Luca Stanco,
INFN-Padova
(for the NESSiE collaboration)

The NESSiE way for sterile neutrinos

- The NESSiE Collaboration
- The “sterile” issue at 1 eV mass scale
- CERN and FNAL proposals
- Prospects
The NESSiE Collaboration

**Neutrino Experiment with Spectrometers in Europe**

or

**Neutrino Experiment with Spectrometers in FERMILAB**

Make a conclusive experiment to clarify the $\nu_\mu$ disappearance behavior at 1 eV scale, by using spectrometers to allow muon charge and momentum measurement.

Spectrometers at a neutrino beam. Extended studies:

- SPSC-P-343, arXiv:1111.2242
- SPSC-P347, arXiv:1203.3432
- ESPP, arXiv:1208.0862
- LOI CENF: [https://edms.cern.ch/nav/P:CERN-0000096725:V0/P:CERN-0000096728:V0/TAB3](https://edms.cern.ch/nav/P:CERN-0000096725:V0/P:CERN-0000096728:V0/TAB3)
- FNAL-P-1057, arXiv:1404.2521
The NESSiE Collaboration

INFN and Physics Departments (Italy), Lebedev Institute (Russia), MSU (Russia), Boskovic Institute (Croatia), CERN.

All these groups have long experience in Neutrino Physics and Hardware (Chorus, Macro, Nomad, Opera, T2K ...)

1. INFN, Sezione di Bari, 70126 Bari, Italy
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3. INFN, Sezione di Bologna, 40127 Bologna, Italy
4. Dipartimento di Fisica dell'Università di Bologna, 40127 Bologna, Italy
5. European Organization for Nuclear Research (CERN), Geneva, Switzerland
6. Laboratori Nazionali di Frascati dell'INFN, 00044 Frascati (Roma), Italy
7. INFN, Sezione di Lecce, 73100 Lecce, Italy
8. Dipartimento di Matematica e Fisica dell'Università del Salento, 73100 Lecce, Italy
9. Dipartimento di Ingegneria dell'Innovazione dell'Università del Salento, 73100 Lecce, Italy
10. Lebedev Physical Institute of Russian Academy of Science, Leninskie pr., 53, 119333 Moscow, Russia.
11. Lomonosov Moscow State University (MSU SINP), 1(2) Leninskie gory, GSP-1, 119991 Moscow, Russia
12. INFN, Sezione di Padova, 35131 Padova, Italy
13. Dipartimento di Fisica e Astronomia dell'Università di Padova, 35131 Padova, Italy
14. Dipartimento di Fisica dell'Università di Roma “La Sapienza” and INFN, 00185 Roma, Italy
15. Rudjer Boskovic Institute, Bijenicka 54, 10002 Zagreb, Croatia

‡ Also at Centre de Recherche en Astronomie Astrophysique et Geophysique, Alger, Algeria
The “sterile” issue

From masses to flavours:

\[
|\nu_e\rangle = U_{e1} |\nu_1\rangle + U_{e2} |\nu_2\rangle + U_{e3} |\nu_3\rangle \\
|\nu_\mu\rangle = U_{\mu1} |\nu_1\rangle + U_{\mu2} |\nu_2\rangle + U_{e\mu3} |\nu_3\rangle \\
|\nu_\tau\rangle = U_{\tau1} |\nu_1\rangle + U_{\tau2} |\nu_2\rangle + U_{e\tau3} |\nu_3\rangle
\]

\(U\) is the 3 × 3 Neutrino Mixing Matrix mixing given by 3 angles, \(\theta_{23}, \theta_{12}, \theta_{13}\) transition amplitudes driven by

\[\Delta m^2_{solar} = \Delta m^2_{21}\]

\[\Delta m^2_{atm} = |\Delta m^2_{31}| \approx |\Delta m^2_{32}|\]

The wonderful frame pinpointed for the 3 standard neutrinos, beautifully adjusted by the \(\theta_{13}\) measurement, left out some relevant questions:

- Leptonic CP violation
- Mass values
- Dark Matter
- Anomalies and discrepancies in several results
The “sterile” issue (cnt.)

The previous picture is working wonderfully. So it should stay whenever extensions are allowed!

Exploit 3+1 or even 3+2 oscillating models, by adding one or more “sterile” neutrinos

\[
\begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\
U_{s1} & U_{s2} & U_{s3} & U_{s4}
\end{bmatrix}
\]

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{\alpha\beta} \sin^2 \left( \frac{\Delta m^2_{41} L}{4E} \right)
\]

**APPEARANCE**

\[
P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \left( \frac{\Delta m^2_{41} L}{4E} \right)
\]

**DISAPPEARANCE**

when \(\Delta m^2_{21} \ll \Delta m^2_{31} \ll \Delta m^2_{41}\) and \(|U_{s4}| \leq 1\)

with

\[
\sin^2 2\theta_{e\mu} = 4 |U_{e4}|^2 |U_{\mu4}|^2
\]

for **APPEARANCE**

and

\[
\sin^2 2\theta_{ee} = 4 |U_{e4}|^2 \left(1 - |U_{e4}|^2\right)
\]

\[
\sin^2 2\theta_{\mu\mu} = 4 |U_{\mu4}|^2 \left(1 - |U_{\mu4}|^2\right)
\]

for **DISAPPEARANCE**

**sterile**: not weakly interacting neutrinos (B. Pontecorvo, JETP, 53, 1717, 1967)
The “sterile” issue (cnt.)

- Experimental hints for more than 3 standard neutrinos, at eV scale
- Strong tension with any formal extension of 3x3 mixing matrix

**ν_e disappearance**

- **Reactor anomaly ~2.5σ**
  - Re-analysis of data on anti-neutrino flux from reactor short-baseline (L~10-100 m) shows a small deficit of
  - \( R = 0.943 \pm 0.023 \)

**ν_e appearance**

- **Accelerator anomaly ~3.8σ**
  - Confirmed (?) by miniBooNE (which also sees appearance of ν_e in a ν_μ beam) A. Aguilar et al. (MiniBooNE Collaboration) Phys.Rev.Lett. 110 161801 (2013)

**Gallex/SAGE anomaly ~3σ**

- Deficit observed by Gallex in neutrinos coming from a ^{51}Cr and ^{37}Ar sources
  - \( R = 0.76 +0.09 -0.08 \)

?? Where is ν_μ disappearance ??
Possible explanation: mixing of the active flavours with a sterile neutrino $\Delta m^2 \sim 1 \text{ eV}^2$

But there are STRONG tensions between $\nu_e$ (appearance and disappearance) and $\nu_\mu$ disappearance

(by J. Kopp at Neutrino2014 and references therein)

What is the community undergoing?
Many proposals and experiments to confirm the anomalies.
Why not directly going to measure the $\nu_\mu$ disappearance?

![Diagram with labels and data points]
Prospects for the measurement of $\nu_\mu$ disappearance at the FNAL-Booster

The NESSiE Collaboration
Key-points of the proposal:

1. The muon-neutrino disappearance is mandatory
   - either in case of null result on electron-neutrino
     (*the sterile possibility might still be there due to interference modes and data mis-interpretation*)
   - or in case of positive result
     (*to address the correct interpretation of sterile, see current tension between appearance/disappearance*)

2. Standalone measurement of muon-neutrinos
   (*fully compatible with upstream LAr, or, in case, a small active scintillator target may be foreseen at Near-site for NC/CC and absolute rate control*)

3. Interplay between systematic and statistical errors:
   optimized configuration for Near and Far site

4. IDENTICAL near and far detector
   (*the same iron slab will be cut in two pieces to be put corresponding in the Near and the Far*)

5. No R&D/refurbishing/upgrade: robustness of the program
   (*80% of re-used well proven detectors, straightforward extension; 100 kWatt needed for each site*)
Careful study of the FNAL-Booster neutrino beam, based on previous knowledge from MiniBooNE, SciBooNE and data obtained by HARP and E910.

- Full simulation of the beam with GEANT4 and FLUKA (from proton to neutrinos)

- Detailed systematic error source analysis (use of Sanford-Wang parametrization)

- Several configurations analyzed, on/off-axis including MicroBooNE site and different detector sizes

A possibility

**Near**: SciBooNE enclosure

**Far**: NOvA NDOS surface building
Near-site | Far | Near-off | Far | Near-size | Far
--- | --- | --- | --- | --- | ---
 configuration | $L_N$ (m) | $L_F$ (m) | $y_N$ (m) | $y_F$ (m) | $s_N$ (m) | $s_F$ (m)
1 | 110 | 710 | 0 | 0 | 4 | 8
2 | 110 | 710 | 0 | 0 | 1.25 | 8
3 | 110 | 710 | 1.4 | 11 | 4 | 8
4 | 110 | 710 | 1.4 | 11 | 1.25 | 8
5 | 460 | 710 | 7 | 11 | 4 | 8
6 | 460 | 710 | 6.5 | 10 | 4 | 6

Table 2: Near-Far detectors configurations. $L_{N(F)}$ is the distance of the Near (Far) detector from the target. $y_{N(F)}$ is the vertical coordinate of the center of the Near (Far) detector with respect to the beam axis which lies at about -7 m from the ground surface. $s_{N(F)}$ is the dimension of the Near (Far) detector.

Near almost on axis
Far on surface,
Full “NESSiE” configuration
Figure 10: Far-to-Near ratios for the six considered configurations. Comparison of FLUKA and GEANT4 for hadroproduction.
Near site

Far site

ABSOLUTE nb. interactions in the FAR fiducial volume, 3 years data taking
Three independent analysis, with different statistical approaches

Sensitivity [95% C.L.]

Above conditions plus a full simulation and a careful treatment of 1% systematics error
Thank you!

NESSiE at FNAL
BACKUP
Iron slabs thinner than those available by OPERA NOT worth

Figure 18: CC efficiency ($\varepsilon_{CC}$, points) and purity ($p$, open circles) as a function of the minimum number of RPC planes for the two spectrometer geometries, 5 cm slabs (in blue) and 2.5 cm slabs (in black). For a given level of purity $p$ the efficiencies for the two geometries are similar, therefore no advantage in statistics is taken requiring the same NC contamination suppression.
The collected neutrino interactions:

<table>
<thead>
<tr>
<th>5cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
</tbody>
</table>

*Nb. RPC slabs (5 cm each)*

(about 400 MeV)
The collected neutrino interactions:

Relative rate at NEAR site

<table>
<thead>
<tr>
<th>hpall</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>704851</td>
<td>4.546</td>
<td>3.986</td>
</tr>
</tbody>
</table>

Relative rate at NEAR site

<table>
<thead>
<tr>
<th>hall</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>543557</td>
<td>359.1</td>
<td>217.8</td>
</tr>
</tbody>
</table>
Resolutions:

Sensitivities from the actual NESSiE configurations (full simulation, with neutrino beam)

Momentum measured by range (ICM) up to 3.5 GeV, then $\approx 30\%$ are provided (goal $\geq 250$ MeV).

Charge-ID measured by iron slabs (ICM: blue line)

Momentum measured by range (ICM) up to 3.5 GeV, then $\approx 30\%$ are provided.
absolute number of $\nu_\mu$ CC interactions, seen by the Near detector at 110 m, either in the $E_\nu$ or the $p_\mu$ variables, normalized to the expected luminosity in 3 years of data taking at FNAL–Booster, or $6.6 \times 10^{20}$ p.o.t.

(full simulation including RPC digitalization, muon momentum resolution 10%)

<table>
<thead>
<tr>
<th>Trigger</th>
<th>NEAR</th>
<th>FAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>num. planes $\geq 2$</td>
<td>$5.1 \times 10^6$</td>
<td>$2.8 \times 10^5$</td>
</tr>
<tr>
<td>num. planes $\geq 3$</td>
<td>$4.1 \times 10^6$</td>
<td>$2.3 \times 10^5$</td>
</tr>
<tr>
<td>num. planes $\geq 5$</td>
<td>$2.7 \times 10^6$</td>
<td>$1.5 \times 10^5$</td>
</tr>
</tbody>
</table>
A bit aggressive, but reliable schedule based on successful OPERA experience.

<table>
<thead>
<tr>
<th>Year(portion)</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; half 2015</td>
<td>Define tenders/contracts</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; half 2015</td>
<td>Site preparation</td>
</tr>
<tr>
<td></td>
<td>Setting up Detectors Test-stands</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; half 2016</td>
<td>Mechanical Structure construction</td>
</tr>
<tr>
<td></td>
<td>Start Magnet installation</td>
</tr>
<tr>
<td></td>
<td>Start detectors installation</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; half 2016</td>
<td>End installation</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; half 2017</td>
<td>Commissioning and Starting Run</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; half 2019</td>
<td>End Data Taking</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (in M €)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Far</td>
<td></td>
</tr>
<tr>
<td>Magnet</td>
<td>2.5 (in-kind)</td>
</tr>
<tr>
<td>RPC detectors</td>
<td>0.8 (in-kind)</td>
</tr>
<tr>
<td>Strips</td>
<td>0.3 (in-kind)</td>
</tr>
<tr>
<td>New Electronics</td>
<td>0.2</td>
</tr>
<tr>
<td>Data Acquisition</td>
<td>0.1</td>
</tr>
<tr>
<td>Near</td>
<td></td>
</tr>
<tr>
<td>Magnet</td>
<td>2.0 (in-kind)</td>
</tr>
<tr>
<td>Top/bottom yokes</td>
<td>1.0</td>
</tr>
<tr>
<td>Coils, Power Supplies</td>
<td>0.2</td>
</tr>
<tr>
<td>RPC detectors</td>
<td>0.6 (in-kind)</td>
</tr>
<tr>
<td>New detectors</td>
<td>0.2</td>
</tr>
<tr>
<td>Strips</td>
<td>0.2 (in-kind)</td>
</tr>
<tr>
<td>New Electronics</td>
<td>0.1</td>
</tr>
<tr>
<td>Data Acquisition</td>
<td>0.1</td>
</tr>
<tr>
<td>Transportation</td>
<td>0.6</td>
</tr>
<tr>
<td>Total</td>
<td>2.5 + 6.4 (in-kind)</td>
</tr>
</tbody>
</table>

(new Electronics, new DAQ, 2 x coil number)
MINOS Preliminary
2014
10.56 \times 10^{20} \text{ POT MINOS}
\nu_\mu \text{ running}

\Delta m^2_{43} / \text{eV}^2

- MINOS data 90% C.L.
- CDHS 90% C.L.
- CCFR 90% C.L.
- SciBooNE + MiniBooNE 90% C.L.

\sin^2(2\theta_{24})