ESSνSB progress on the design of the near and far neutrino detectors and the simulation of the physics potential

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Why ESSνSB?

ESSνSB = European design study* for an experiment to measure CP violation at 2\textsuperscript{nd} neutrino oscillation maximum.

\[
\frac{(P_{\mu \rightarrow e} - P_{\mu \rightarrow \bar{e}})}{(P_{\mu \rightarrow e} - P_{\mu \rightarrow \bar{e}})} \text{ @ 2nd osc. max.} \sim 3
\]

➢ 3x signal at 2\textsuperscript{nd} osc. maximum is less obscured by systematics

➢ But less statistics because:
  • move further than 1\textsuperscript{st} maximum
  • the smaller the energy -> the smaller the cross section

➢ Intense beam on target -> intense neutrino flux

* A Horizon 2020 EU Design Study Project: grant agreement No 777419; start: 2018, end: 2022
Accelerator, accumulator, target and Near Detector site

- ESS proton linac near Lund, Sweden
  - Increase proton kinetic energy to 2.5 GeV
  - Double the linac rate (14 Hz → 28 Hz)

- ESS proton pulse is too long - accumulator ring (C~400 m) needed to compress proton pulses to ~ 1.3 μs, otherwise:
  - magnetic horns would melt
  - atmospheric neutrino background would be too large for CP violation measurement

- Neutrino optimised target station
  - 4 targets made of titanium spheres

- Underground near detector hall
  - Located ~250 m from the target
Far Detector site

- **Baseline:**
  - Garpenberg mine, 540 km from the neutrino source
  - corresponding to 2\textsuperscript{nd} oscillation maximum
  - depth 1200 m

- **Alternative:**
  - Zinkgruvan mine, 340 km from source
  - depth 1500 m
Aim of detectors

➢ Near detectors
  • Constrain the prompt neutrino flux
  • Measure neutrino interaction cross-sections (both inclusive and exclusive)

➢ Far detectors
  • Observe $\bar{\nu}_e$ appearance in the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation channel
Neutrino energy distributions (without optimisation)

at 100 km from the target and per year (in absence of oscillations)

Near Detectors
Near detectors

• Main purposes:
  • Constrain the prompt neutrino flux
  • Measure neutrino interaction cross-sections (both inclusive and exclusive)

➢ A water Cherenkov detector

➢ A magnetized fine-grained tracker (SFGD)

➢ NINJA-like emulsion detector:
  • water target mass of about 1 ton
  • 130 Emulsion Cloud Chambers (ECC)
Near Water Cherenkov detector

Water Cherenkov detector is used for:
- event rate measurement
- flux normalization
- event reconstruction comparison with the far detector.

➢ Some figures:
- radius $R = 7$ m, length $L = 11$ m
- $1725 \text{ m}^3$ total volume
- $\sim 1000 \text{ m}^3$ fiducial volume
- Readout: 40% PMT coverage
Interaction rates in Near Water Cherenkov

Neutrino mode

Antineutrino mode

Expected number of interactions at 250 m in 500 t of water for $2.16 \times 10^{23}$ p.o.t. (effective year):

<table>
<thead>
<tr>
<th>Neutrino</th>
<th>Expected number</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$</td>
<td>27.5 M</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>66 k</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>150 k</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>300</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Neutrino</th>
<th>Expected number</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$</td>
<td>265 k</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>4.7 M</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>1.8 k</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>15 k</td>
</tr>
</tbody>
</table>
Near Water Cherenkov performance

Charged lepton energy reconstruction
Fiducial cut - 2m

Charged lepton identification
Fiducial cut - 2m
Super Fine-Grained Tracker (SFGD)

SFGD detector is used for measurements of neutrino cross-sections in energy region (60–600 MeV).

- Some figures:
  - scintillating cubes 1x1x1 cm$^3$
  - WLS fibers in three dimensions
  - overall dimensions 1.4x1.4x0.5 m$^3$
  - Dipole magnetic field up to 1 T
  - Readout MPPCs

SFGD prototype tested at CERN 2018
Super Fine-Grained Tracker performance

➢ Separation $\nu_e / \nu_\mu$ CC events with machine learning methods (TMVA):
  • signal efficiency of 95.5%
  • signal purity of 99.8%

➢ Neutrino energy reconstruction for $\nu_\mu$ (left) and $\nu_e$ (right) with machine learning methods (TMVA):
  • resolution in both cases in the order of 25 MeV
  • assuming true charged lepton momentum
Emulsion detector NINJA-like

- **Usage in ESSnuSB**
  - Study of neutrino interaction topology
  - Measurement of interaction cross-section

- **Advantages of the emulsion detector**
  - Can reconstruct all charged particle tracks with high precision
  - Can detect gammas via conversion
  - Good electron/muon/hadron discrimination

- **Disadvantages of the emulsion detectors**
  - No timing information
    - But can be restored by connecting tracks with SFGD
  - Price per mass
  - No online event reconstruction
  - Labour intensive

![Water target emulsion detector](image1)

Possible configuration in ESSnuSB

Courtesy T. Fukuda
Cross-section measurements

➢ Main problem:
  • Event rate (what we measure) is proportional to (flux) x (cross-section).
  • So, we need one to measure the other, if using event rate as observable.

➢ Strategies:
  • Use elastic scattering of neutrinos on electrons (known cross-section) to constrain the flux
    • measured in the Near WC detector
    • neutrino cross-section scales with target mass:
      - having electron as a target, the cross-section is much smaller than having nucleon as a target
  • Event selection:
    - ν - e scattering has a very forward single electron in the final state.

• Having constraint on the flux, we can measure interaction cross-sections in all Near Detectors:
  • WCKov, Super FGD, emulsion
Far Detector
Far Detectors

Main purpose: observe $\nu_e$ appearance in the $\nu_\mu \rightarrow \nu_e$ oscillation channel

- Two identical water Cherenkov detectors.
- Each module is a standing cylinder:
  - diameter $D = 78$ m, height $h = 78$ m
  - $373k$ m$^3$ total volume
  - $270k$ m$^3$ fiducial volume (~10xSuperK)
  - Readout: 38k 20” PMTs
  - 30% optical coverage

- Can also be used for other purposes:
  - Proton decay
  - Astroparticles
  - Galactic SN $\nu$
  - Supernovae "relics"
  - Solar Neutrinos
  - Atmospheric Neutrinos
Interaction rates in Far Detectors

Neutrino mode

Antineutrino mode

Expected number of interactions at 540 km in 540 kt of water for $2.16 \times 10^{23}$ p.o.t. (effective year), assuming $\delta_{CP} = 0$:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Expected number</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu \rightarrow \nu_e$</td>
<td>200</td>
</tr>
<tr>
<td>$\nu_\mu \rightarrow \nu_\mu$</td>
<td>3600</td>
</tr>
<tr>
<td>$\nu_e \rightarrow \nu_e$</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel</th>
<th>Expected number</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$</td>
<td>40</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu \rightarrow \bar{\nu}</em>\mu$</td>
<td>600</td>
</tr>
<tr>
<td>$\bar{\nu}_e \rightarrow \bar{\nu}_e$</td>
<td>3</td>
</tr>
</tbody>
</table>
Neutrino energy reconstruction

Kinematical neutrino energy reconstruction formula

\[ E_{\nu}^{\text{rec}} = \frac{m_f^2 - (m_f')^2 - m_i^2 + 2m_i'E_l}{2(m_i' - E_l + p_l \cos \theta_l)} \]  

where \( E_{\nu}^{\text{rec}} \) is the reconstructed neutrino energy, \( m_i \) and \( m_f \) are the initial and final nucleon masses respectively, and \( m_i' = m_i - E_b \), where \( E_b = 27 \text{ MeV} \) is the binding energy of a nucleon inside \(^{16}\text{O}\) nuclei. \( E_l, p_l \) and \( \theta_l \) are the reconstructed lepton energy, momentum, and angle with respect to the beam, respectively. The selec-

Given that you know:
- momentum of the outgoing charged lepton
- its angle w.r.t. incoming neutrino
- that it is a quasielastic interaction
- which nucleus neutrino interacted with \((^{16}\text{O})\)

you can approximately calculate neutrino energy.

Intrinsic uncertainties come from nuclear effects, most notably Fermi motion of nucleons in nuclei.

From: Phys. Rev. D 96, 092006
Neutrino energy resolution

- Quasi-elastic scattering.
- Fiducial volume cut – 2 m from walls.

Neutrino energy resolution: 140 MeV for neutrinos and 100 MeV for antineutrinos.
Conclusions

➢ The Project ESSnuSB:
  • aims to observe CP violation in neutrino oscillations at the 2\textsuperscript{nd} oscillation maximum using 500 kt WC detector
  • large associated detectors have a rich astroparticle physics program.
  • a preparatory phase is needed

➢ The detectors:
  • observe $\bar{\nu}_e$ appearance in the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation channel
  • constrain the prompt neutrino flux
  • measure neutrino interaction cross-sections (both inclusive and exclusive)