Neutrino CP Violation with the ESS\(\nu\)SB project

Marcos Dracos
on behalf of the ESS\(\nu\)SB group
European Spallation Source

under construction phase
(~1.85 B€ facility)
• The ESS will be a copious source of spallation neutrons.
• 5 MW average beam power.
• 125 MW peak power.
• 14 Hz repetition rate (2.86 ms pulse duration, $10^{15}$ protons).
• Duty cycle 4%.
• 2.0 GeV protons (up to 3.5 GeV with linac upgrades).
• $>2.7 \times 10^{23}$ p.o.t/year.

Linac ready by 2023 (full power and energy)
ESSνSB ν energy distribution

- almost pure $\nu_\mu$ beam
- small $\nu_e$ contamination which could be used to measure $\nu_e$ cross-sections in a near detector

<table>
<thead>
<tr>
<th></th>
<th>positive</th>
<th>negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_\nu \times 10^{10}$/m²</td>
<td>%</td>
<td>$N_\nu \times 10^{10}$/m²</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>396</td>
<td>11</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>6.6</td>
<td>206</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>1.9</td>
<td>0.04</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>0.02</td>
<td>1.1</td>
</tr>
</tbody>
</table>

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

\((\nu_\mu \rightarrow \nu_e)\)

\[ P_{\nu_\mu \rightarrow \nu_e (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} = s_{23}^2 \sin^2 2\theta_{13} \left( \frac{\Delta_{13}}{\bar{B}_\mp} \right)^2 \sin^2 \left( \frac{\bar{B}_\mp L}{2} \right) \]

\[ + c_{23}^2 \sin^2 2\theta_{12} \left( \frac{\Delta_{12}}{A} \right)^2 \sin^2 \left( \frac{AL}{2} \right) \]

\[ + \tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{\bar{B}_\mp} \sin \left( \frac{AL}{2} \right) \sin \left( \frac{\bar{B}_\mp L}{2} \right) \cos \left( \pm \delta_{CP} - \frac{\Delta_{13} L}{2} \right) \]

Non-CP terms

interference

\( \tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \), \( \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_v} \), \( \bar{B}_\mp \equiv \left| A \mp \Delta_{13} \right| \), \( A = \sqrt{2}G_F N_e \)

matter effect

\( \neq 0 \Rightarrow CP \) Violation

⇒ accessibility to mass hierarchy

⇒ long baseline

be careful, matter effects also create asymmetry
$\delta_{\text{CP}}$ and matter-antimatter asymmetry magnitude

\[ A_{\alpha\beta}^{\text{CP}} = P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \]
\[ = J_{\text{CP}}^{\text{PMNS}} \cdot \sin\delta_{\text{CP}} \]

with: $J_{\text{CP}}^{\text{PMNS}} \sim 3 \times 10^{-3}$ (Jarlskog invariant)

(for hadrons: $J_{\text{CP}}^{\text{CKM}} \sim 3 \times 10^{-5}$, not enough to explain the matter-antimatter asymmetry in the Universe even if $\delta_{\text{CP}} \sim 70^\circ$)

Theoretical models predict that if $|\sin\delta_{\text{CP}}| \geq 0.7$ (45°$<\delta_{\text{CP}}<$135° or 225°$<\delta_{\text{CP}}<$315°), it could be enough to explain the observed asymmetry.
Neutrino Oscillations with "large" $\theta_{13}$

- $\theta_{13}=1^\circ$ ("small" $\theta_{13}$)
  - solar
  - atmospheric
  - CP interference

- $\theta_{13}=8.8^\circ$ ("large" $\theta_{13}$)
  - solar
  - atmospheric
  - CP interference

• for small $\theta_{13}$ 1st oscillation maximum is better (arXiv:1110.4583)

• for "large" $\theta_{13}$ 1st oscillation maximum is dominated by atmospheric term

- 1st oscillation max.: $A=0.3\sin\delta_{CP}$
- 2nd oscillation max.: $A=0.75\sin\delta_{CP}$

- $\theta_{13}=8.8^\circ$ ("large" $\theta_{13}$)
  - $\delta_{CP}=-90$
  - $\delta_{CP}=0$
  - $\delta_{CP}=+90$

more sensitivity at 2nd oscillation max.

Can we go to the 2nd oscillation maximum using our proton beam?

Yes, if we place our far detector at around 500 km from the neutrino source.

MEMPHYS like Cherenkov detector
(MEGaton Mass PHYSics studied by LAGUNA)

- Neutrino Oscillations (Super Beam, Beta Beam)
- Proton decay
- Astroparticles
- Understand the gravitational collapsing: galactic SN
- Supernovae "relics"
- Solar Neutrinos
- Atmospheric Neutrinos

- 500 kt fiducial volume (~20xSuperK)
- Readout: ~240k 8” PMTs
- 30% optical coverage

(arXiv: hep-ex/0607026)
2nd Oscillation max. coverage

-detected (electron) neutrinos by MEMPHYS detector

1st oscillation max.

2nd oscillation max. well covered by the ESS neutrino spectrum
ESS Linac modifications to produce a neutrino Super Beam
How to add a neutrino facility?

- The neutron program must not be affected and if possible synergetic modifications.
- Linac modifications: double the rate (14 Hz → 28 Hz), from 4% duty cycle to 8%.
- Accumulator (C~400 m) needed to compress to few μs the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA, power consumption, Joule effect)
- H source (instead of protons),
- Target station (studied in EUROν),
- Underground detector (studied in LAGUNA).
- Short pulses (~μs) will also allow DAR experiments (as those proposed for SNS) using the neutron target.
Mitigation of high power effects
(4-Target/Horn system for EUROnu Super Beam)

Packed bed canister in symmetrical transverse flow configuration (titanium alloy spheres)

4-target/horn system to mitigate the high proton beam power (4 MW) and rate (50 Hz)

target inside the horn
- little dependence on mass hierarchy (not so long baseline),
- \( \delta_{CP} \) coverage at 5 \( \sigma \) C.L. up to 60%,
- \( \delta_{CP} \) accuracy down to 6° at 0° and 180° (absence of CPV for these two values),
- not yet optimized facility.
Which baseline?

CPV \textit{(Nucl. Phys. B 885 (2014) 127)}

- \(~60\%\) $\delta_{CP}$ coverage at $5\,\sigma$ C.L.
- $>75\%$ $\delta_{CP}$ coverage at $3\,\sigma$ C.L.
- \textbf{systematic errors:} $5\%/10\%$ (signal/backg.)

EPS2017, July 2017
M. Dracos IPHC-IN2P3/CNRS/UNISTRA
Muons at the level of the beam dump

2.7x10^{23} p.o.t/year

muons at the level of the beam dump (per proton)

4.2x10^{20} μ/year
(16.3x10^{20} for 4 m²)

4.1x10^{20} μ/year

• input beam for future 6D μ cooling experiments (for muon collider),
• good to measure neutrino x-sections (ν_μ, ν_e) around 200-300 MeV using a near detector,
• low energy nuSTORM,
• Neutrino Factory,
• Muon Collider.
Muons of average energy ~0.5 GeV at the level of the beam dump (per proton)

more than $4 \times 10^{20}$ $\mu$/year from ESS compared to $10^{14}$ $\mu$ used by all experiments up to now ($10^{18}$ $\mu$ for COMET in the future).
ESSνSB at the European level

- COST application for networking has been succeeded: CA15139 (2016-2019)

  - EuroNuNet: *Combining forces for a novel European facility for neutrino-antineutrino symmetry violation discovery* ([http://www.cost.eu/COST_Actions/ca/CA15139](http://www.cost.eu/COST_Actions/ca/CA15139))

- Major goals of EuroNuNet:
  - to aggregate the community of neutrino physics in Europe to study the ESSνSB concept in a spirit of inclusiveness,
  - to impact the priority list of High Energy Physics policy makers and of funding agencies to this new approach to the experimental discovery of leptonic CP violation.
  - 13 participating countries (network still growing).
A **H2020 EU Design Study** has been submitted end of March (Call INFRADEV-01-2017)

**Title of Proposal**: Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator

**Duration**: 4 years

**Total cost**: 4.7 M€

**Requested budget**: 3 M€

15 participating institutes from 11 European countries including CERN and ESS

6 Work Packages

Decision before end of August

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**WP2**: linac

**WP3**: accumulator

**WP4**: target hadrons (focusing)

**WP5**: decay tunnel near

**WP6**: far

**physics**

Detectors

ESSvSB

BENE (2004-2008)

ISS (2005-2007)

EUROv (2008-2012)

LAGUNA (2008-2010)

LAGUNA-LBNO (2010-2014)

COST Action CA15139 (2015-2019)
Possible Schedule for ESSvSB

- COST CA15139: 2016-2019
- EU H2020 Design Study: 2018-2021
- Decision for ESSvSB: 2022
- End of Linac construction: 2023
- Construction of ESSvSB: 2023-2030
- Data taking: 2030-2040 (for CPV).
- Rich muon program after.
Conclusion

• Significantly better CPV sensitivity at the 2\textsuperscript{nd} oscillation maximum.
• The European Spallation Source Linac will be ready in less than 10 years (5 MW, 2 GeV proton beam by 2023).
• ESS will have enough protons to go to the 2\textsuperscript{nd} oscillation maximum and increase its CPV sensitivity.
• CPV: $5 \sigma$ could be reached over 60% of $\delta_{CP}$ range (ESSvSB) with large potentiality.
• Large associated detectors have a rich astroparticle physics program.
• Rich muon program.
• A Design Study is needed.
• COST network project CA15139 already supports this project.
Neutrino spectra

540 km (2 GeV), 10 years
below $\nu_\tau$ production, almost only QE events

$\delta_{CP}=0$

neutrinos

<table>
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<th>Events/100 MeV</th>
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<tbody>
<tr>
<td>80</td>
</tr>
<tr>
<td>60</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>20</td>
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anti-neutrinos

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$\nu_e$ signal
$\nu_\mu$ missID
$\nu_e$ beam
$\bar{\nu}_e$ beam
NC back.
$\nu_\mu \rightarrow \bar{\nu}_e$

2 years

8 years
ESS under construction

September 2014

Cryo Compressor Building

Beam Line Gallery

monolith and active cells
Preparing the ESS linac for operation at 10 MW with a 8% duty cycle and 28 Hz pulsing

For the medium-beta elliptical-cavity part ESS is planning to use tetrodes. Thales has developed a new screen grid with graded wire thickness making operation at 10 % duty cycle possible.

The picture shows the cryostat and test bunker at the FREIA Lab in Uppsala where a first prototype of the ESS 352 MHz spoke accelerating cavity is currently under test at 14 Hz and later on will be tested at 28 Hz.
Systematic errors and exposure

for ESSnuSB systematic errors see 1209.5973 [hep-ph] (lower limit "default" case, upper limit "optimistic" case)

P5 requirement: 75% at 3σ

High potentiality

Impact of systematics
Setup: 2GeV – 360 km

(courtesy P. Coloma)
\( \delta_{CP} \) accuracy performance
(USA snowmass process, P. Coloma)

for systematic errors see (7.5%/15% for ESSnuSB):

Comparisons

\[ \chi^2 \delta_{CP} \]

\[ \text{ESS: } L = 360 \text{ km} \]
\[ \text{ESS: } L = 540 \text{ km} \]
\[ \text{ESS: } E = 2 \text{ GeV} \]
\[ \text{ESS: } E = 2.5 \text{ GeV} \]

5% sys. Normal Hierarchy

\[ \text{fraction of } \delta_{CP} \]

\[ \text{T2HK} \]
\[ \text{DUNE} \]
\[ \text{ESS: } L = 360 \text{ km} \]
\[ \text{ESS: } E = 2 \text{ GeV} \]
\[ \text{ESS: } L = 540 \text{ km} \]
\[ \text{ESS: } E = 2.5 \text{ GeV} \]
CPV (2 GeV protons)

Systematic errors (nominal values): 5%/10% for signal/background

More than 50% $\delta_{CP}$ coverage using reasonable assumptions on systematic errors
The MEMPHYS Detector (Proton decay)

\( p \rightarrow e\pi^0 \) sensitivity (90\% CL)

\( p \rightarrow \nu K^+ \) sensitivity (90\% CL)

- Detector: (A) Super-K
- \( \text{eff}_{SK} = 44\% \)
- \( \text{BG}_{SK} = 2.2\text{ev/Mtyr} \)
- \( \text{eff} = 3/4 \times \text{eff}_{SK} \)
- \( S/N = \sqrt{4} \times (S/N)_{SK} \)
- \( \text{eff} = 1/2 \times \text{eff}_{SK} \)
- \( S/N = 1/2 \times (S/N)_{SK} \)

Current status:
- 79ktyr, \( 5.0 \times 10^{33} \) yrs

Current limit:
- 79.3ktyr, \( 1.6 \times 10^{33} \) yrs

Prompt \( \gamma \) spectrum

\( \pi^+\pi^0 \)

(arXiv: hep-ex/0607026)
The MEMPHYS Detector (Supernova explosion)

For 10 kpc: \( \sim 10^5 \) events

Diffuse Supernova Neutrinos
(10 years, 440 kt)