Oscillation Investigations in Soudan 2:

Atmospheric $\square \leftrightarrow \square$

and

$n \leftrightarrow \bar{n}$ in Iron

Argonne, Minnesota, Oxford, Rutherford, Tufts, W. Washington
The Soudan 2 Detector:

- Soudan 2 is located in the Soudan mine in Northern Minnesota under 2100 mwe overburden.
- Data exposure is 5.90 fiducial kiloton-years
Track, Shower, Multiprong Events in Soudan 2:
Partially contained events:

- exiting muon
- exiting muon
## Neutrino data samples:

<table>
<thead>
<tr>
<th>Event Category</th>
<th>Neutrino flavor</th>
<th>No. Events (bkgrd-subt’ed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contained, L/E(\pm) HiRes</td>
<td>(\nu)</td>
<td>102.1</td>
</tr>
<tr>
<td></td>
<td>(e)</td>
<td>144.0</td>
</tr>
<tr>
<td>Contained, L/E(\pm) LoRes</td>
<td>(\nu)</td>
<td>58.3</td>
</tr>
<tr>
<td></td>
<td>(e)</td>
<td>65.7</td>
</tr>
<tr>
<td>Partially Contained ((\pm) exits)</td>
<td>(\nu)</td>
<td>49.0</td>
</tr>
<tr>
<td>Neutral Current + ambig. flavor</td>
<td>-</td>
<td>33.3</td>
</tr>
<tr>
<td><strong>Total Neutrino Events Analyzed</strong></td>
<td></td>
<td><strong>452.4</strong></td>
</tr>
</tbody>
</table>
Oscillations of atmospheric neutrinos

- Neutrinos $\nu$, $\bar{\nu}$, $\nu_e$, $\bar{\nu}_e$ originate with cosmic ray interactions in upper atmosphere.

- Neutrino flux at underground sites:
  - $\nu_e$-flavor component at expected strength
  - BUT $\nu_{\mu}$-flavor component diminished.

- $\nu_{\mu}$ depletion varies with neutrino zenith angle i.e with neutrino path length $L$.

- $\nu_{\mu}$ disappearance is described by
  \[
P(\nu_{\mu}, \bar{\nu}_e, \bar{\nu}_e) = \sin^2(2\theta) \sin^2 \left( \frac{1.27 m^2 L}{E_{\nu}} \right)
  \]

- Measure $\sin^2(2\theta)$ and $m^2$. 
We measure via the flavor **ratio of ratios**:

\[ R = \frac{\left( m_{\text{like}}/e_{\text{like}} \right)_{\text{DATA}}}{\left( m_{\text{like}}/e_{\text{like}} \right)_{\text{MC}}} \]

MC = null osc.

\[ R = 1.0 \text{ if no osc.} \]

• Use all contained events having identified flavor (multiprongs events now included).

\[ R_{\text{raw}} = 0.73 \pm 0.10 \]

• De-convolve using **Flavor Identification Matrix**:

<p>| | | | |</p>
<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>e</td>
<td>“NC”</td>
<td></td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>76</td>
<td></td>
</tr>
<tr>
<td>1466</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1337</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>67</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>123</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ R_{\text{e}/\text{m}} = 0.68 \pm 0.12 \]
Dependence on $L/E$:

- Neutrino energy $E_n$: For charged current interactions, we reconstruct $E_n$ from final state track and shower prongs.

\[
L(q_z) = \sqrt{R^2 \cos^2 q_z + 2Rh + h^2} - R \cos q_z
\]

- Neutrino path length $L$: We reconstruct the neutrino zenith angle $q_z$ and calculate:

\[
\begin{array}{c|c|c}
\text{CC} & \text{e CC} \\
\hline
E/E & 20\% & 23\%
\end{array}
\]
We define a “High Resolution” sample:  
- High energy quasi-elastics  
- Low energy quasi-elastics with proton  
- High energy multiprongs

Good $\frac{\Delta z}{L}$ determination when:

1) **Lepton energy is high,** and/or
2) **recoil hadronic system is imaged.**

<table>
<thead>
<tr>
<th>Lepton Energy (MeV)</th>
<th>0-200</th>
<th>200-400</th>
<th>400-600</th>
<th>&gt;600</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\Delta z}{L}$ -lepton (degrees)</td>
<td>~90°</td>
<td>75°</td>
<td>49°</td>
<td>28°</td>
</tr>
<tr>
<td>$\frac{\Delta z}{L}$ - (lepton+proton) (degrees)</td>
<td>30°</td>
<td>23°</td>
<td>15°</td>
<td>8°</td>
</tr>
</tbody>
</table>

**We define a “High Resolution” sample:**
- High energy quasi-elastics  
- Low energy quasi-elastics with proton  
- High energy multiprongs
Neutrino azimuthal angle:

- Observe azimuthal symmetry for both $\nu_e$ and $\bar{\nu}_e$ fluxes - as expected.

- The $\bar{\nu}_e$ is uniformly depleted relative to null oscillation expectation.
Neutrino zenith angle:

- $\bar{\nu}_e$ flux follows null oscillation expectation.

- $\bar{\nu}_\mu$ disappearance:
$L/E$:
Data versus null oscillations
$L/E$:

$\square$-data vs. oscillation hypotheses

\begin{align*}
\Delta m^2 &= 0.0001 \\
\Delta m^2 &= 0.0010 \\
\Delta m^2 &= 0.0070 \\
\Delta m^2 &= 0.1000
\end{align*}
Feldman-Cousins analysis:

We assume $n_m \equiv n_t$; $n_e$ is unaffected.

For points $(i, j)$ over the physical region of the $(\sin^2(2\theta)_i, \log_{10} m^2_j)$ plane, we fit the oscillation expectation to our data at each point using Maximum-Likelihood:

$$(\mathcal{L}_{\text{data}})_{ij} = \mathcal{L}(\sin^2(2\theta)_i, \log_{10} m^2_j; f_\theta)$$

where $f_\theta = \theta$ flux normalization (Bartol '96 atm. flux).

We find $(\mathcal{L}_{\text{data}})_{\text{min}}$, and plot:

$$(\Delta \mathcal{L}_{\text{data}})_{ij} = (\mathcal{L}_{\text{data}})_{ij} - (\mathcal{L}_{\text{data}})_{\text{min}}$$
The likelihood function includes:

<table>
<thead>
<tr>
<th>Description</th>
<th>Bins</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L/E_\text{m}$ for contained HiRes</td>
<td>20</td>
</tr>
<tr>
<td>$L/E_\text{m}$ for partially contained</td>
<td>5</td>
</tr>
<tr>
<td>Rate for contained $\bar{e}$</td>
<td>1</td>
</tr>
<tr>
<td>$L/E_\text{m}$ for LoRes track events</td>
<td>3</td>
</tr>
<tr>
<td>Rate for LoRes multiprong events</td>
<td>1</td>
</tr>
<tr>
<td>Rate for NC/flavor ambig. events</td>
<td>1</td>
</tr>
</tbody>
</table>

Schematically □
$\mathcal{L}$ surface over the $(\sin^2(2\theta), \mu m^2)$ plane:

Flux normalization $f_\theta$ is allowed to adjust at each point.
Feldman-Cousins procedure to find 90% confidence level region:

At each of 2000 points ($i, j$) = ($\sin^2(2\theta)_i$, $\log_{10} m^2_j$) in the physical region, we run 1000 simulated experiments.

We find ($L_{90}$)$_{ij}$ such that ($L_{\text{sim}}$)$_{ij}$ < ($L_{90}$)$_{ij}$ for 90% of the experiments at ($i, j$).

The surface defined by local $L_{90}$ over the oscillation parameters plane:
Oscillation parameters allowed region: (Feldman-Cousins)

Best Fit:
\[ \Delta m^2 = 0.007 \]
\[ \sin^2 2\theta = 0.98 \]
\[ f_{(\text{data/MC})} = 0.90 \]
MC □ Bartol '96 flux

\[ \chi^2 / \text{dof} = 33.2 / 28 \]
Bartol ‘96 flux VS Battistoni 3D flux

Results based on flux calculation using 1-dimensional model atmosphere.

We have also fitted using Battistoni et al. neutrino flux based on 3-dimensional model atmosphere.

• Main differences are:
  – Overall flux normalization for 3D model is lower.
  – Use of FLUKA (Battistoni) vs. TARGET (Bartol) for hadronic processes.
  – Flux shape: The 3D atmospheric flux peaks near the horizon; the effect is dramatic at few-hundreds MeV neutrino energies.
Allowed region using 3D atmospheric flux calculation:

Best Fit:
\[ D_m^2 = 0.007 \]
\[ \sin^2 2\theta = 0.98 \]
\[ f_{\text{data/mc}} = 1.05 \]
MC \[ \text{Battistoni '02} \]

\[ \chi^2/\text{dof} = 34.7/28 \]
Upward stopping muons

• We have isolated a data sample of upward range-to-stopping muons containing 40 events.

• A realistic Monte Carlo for neutrino production of this is in preparation.

• We hope to include these events in a future analysis.
• Allowed region and best fit values are robust with respect to exchange of Bartol 1D and Battistoni 3D atmospheric neutrino flux calculations:

\[ \text{Bartol '96} \]
\[ m^2 = 0.007 \text{ eV}^2 \]
\[ \sin^2 2\theta = 0.98 \]
\[ f_\pi = 0.90 \]

\[ \text{Battistoni '02} \]
\[ m^2 = 0.007 \text{ eV}^2 \]
\[ \sin^2 2\theta = 0.98 \]
\[ f_\pi = 1.05 \]

We’ve mostly done what we can do…

Onward with MINOS!
n ↔ ¯n transitions — “too crazy”?

But neutral meson \( |q\bar{q}| \) states oscillate -

\[
K^0, B^0 \quad \xrightarrow{2^{\text{nd}} \text{ order weak interactions}} \quad \bar{K}^0, \bar{B}^0
\]

And neutral fermions can oscillate too -

\[
\vdots \quad \xrightarrow{\text{GUT}} \quad \bar{n}
\]

So why not -

\[
n \quad \xrightarrow{\text{GUT}} \quad \bar{n}
\]

\( n\bar{n} \) signature is \( \bar{n}N \) annihilation:

Nucleus \( A \rightarrow A^* + \bar{n} \)

\( \bar{n}N \rightarrow \text{pions} \)
Neutron oscillation time:

\[ \varnothing_{n\bar{n}} = \sqrt{\frac{T_A}{T_R}} \]

Lower limits for \( T_A \) \( \varnothing_{n\bar{n}} \) previously obtained by many underground expt’s - Homestake, NUSEX, KOLAR, IMB, Kamiokande, Frèjus.

New Soudan 2 measurement


i) Modest refinements to expt’l approach,

ii) Modest improvement in oscillation time limits for \( T_A \) and \( \varnothing_{n\bar{n}} \),

* iii) Evidence for an irreducible neutrino background \( \sim (0.7 \varnothing - \text{multiprongs})/(\text{kiloton-year}) \).

\[ \varnothing \] Implications for future searches - underground vs reactor neutron beam.
Simulation of $\bar{n}N$ annihilation in iron nuclei

Considerations for coding an $\bar{n}N$ generator:

- Assign initial state $\bar{n}$ and $N = n$ or $p$ momenta in accord with Fermi motion.

- $\bar{n}N$ reactions weighted according to cross section data for $\bar{p}p$, $\bar{p}d$ annihilation at rest.

- Generate secondary decays for $\pi^0$, $\pi^0$, $\eta^0$, $\eta^0$... according to known branching ratios.

- Include pion IntraNuclear reScattering processes (INS). For pions born in Fe, probable fates are-
  
  No scatter or elastic scatter: 45%
  Inelastic scatter: 16%
  Charge exchange: 9%
  $\rightarrow$ Absorption: 30%
¯¯N events are fed to the detector Monte Carlo for simulation of particle tracking, detector noise, and electronic response. Events then subjected to the same processing chain as for data events.

For the primary simulation -

<table>
<thead>
<tr>
<th></th>
<th>emerge from nucleus</th>
<th>after all processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>meson multiplicity</td>
<td>3.8</td>
<td>—</td>
</tr>
<tr>
<td>prong multiplicity</td>
<td>5.0</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Scan views (magnified) of two ¯N events:
nN in the Soudan 2 calorimeter - Effect of pion intranuclear rescattering:

Without INS

With INS

How to distinguish $n \rightarrow \bar{n} \rightarrow \bar{n}N$ from atmospheric neutrino events?

From $\bar{n}N$ simulations and knowledge about neutrino interactions, we note -

i) $\bar{n}N$ yields energetic, isotropic events.

ii) $\bar{n}N$ yields relatively high prong multiplicities.

iii) $\bar{n}N$ does not produce primary protons of momenta above tracking threshold.

iv) $\bar{n}N$ does not produce prompt leptons i.e. no leading muon tracks.

To formulate kinematic separation of $\bar{n}N$ from $\bar{N}$, we rely upon our atmospheric neutrino Monte Carlo:

**NEUGEN** with Bartol ‘96 atm. $\bar{N}$ flux.
Event topology distributions:

Data multiprong events

Atm. MC events
$E_{vis}$ versus $P_{net}$ distributions:

Data compared to atm. neutrino Monte Carlo

![Data](image1)

![Neutrino Monte Carlo](image2)
n $\leftrightarrow$ $\bar{n}$ candidate criteria

1) **Require prong multiplicity** (tracks+showers) \[ N_{\text{prong}} \geq 4. \]

2) **Exclude events with primary proton tracks** (~24% of atm. neutrino events have visible recoil protons).

3) **Exclude events having a non-scattering “muon” track** $> 150$ cm (hadronic interaction length = 80 cm; mitigates against $\bar{\nu}_e$ CC events).

4) **Event kinematics - require**

\[ 700 < E_{\text{vis}} < 1800 \text{ MeV} \]

and

\[ \frac{P_{\text{net}}}{E_{\text{vis}}} < 0.6. \]
Momentum fraction $P/E$ vs $E_{vis}$ for $n\bar{n}$ simulations after topology cuts:

Without INS:

With INS:

Kinematic selection leaves 70% of $n\bar{n}$ in search region.
Neutron oscillation candidates:

- Upon applying selections (1) - (4) to data, five candidate events are found:

<table>
<thead>
<tr>
<th>Run_event</th>
<th>No. of Tracks</th>
<th>No. of Showers</th>
<th>$E_{\text{vis}}$ (MeV)</th>
<th>$P_{\text{net}}$ (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31606_633</td>
<td>1</td>
<td>4</td>
<td>1462.</td>
<td>623.</td>
</tr>
<tr>
<td>58856_477</td>
<td>3</td>
<td>2</td>
<td>982.</td>
<td>469.</td>
</tr>
<tr>
<td>6882_746</td>
<td>4</td>
<td>0</td>
<td>1118.</td>
<td>289.</td>
</tr>
<tr>
<td>68882_746</td>
<td>2</td>
<td>2</td>
<td>772.</td>
<td>277.</td>
</tr>
<tr>
<td>88430_57</td>
<td>3</td>
<td>1</td>
<td>1119.</td>
<td>455.</td>
</tr>
</tbody>
</table>
Background rates:

Atmospheric neutrino MC events after topology selections -

i) Atmospheric neutrino background:
   Selected (null $\nu$ osc. MC): 28 events
   Correction for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$: 24.5 events
   Norm to data exposure: $4.0 \pm 1.0 \text{ bkgrd}$

ii) “Rock” events:
   (188 events) $0.06 \pm 0.04 = 0.5 \pm 0.5 \text{ rock bkgrd}$

$4.5 \pm 1.2$ background events (neutrinos + rock)
Limit on $n\bar{n}$ oscillation time:

Data candidate events: 5.0 events
Backgrounds ($\square$’s + CR n’s): 4.5 events

At 90% CL, $n_{90} = 5.5$ events and we use

$$T_A > \frac{N_n \cdot T_f \cdot \square}{n_{90}}$$

where,

$$N_n = 3.15 \, \square \, 10^{32} \text{ neutrons per kton-yr}$$

in Soudan 2

$$T_f = 6.96 \text{ kton-years}$$
(detector total exposure)

$$\square = 0.18 \pm 0.02$$
(detection efficiency for full detector).
We obtain, at 90% confidence level,

\[ T_A > 7.2 \times 10^{31} \text{ years} \quad (A = \text{Fe}) \]

using

\[ \Box_{nn} = \sqrt{\frac{T_A}{T_R}} \]

With \( T_R = 1.4 \times 10^{23} \text{ s}^{-1} \) for iron, we obtain

\[ \Box_{n\bar{n}} > 1.3 \times 10^8 \text{ seconds.} \]

<table>
<thead>
<tr>
<th>n\bar{n} Simulation</th>
<th>( T_A ) lower limit</th>
<th>( \Box_{n\bar{n}} ) lower limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>n\bar{n} without INS</td>
<td>( 11.0 \times 10^{31} \text{ yr} )</td>
<td>( 1.6 \times 10^8 \text{ s} )</td>
</tr>
<tr>
<td>n\bar{n} in nuclear periphery, with INS</td>
<td>( 8.4 \times 10^{31} \text{ yr} )</td>
<td>( 1.4 \times 10^8 \text{ s} )</td>
</tr>
<tr>
<td>n\bar{n} throughout nucleus, with INS</td>
<td>( 7.2 \times 10^{31} \text{ yr} )</td>
<td>( 1.3 \times 10^8 \text{ s} )</td>
</tr>
</tbody>
</table>
## Experimental limits:

<table>
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<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Source of neutrons</td>
<td>Reactor beam</td>
<td>$^{16}\text{O}$</td>
<td>$^{56}\text{Fe}$</td>
<td>$^{56}\text{Fe}$</td>
</tr>
<tr>
<td>$T_R$ ($10^{23}$ s$^{-1}$)</td>
<td>—</td>
<td>1.0</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Kton yrs fiducial (total)</td>
<td>—</td>
<td>1.11</td>
<td>1.56 (2.56)</td>
<td>5.56 (6.96)</td>
</tr>
<tr>
<td>Est. bkgrd</td>
<td>0</td>
<td>1.2</td>
<td>2.5, 2.1</td>
<td>4.5</td>
</tr>
<tr>
<td>Candidate events</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>$T_A$ ($10^{31}$ yr)</td>
<td>—</td>
<td>4.3</td>
<td>6.5</td>
<td>7.2</td>
</tr>
<tr>
<td>$\bar{\nu}_\text{e} (10^8$ s)</td>
<td>0.86</td>
<td>1.2</td>
<td>1.2</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Recap and conclusion:

A 5.56 fiducial kty exposure of Soudan 2 has been used to set a new lower limit for n̅n oscillations in iron:

\[ T_A(\text{Fe}) > 7.2 \times 10^{31} \text{ years} \] - at 90% CL.

The corresponding limit for free neutrons, assuming \( T_R = 1.4 \times 10^{23} \) s, is

\[ \text{h}_n > 1.3 \times 10^8 \text{ seconds}. \]

Background arising from multiprong interactions of atmospheric neutrinos is observed:
\~ 0.7 \text{ evts/kty}.

Limit-setting to \( \text{h}_n > (4 - 5) \times 10^8 \text{ secs} \) is achievable “soon” by SNO and SuperK.

Extending search limit sensitivity to/beyond \( \text{h}_n = 10^9 \text{ secs} \) requires a different approach. For n̅n exploration, the future lies with new reactor neutron beam experiments.