Kate Scholberg, Duke University
for the DAEδALUS collaboration
LVNU 2012
Outline

The DAEδALUS concept

The Experimental Setup
  The neutrino source
  Detector
  Normalization and backgrounds

Physics Sensitivity
  Standard 3-flavor oscillation physics
  Other physics at short baseline

Summary
Neutrino Oscillations: Standard 3-Flavor Picture

\[ U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

atmospheric \quad \text{?} \quad \text{solar}

Remaining unknowns:

**Masses**

\[ m_1, m_2, m_3 \leftrightarrow \Delta m_{12}^2, |\Delta m_{23}^2|, \text{sign}(\Delta m_{23}^2), m_i \]

- \( \checkmark \)
- \( \checkmark \)
- ?

**Angles**

\( \theta_{12}, \theta_{23}, \theta_{13}, \delta \)

(plus Majorana phases)

- \( \checkmark \)
- \( \checkmark \)
- \( \checkmark !! \)
- ?
Oscillation Probabilities

(in vacuum; modified in matter)

\[ \nu \rightarrow (\nu_e) \]

\[ \Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu} \]

\[ P = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{13} \]

\[ + \sin \delta_{cp} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin^2 \Delta_{13} \sin \Delta_{12} \]

\[ + \cos \delta_{cp} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin \Delta_{13} \cos \Delta_{13} \sin \Delta_{12} \]

\[ + \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta_{12}, \]
Oscillation Probabilities

(in vacuum; modified in matter)

\[ P = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{13} \]

\[ + \sin \delta_{cp} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin^2 \Delta_{13} \sin \Delta_{12} \]

\[ + \cos \delta_{cp} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin \Delta_{13} \cos \Delta_{13} \sin \Delta_{12} \]

\[ + \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta_{12}, \]

\[ \nu \rightarrow (-) \nu_e \]

\[ \Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_{\nu}} \]

CP terms \[ \Rightarrow \] get at \( \delta \) by measuring probabilities for neutrinos / antineutrinos
Oscillation Probabilities

(in vacuum; modified in matter)

\[
P = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{13} \\
+ \sin \delta_{cp} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin^2 \Delta_{13} \sin \Delta_{12} \\
+ \cos \delta_{cp} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin \Delta_{13} \cos \Delta_{13} \sin \Delta_{12} \\
+ \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta_{12}
\]

\[\nu_\mu \rightarrow \nu_e\]

\[
\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}
\]

CP terms → get at \( \delta \) by measuring probabilities for neutrinos / antineutrinos

lower frequency wiggling as a function of L/E
Oscillation Probabilities

(in vacuum; modified in matter)

\[ P = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{13} \]

\[ + \sin \delta_{cp} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \]

\[ + \cos \delta_{cp} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \]

\[ + \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta_{12} \]

\( \nu \rightarrow \nu_e \)

\( (\sim) \quad \Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E_{\nu}} \)

CP terms

\( \Rightarrow \) get at \( \delta \) by measuring probabilities for neutrinos / antineutrinos

lower frequency wiggling as a function of L/E

higher frequency wiggling as a function of L/E
Oscillation Probabilities

(in vacuum; modified in matter)

\[ P = \frac{\sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{13}}{\Delta_{ij}} \]

\[ \frac{\Delta m_{ij}^2 L}{4E_{\nu}} \]

\[ \nu \rightarrow \overline{\nu} \]

\[ \sin \delta_{cp} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \]

\[ \cos \delta_{cp} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \]

\[ \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta_{12} \]

CP terms \( \rightarrow \) get at \( \delta \) by measuring probabilities for neutrinos / antineutrinos

lower frequency wiggling as a function of \( L/E \)

higher frequency wiggling as a function of \( L/E \)

amplitudes (need to know them sufficiently well: probably will)

\( \nu_{\mu} \rightarrow \nu_{e} \)
The Conventional Approach: $\sim$GeV beam + detector(s)

$\nu_\mu \rightarrow \nu_e$ oscillation probabilities depend on mass hierarchy and CP $\delta$

- Good sensitivity at $\sim$1000 km baseline, $\sim$few GeV energy

- Matter matters
- Neutrinos & antineutrinos (but antinus harder)
A Different Approach:

Multiple stopped-pion neutrino sources:

\[ L \sim 1.5-20 \text{ km} \]
\[ E \sim 10-50 \text{ MeV} \]

\[
\frac{L}{E} \sim \frac{1000 \text{ km}}{3000 \text{ MeV}} \sim \frac{10 \text{ km}}{30 \text{ MeV}}
\]

Two major developments since the specific studies presented here were done:

1. The LBNE detector technology decision is for a liquid argon TPC, not a large water Cherenkov far detector;

   argon sensitivity at low energy is primarily to $\nu_e$ $\rightarrow$ not good for DAE$\delta$ALUS

   Other scenarios may be possible: Hyper-K? LENA? Under study...
   Consider studies here to be an illustration of the idea

2. $\theta_{13}$ is indeed large! $\sin^22\theta_{13} \sim 0.1$
   (generally good news for sensitivity)
References

Expression of Interest:  arXiv:1006.0260

see also…


• A Study of Detector Configurations for the DUSEL CP Violation Searches Combining LBNE and DAEδALUS, arXiv:1008.4967

• The DAEδALUS Project: Rationale and Beam Requirements, arXiv:1010.0971

• A Multi Megawatt Cyclotron Complex to Search for CP Violation in the Neutrino Sector, arXiv:1010.1493, arxiv:1104.4985
### Experimental Setup: the neutrino ‘beam’

- **3-body decay:** range of energies between 0 and $m_\mu/2$ (2.2 $\mu$s)

- **2-body decay:** monochromatic 29.9 MeV $\nu_\mu$

- $\bar{\nu}_e$ is $\sim$ absent in the flux: look for its appearance

---

*Graph showing the spectrum and decay processes of neutrinos.*

- Well understood spectrum, isotropic.
Cyclotrons: possible inexpensive source of ~1 MW of ~800 MeV protons

- no sharp timing structure
- <~GeV energy, which is fine
- can exploit connections to industry

Under consideration:
an H2+ accelerator for ADS applications
(Accelerator-Driven Systems for subcritical reactors)

Under development by INFN, PSI, MIT, Cockcroft Inst.
First generation design: arXiv:1104.4985
Choose proton energies (~800 MeV) in the “delta plateau” range to optimize pion production.
Beam timing structure

We can know the distance for an event by the timing
Detector: Water Cherenkov

Inverse Beta Decay (CC)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

large cross-section.
tag n by gammas from Gd-capture

LBNE WC at Homestake

Requires
Gd-loading
and high PMT coverage

→ Hyper-K?
→ LENA? (scintillator)
For **absolute flux normalization**, use $\nu$-e elastic scattering (known to 0.5%); identify in WC by forward angular distribution

$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

For **relative flux normalization**, use CC interactions on $^{16}$O: backscattered electron produced

$$\nu_e + ^{16}$O \rightarrow ^{16}F + e^-$$
Backgrounds

Processes that can fake a tagged electron antineutrino (coincident electron-like event + neutron capture)

**Non-beam-related** (can measure off-beam)
- Atmospheric neutrinos w/ accompanying n’s
  \[ \bar{\nu}_e + p \rightarrow e^+ + n \]
  \[ \bar{\nu}_\mu + p \rightarrow \mu^+ + n \]  
  where muon is below Cherenkov threshold and produces a Michel electron

- Relic supernova electron antineutrinos

**Beam-related**
- Intrinsic electron antineutrinos (\( \sim 4 \times 10^{-4} \))
- Electron neutrinos with fake coincident neutron (small)
- nue-O CC with ejected neutron (small)
Expected signal and background events in 10 years
(assumes 300 kt WC)

\[ \sin^2 2\theta_{13} = 0.05 \]

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Normalization</th>
<th>Off Osc Max</th>
<th>Osc Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBD Oscillation Events (( E_\nu &gt; 20 \text{ MeV} ))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \delta_{CP} = 0^0 ), Normal Hierarchy</td>
<td>763</td>
<td>1270</td>
<td>1215</td>
</tr>
<tr>
<td>”, Inverted Hierarchy</td>
<td>452</td>
<td>820</td>
<td>1179</td>
</tr>
<tr>
<td>( \delta_{CP} = 90^0 ), Normal Hierarchy</td>
<td>628</td>
<td>1220</td>
<td>1625</td>
</tr>
<tr>
<td>”, Inverted Hierarchy</td>
<td>628</td>
<td>1220</td>
<td>1642</td>
</tr>
<tr>
<td>( \delta_{CP} = 180^0 ), Normal Hierarchy</td>
<td>452</td>
<td>818</td>
<td>1169</td>
</tr>
<tr>
<td>”, Inverted Hierarchy</td>
<td>764</td>
<td>1272</td>
<td>1225</td>
</tr>
<tr>
<td>( \delta_{CP} = 270^0 ), Normal Hierarchy</td>
<td>588</td>
<td>870</td>
<td>756</td>
</tr>
<tr>
<td>”, Inverted Hierarchy</td>
<td>588</td>
<td>870</td>
<td>766</td>
</tr>
<tr>
<td>IBD from Intrinsic ( \bar{\nu}<em>e ) (( E</em>\nu &gt; 20 \text{ MeV} ))</td>
<td>600</td>
<td>42</td>
<td>17</td>
</tr>
<tr>
<td>IBD Non-Beam (( E_\nu &gt; 20 \text{ MeV} ))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>atmospheric ( \nu_\mu p ) “invisible muons”</td>
<td>270</td>
<td>270</td>
<td>270</td>
</tr>
<tr>
<td>atmospheric IBD</td>
<td>55</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>diffuse SN neutrinos</td>
<td>23</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>( \nu_e - e ) Elastic (( E_\nu &gt; 10 \text{ MeV} ))</td>
<td>16750</td>
<td>1178</td>
<td>470</td>
</tr>
<tr>
<td>( \nu_e - \text{Oxygen} ) (( E_\nu &gt; 20 \text{ MeV} ))</td>
<td>101218</td>
<td>7116</td>
<td>2840</td>
</tr>
</tbody>
</table>
Events vs $\delta$ at different distances

$$\sin^2 2\theta_{13} = 0.05$$

Note hierarchy degeneracy: need to combine with another experiment to resolve mass hierarchy
CP sensitivity
(assumes 300 kt WC, normal hierarchy)
Combining with LBNE

Studies show that 5 LBNE + 5 DAE\(\delta\)ALUS is better than 10 LBNE or 10 DAE\(\delta\)ALUS

- A Study of Detector Configurations for the DUSEL CP Violation Searches Combining LBNE and DAE\(\delta\)ALUS, arXiv:1008.4967
Combining with LBNE

(Remote preprint has similar conclusions:

Fraction of $\delta_{CP}$

$\sin^2(2\theta_{13})$
Possibilities for a short-baseline neutrino program

Possible physics with near detectors
- Sterile oscillation searches
- Supernova-relevant cross-sections
- Coherent elastic $\nu A$ scattering
- Neutrino magnetic moment
- $\Delta s$ measurements
- Others?

DAEδALUS duty cycle not ideal, but some overburden will help
Study CC and NC interactions with various nuclei, in few to 10’s of MeV range

1. Understanding of core-collapse SN processes, nucleosynthesis
2. Understanding of SN $\nu$ detection processes

Supernova neutrino spectrum overlaps very nicely with stopped $\pi$ neutrino spectrum
Fluence at ~70 m from the stopped pion source amounts to ~ a supernova a day!
Coherent neutral current neutrino-nucleus elastic scattering

\[ \nu + A \rightarrow \nu + A \]

\sim \text{tens of keV nuclear recoils: visible with WIMP-type detectors}

- Coherent up to $E_\nu \sim 50$ MeV
- Important in SN processes & detection
- Standard model test: $\sin^2 \theta_W$, NSI

DAEδALUS neutrinos can enable a recoil cross-check for WIMP detectors

A.J. Anderson et al., arXiv:1103.4894

Rates in DM detectors at DUSEL 1.5 km with near DAEδALUS accelerator

Minor degradation of DM sensitivity from loss of livetime
The DAEδALUS program offers an approach to measurement of CP-violating δ complementary to the long baseline beam approach:

Stopped-π neutrinos at different baselines produced with multiple cyclotrons + tagged IBD signal in WC detector

Excellent sensitivity gets even better in combination with LBNE

Stopped-pion ν sources also enable broad program of short-baseline experiments
Extras/Backups
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Present:</th>
<th>Assumed</th>
<th>Future:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>Value</td>
<td>Value</td>
</tr>
<tr>
<td></td>
<td>(±)</td>
<td>(±)</td>
<td>(±)</td>
</tr>
<tr>
<td>$\Delta m_{21}^2 \times 10^{-5}\text{eV}^2$</td>
<td>7.65</td>
<td>7.65</td>
<td>NIN</td>
</tr>
<tr>
<td></td>
<td>0.23</td>
<td>NIN</td>
<td>NIN</td>
</tr>
<tr>
<td>$\Delta m_{31}^2 \times 10^{-3}\text{eV}^2$</td>
<td>2.40</td>
<td>2.40</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
<td>0.02</td>
<td>0.002</td>
</tr>
<tr>
<td>$\sin^2(2\theta_{12})$</td>
<td>0.846</td>
<td>0.846</td>
<td>NIN</td>
</tr>
<tr>
<td></td>
<td>0.033</td>
<td>0.033</td>
<td>NIN</td>
</tr>
<tr>
<td>$\sin^2(2\theta_{23})$</td>
<td>1.00</td>
<td>1.00</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>0.02</td>
<td>0.005</td>
</tr>
<tr>
<td>$\sin^2(2\theta_{13})$</td>
<td>0.06</td>
<td>0.06</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>0.04</td>
<td>0.04</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Table 2.1: Left: Present values and uncertainties for oscillation parameters, reported in the listed references. Right: Future expectations used in this study, based on assumptions from the associated references. NIN means “No Improvement Needed” for the DAE$\delta$ALUS analysis – the present values are sufficiently precise.
Daedalus Event Energy Distributions (Signal & Background) 

\( \sin^2 2\theta_{13} = 0.04 \)
Mass Hierarchy Determination at $3\sigma$

- Daedalus plus LBNE($\nu$-only) has good sensitivity for hierarchy determination comparable to LBNE($\nu + \bar{\nu}$) around the 50% point.
- If hierarchy is not determining with Daedalus plus LBNE($\nu$-only), then run with LBNE antineutrinos
  ⇒ Combination of Daedalus plus LBNE($\nu + \bar{\nu}$) better by almost x2
• LBNE sensitivity estimates use:
  – Standard neutrino flux files from the LBNE
  – 300kt Water Cherenkov
  – Proton rate = $6 \times 10^{20}$ pot/yr

• Results calculated for four scenarios
  – “Standard DAEdALUS” -- 10 years $\bar{\nu}$ data
  – “Standard LBNE” -- 5 years $\nu$ and 5 years $\bar{\nu}$
  – “Short Combined” -- 5yrs Daedalus $\bar{\nu}$ data + 5yrs LBNE $\nu$-only data
  – “Long Combined” -- 10yrs Daedalus $\bar{\nu}$ data + 10yrs LBNE $\nu$-only data
Expression of Interest for
A Novel Search for CP Violation in the
Neutrino Sector:

DAEδALUS

J. Alonso\textsuperscript{13}, F.T. Avignone\textsuperscript{18}, W.A. Barletta\textsuperscript{13},
R. Barlow\textsuperscript{5}, H.T. Baumgartner\textsuperscript{13}, A. Bernstein\textsuperscript{11}, E. Blucher\textsuperscript{4},
L. Bugel\textsuperscript{13}, L. Calabretta\textsuperscript{9}, L. Camilleri\textsuperscript{6}, R. Carr\textsuperscript{6},
J.M. Conrad\textsuperscript{13,*}, S.A. Dazeley\textsuperscript{11}, Z. Djuric\textsuperscript{2}, A. de Gouvêa\textsuperscript{17},
P.H. Fisher\textsuperscript{13}, C.M. Ignarra\textsuperscript{13}, B.J.P. Jones\textsuperscript{13}, C.L. Jones\textsuperscript{13},
G. Karagiorgi\textsuperscript{13}, T. Katori\textsuperscript{13}, S.E. Kopp\textsuperscript{20}, R.C. Lanza\textsuperscript{13},
W.A. Loinaz\textsuperscript{1}, P. McIntyre\textsuperscript{19}, G. McLaughlin\textsuperscript{16}, G.B. Mills\textsuperscript{12},
J.A. Nolen\textsuperscript{2}, V. Papavassiliou\textsuperscript{15}, M. Sanchez\textsuperscript{2,10}, K. Scholberg\textsuperscript{7},
W.G. Seligman\textsuperscript{6}, M.H. Shaevitz\textsuperscript{6,*}, S. Shalgar\textsuperscript{17}, T. Smidt\textsuperscript{13},
M.J. Syphers\textsuperscript{14}, J. Spitz\textsuperscript{22}, H.-K. Tanaka\textsuperscript{13}, K. Terao\textsuperscript{13},
C. Tscharra\textsuperscript{13}, M. Vagins\textsuperscript{3,21}, R. Van de Water\textsuperscript{12},
M.O. Wascko\textsuperscript{8}, R. Wendell\textsuperscript{7}, L. Winslow\textsuperscript{13}

June 3, 2010