» might be seen!

It does not depend on the activity measurements

Both the oscillation parameters can be extracted independently

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Phys. Rev. D91 (2015) 7, 072005
What we need:

- The source production /authorizations
- The activity measurement (1%) by two calorimeters
- The $\nu_e$ spectrum measurement

The final sensitivity will depend on:

- source activity (100-150 kCi)
- precision level of activity and spectrum measurements
- fiducial volume estimation
The source production process

From spent nuclear fuel from Research Reactor
- purification
- calcination
- separation processes
- CeO₂ powder
- Pressed up to density of 3 - 5 g/cm³
- Put inside the copper capsule
- inside the two welded containers
- Inserted in the biological shield

At Mayak in Russia

Copper disk for better heat transfer
Free volume 25%
3 Cu- capsules
CeO₂ powder
2 Stainless Steel cases

The contract was signed last December!!
Source constrains

- **Radioactivity**
  - It must be very PURE!
    - $\gamma$ emitter activity < $10^{-3}$ Bq/Bq with respect to $^{144}$Ce
    - neutron rate: $^{244}$Cm activity < $10^{-5}$ Bq/Bq
      - with respect to $^{144}$Ce (max $10^5$ n/s)
    - A limit is put on several nuclides measured at Mayak spectroscopy before the delivery
  - Power from impurities $10^{-3}$ W/W with respect to $^{144}$Ce
Tungsten alloy shield

W-Ni-Fe alloy for mechanical properties

95% Tungsten (high density shield)

Dosimetry issue

→ Gamma dose:
  8 μSv/h at 1 m
  from Pr decay (gamma of 2.2 MeV)

→ Neutron dose:
  5 nSv/h at 1 m

Weight: 2.2 ton

Built in Xiamen Ltd, China

Neutrino Telescopes
The logistic

A journey to minimize borders:
- Mayak → St. Petersburg by train
- St. Petersburg → Le Havre by boat
- Le Havre → Saclay → LNGS by truck

Container: TN MTR
- 24 t container for nuclear fuel (CEA)

Transportation from Mayak to Hall C
In the clean room for the activity measurement: 1 month
In the pit for data taking 2 weeks 1.5 year

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Neutrino Telescopes
The activity measurement

The activity is measured by knowing the heat released inside the shield and absorbed by a water flow

$$P = \dot{m}[h(T_{out}, \bar{p}) - h(T_{in}, \bar{p})]$$

150 kCi $\rightarrow$ 1200 W

$T_{1/2} = 285$ days

Final precision due to:

- Heat losses (systematic)
- Massflow measurement (0.05 % accuracy)
- Temperature sensors (mK accuracy!!)
- Entalphy function (0.1% IAPWS)
- Estimation of the system time constant

The goal was 1 %...but we are going to do better!!
**INFN/TUM calorimeter**

**CONVECTION**
- Vacuum system
- Scroll pump
- Turbo molecular pump
  $P < 5 \cdot 10^{-5}$ mbar

**RADIATION**
- 2 stages of superinsulator (10 layers each one)
- Thermalization of the external chamber by hot water

**CONDUCTION**
- System suspended by 3 kevlar ropes

$P_{\text{loss}} \approx 0 \text{ W}$

$P_{\text{loss}} < 1 \text{ W}$

$P_{\text{loss}} < 0.1 \text{ W}$
Steady state: a constant power was applied

The temperature distribution in the system was studied as a function of the setting parameters in order to estimate the losses.

In the best condition of measurement the losses result negligible!

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Results from the electrical source calibration

Parameters:
- massflow value
- entering temperature value
- temperature of the external vacuum chamber

Blind measurement:
Measured $P = 927.8 \pm 1.3 \text{ W}$  
Set Power = 929 W  
0.3 % precision!!
Results from calibration

Time dependent power, like the exponential decay

The time constant of the system is estimated for the final measurement:

\[ P(t) = P_0 e^{-\frac{t-\Delta t}{\tau}} + P_W \]

Heat propagation time

\[ \Delta t = 15 \text{ h} \quad P_w = 0 \text{ W} \]
\[ \Delta t = 5 \text{ h} \quad P_w = 0 \text{ W} \]
\[ \Delta t = 0 \quad P_w = 0 \text{ W} \]
\[ \Delta t = 0 \quad P_w = -0.6 \text{ W} \]

We are ready for the final measurement!

Lost power < 1 W
**The beta spectrum measurement**

It influences:

- the source heat power (source-activity conversion)
- expected IBD interaction rate in Borexino

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

Some apparatus are under development:

- **at CEA in Paris**
- **at TUM in Munich**

A proposal is submitted for using **PERKEO III** spectrometer at Munich
The SOX sensitivity

Assuming
\[ \sigma = 0.015 \] activity meas
\[ \sigma = 0.03 \] spectrum meas

Thanks to both the analysis the puzzle of 1 eV sterile neutrino might be closed!!
Thanks

Borexino detector

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