The STEREO experiment: a search for sterile neutrino $\sim 1$eV at ILL

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on behalf of the Stereo collaboration
Motivation : $\bar{\nu}_e$ disappearance

2011: reevaluation of the $\bar{\nu}_e$ reactor flux prediction

$\rightarrow$ **Reactor Antineutrino Anomaly** : All reactor short-baseline experiments are observing a deficit (very accurate measurements : Daya Bay, RENO & Double Chooz)

- Wrong prediction ?
- Sterile neutrino ?

\[
P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} (E_{\bar{\nu}_e}, L) = 1 - \sin^2(2\theta_{\text{new}}) \sin^2 \left( 1.27 \frac{\Delta m^2_{\text{new}} [eV^2]}{E_{\bar{\nu}_e} [MeV]} L [km] \right)
\]

$\sim$ 1eV sterile neutrino

$\rightarrow$ Need dedicated measurements
A quest for a sterile neutrino in the eV range

More exactly, we need ...

- Non-ambiguous measurements to sign the existence -or not- of a light sterile neutrino
- Accurate energy measurements to constrain antineutrinos spectra
Experimental site
ILL research facility, Grenoble, France

Research reactor core $\sim 58 \text{ MW}_{th}$
$\rightarrow 10^{19} \bar{\nu}_e \text{ s}^{-1}$

- **Compact** core (40cm $\Phi$)
- **Highly enriched** $^{235}\text{U}$
- **Short baseline** measurement: $8.9\text{m} < L_{core} < 11.1\text{m}$

× **Surface-level** experiment (BUT 15 m.w.e only thanks to water channel)
× $\gamma$ and neutron background from neighboring experiments

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The STEREO experiment

1- Designed to probe the RAA region by measuring relative distortions of the $\bar{\nu}_e$ energy spectrum as a function of the distance [9-11m]

✓ Independent from predicted energy spectrum (norm. + shape)

2- Measurement of a pure $^{235}$U $\bar{\nu}_e$ energy spectrum
**Data taking**

**STEREO** is running since Nov. 2016

<table>
<thead>
<tr>
<th>Year</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>Nov. Commissioning, Installation</td>
</tr>
<tr>
<td>2017</td>
<td>March Reactor maintenance, Stereo maintenance (Effective data ON = 66 days, OFF = 25 days)</td>
</tr>
<tr>
<td>2018</td>
<td>March Reactor maintenance, May-June Data taking Phase II (Effective data ON = 47 days, OFF = 113 days)</td>
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</table>

**Phase-I:**
- Loss of optical coupling between PMTs and target for one target and on GC cell
- Evolving light cross-talks between cells → repaired during summer 2017

**Phase-II:**
- Stable conditions

Physics runs: \(~95\%\) of data taking time
• **Monitoring of liquids/electronics:**
  Automatic daily **LED measurement**: PMT gain, liquid stability, electronics linearity

• **Monitoring of the energy response:**
  On a weekly basis: internal and external calibrations using **radioactive sources**
  Ge$^{68}$, Sb$^{124}$, Cs$^{137}$, Mn$^{54}$, Zn$^{65}$, Na$^{24}$, H$^{1}(n,\gamma)$

• **Monitoring of the neutron capture:**
  Using dedicated AmBe source

→ Tuning of the MC simulation of the detector: Light collection, liquid properties, non linearity ($k_b$)
Tool developed to take into account:
- Light collection loss
- Evolving light leaks along time

\[ Q_i = \sum_{j=\text{cells}} E_j C_j L_{ji} \]

- Stability of the reconstructed n-H & n-Gd peaks (whole target volume) and deviation to MC

![Graphs showing reconstructed energy, counts, time stability, and cell to cell deviation]
Shielding against background

Passive and active shieldings against gamma, neutron and muon induced background

Detector
Borated polyethylene

µ-Veto
B₄C
Soft iron
Lead

Support structure

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Inverse Beta Decay reaction

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

Gd(n,γ) \rightarrow e^+ + n \sim 8\text{MeV} γ cascade

thermalisation
diffusion

No preceding μ (100μs veto)

\[ \Delta T < 70\mu s \]
\[ \Delta L < 600\text{mm} \]

space-time correlation

clean before 100μs
clean after 100μs

\[ 1.6 < E_{\text{prompt}} < 7.1\text{ MeV} \]
\[ 4.5 < E_{\text{delayed}} < 10\text{ MeV} \]

Prompt contained in vertex cell and 4 neighbouring cells

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Correlated background

Neutron induced reactions:

- **Fast neutrons**
  Prompt: proton recoil

- **Multiple neutron captures**
  Prompt: 2.2 MeV $\gamma$ or a 8 MeV $\gamma$ cascade from n-capt

- $^{12}\text{C}(n,n'\gamma)^{12}\text{C}$ reactions
  Prompt: mixing between 4.4 MeV $\gamma$ and proton recoil

Stopping muons:

- Prompt: $\mu$ stop
- Delayed: Michel e$^+$/$-$
  - Mainly rejected by asymmetry based cut

Pulse Shape Discrimination for prompt signal

![PSD in cell 1](image)

$\tau_e < \tau_p$

$Q_{\text{tail}}/Q_{\text{tot}} (e) < Q_{\text{tail}}/Q_{\text{tot}} (p)$
Prompt energy spectrum in the region of interest

\[
\text{(n,\gamma)H} \quad \text{12C(n,n'\gamma)12C}
\]

- e-recoil correlated background
- accidental background
- p-recoil correlated background

\[
\langle S/B \rangle_{\text{tot}} > = 0.6 \\
\langle S/B \rangle_{\text{corr}} > = 0.8 \\
\langle S/B \rangle_{\text{acc}} > = 6.8
\]
\( \bar{\nu}_e \) signal extraction: from PSD distributions

**OFF periods** → background model

**ON periods** → neutrino extraction

**Cell 1** - 
- \([3.125, 3.625]\) MeV
- \(\text{Teff} = 23\) days

![Graphs showing background and neutrino extraction](image)

- **Background**
- **Antineutrino component**

- Multi-Gaussian fit for each cell / energy / time bin
- \(A_\gamma/A_p\) ratio constrained by the OFF model

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**Coherent method to estimate background under \( \bar{\nu}_e \) component:**

- No assumption on PSD stability (temperature sensitivity)
- No assumption on global norm (pressure sensitivity)

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$\bar{\nu}_e$ signal extraction:
what’s new with phase-2?

**OFF period of phase-II:**
- 84 days ($t_{\text{eff}}$) with **more stable** conditions $\rightarrow$ increased statistics (larger time binning)

**Updated background model**
Additionnal gaussian (multiple proton recoils hypothesis (under study))
Relative comparison of $\nu$ energy distributions: Ratio method

Compare measured and simulated ratios of energy distributions - cell 1 taken as reference

- Insensitive to absolute flux normalization
- Insensitive to predicted spectrum shape

$$R_{i,j}^{\text{Data}} = \frac{\text{Data}_{i,j}}{\text{Data}_{i,\text{ref}=1}}$$ compared with $$R_{i,j}^{\text{MC}} = \frac{\text{MC}_{i,j}}{\text{MC}_{i,\text{ref}=1}}$$

$$\chi^2 = \sum_{i=1}^{N_{\text{Ebins}}} \left( R_{i}^{\text{Data}} - R_{i}^{\text{MC}}(\alpha) \right)^t V_i^{-1} \left( R_{i}^{\text{Data}} - R_{i}^{\text{MC}}(\alpha) \right) + \sum_{j=1}^{N_{\text{Cells}}} \left( \frac{\alpha_j^{\text{Norm}}}{\sigma_j^{\text{Norm}}} \right)^2 \quad + \sum_{j=0}^{N_{\text{Cells}}} \left( \frac{\alpha_j^{\text{Escale}}}{\sigma_j^{\text{Escale}}} \right)^2$$

$V_i$ is the covariance matrix of the 5 ratios (common reference for each cell) for the energy bin $i$.

\{\alpha\} are nuisance parameters to take into account estimated systematics

<table>
<thead>
<tr>
<th></th>
<th>Cell-to-cell correlated</th>
<th>Uncorrelated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy scale $\sigma_j^{\text{Escale}}$</td>
<td>0.35 %</td>
<td>1.00 %</td>
</tr>
<tr>
<td>Normalization $\sigma_j^{\text{Norm}}$</td>
<td>-</td>
<td>1.70 %</td>
</tr>
</tbody>
</table>

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Ratio method: cell 1 taken as reference

- Measured ratios
- Non-oscillation prediction

- Minimized pull terms stay within ±1σ

- Non-oscillation hypothesis ($H_0$) can not be rejected: p-value = 34% (40%) for phase-I (phase-I+II)

Measured ratios for the cells from 2 to 6 (blue) compared to the null oscillation hypothesis model (red)
Exclusion contours Phase-I+II combined

- Phase-I + Phase-II combined results
  (66+47) days reactor-ON
  (396 ± 4) $\bar{\nu}_e$ day$^{-1}$
  Considered as two independent measurements:
  $\chi^2 = \chi^2_I(\bar{\alpha}_I) + \chi^2_{II}(\bar{\alpha}_{II})$
  $\bar{\alpha}_I \neq \bar{\alpha}_{II}$

- Raster-scan approach ($\Delta^2_m$ slices)

- $\Delta \chi^2$ distributions estimated by MC pseudo experiments

- Best-fit value of the RAA rejected at 98% C.L.
Conclusions and perspectives

- **STEREO** is now running under **very stable conditions**

- The **correlated background understanding improves** using reactor-OFF periods

- First exclusion contour obtained, original RAA is rejected at 98%CL using the **robust ratio method**. Data taking will continue until end 2019, reaching **300 days of reactor-ON data**
  

- Improved results are coming soon, with a **pure $^{235}$U spectrum**

~ Thanks for your attention ! ~
BACKUP
Quenching curve
Non-linear light production in the large dE/dx regime (low E – Bragg peak)

Data
MC
Energy [MeV]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Data/MC
0.98
0.99
1
1.01
0.98
0.99
1
1.01
Energy [MeV]
Am-Be neutron source in target cells:

- n-capt time from AM-Be in agreement with IBD candidates
- Relative variations of n efficiency in agreement between MC and data
- Absolute fraction of Gd-capture fine-tuned in MC: determination of the glocal n-capture efficiency
# Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Contrib to $\sigma_{\text{Cell}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell volume</td>
<td>0.85 %</td>
</tr>
<tr>
<td>n-capture efficiency</td>
<td>1.20 %</td>
</tr>
<tr>
<td>Asym cut efficiency</td>
<td>0.50 % (3% cell4)</td>
</tr>
<tr>
<td>$D_{p-d}$ cut efficiency</td>
<td>0.50 %</td>
</tr>
<tr>
<td>Annihilation cut efficiency ($E_{j\text{vertex}}&lt;0.8$ MeV)</td>
<td>0.50 %</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>1.7% (3.4% cell4)</strong></td>
</tr>
</tbody>
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<thead>
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<th>Source</th>
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<td>Escale correlated</td>
<td>0.35 %</td>
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<td>Escale uncorrelated</td>
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</table>
Ratios - PSD fit with 2g  
Ratios - PSD fit with 3g  

D, D/1, D/2  
E\text{\textsubscript{visible}} [MeV]  

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Counts [A.U.]

- Evolution in cell 2 at energy 2.38 MeV
- Evolution in cell 2 at energy 3.88 MeV

Phase-I
Phase-II

reactor-OFF spectrum of (IBD) candidates

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- $A_\gamma/A_p$ compatible with a constant in all cell/energy bin
- Same correlation with atmospheric pressure for e-recoils rates and p-recoils rates

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PSD (electronic) correlation with temperature

PSD follows temperature changes
- Temperature changes occur when reactor goes on, or off, and lasts for several weeks
- Linear correlation with slope \([-0.015 / -0.020]\) (PSD unit/Celsius degree)