A Path to Measuring $\delta_{CP}$ Using Cyclotron Decay-at-Rest Neutrino Sources

NOW 2012
Matt Toups, MIT
A two-part talk:

1. The experimental design for the flagship measurement:
   
   **CP Violation**

2. Implementing a phased approach with rich physics, highlighting:
   
   The IsoDAR sterile neutrino program (Phase II)
A two-part talk:

1. The experimental design for the flagship measurement:
   **CP Violation**

2. Implementing a phased approach with rich physics, highlighting:
   **The IsoDAR sterile neutrino program (Phase II)**
\[
\nu_\mu \leftrightarrow \nu_e \quad \text{Oscillations at } 2\pi \frac{E}{L} \sim |\Delta m_{13}^2| \\
\text{Are Sensitive to } \delta_{\text{CP}}
\]

in a vacuum…

\[
P = \left( \sin^2 \theta_{23} \sin^2 2\theta_{13} \right) \left( \sin^2 \Delta_{31} \right)
\]

\[
+ \sin \delta \left( \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \right) \left( \sin^2 \Delta_{31} \sin \Delta_{21} \right)
\]

\[
+ \cos \delta \left( \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \right) \left( \sin \Delta_{31} \cos \Delta_{31} \sin \Delta_{21} \right)
\]

\[
+ \left( \cos^2 \theta_{23} \sin^2 2\theta_{12} \right) \left( \sin^2 \Delta_{21} \right).
\]

We want to see if \( \delta \) is nonzero

terms depending on mixing angles

terms depending on mass splittings

\[
\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}
\]
We want to see if $\delta$ is nonzero in a vacuum...

$$P = \left( \sin^2 \theta_{23} \sin^2 2\theta_{13} \right) \left( \sin^2 \Delta_{31} \right)$$

$$+ \sin \delta \left( \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \right) \left( \sin^2 \Delta_{31} \sin \Delta_{21} \right)$$

$$+ \cos \delta \left( \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \right) \left( \sin \Delta_{31} \cos \Delta_{31} \sin \Delta_{21} \right)$$

$$+ \left( \cos^2 \theta_{23} \sin^2 2\theta_{12} \right) \left( \sin^2 \Delta_{21} \right).$$

We want to see if $\delta$ is nonzero
terms depending on mixing angles terms depending on mass splittings

$$\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu$$
The Traditional Approach To $\bar{\nu}_e$ Appearance:

- Single neutrino source
- Multiple neutrino detectors at different baselines

The DAEđALUS Approach To $\bar{\nu}_e$ Appearance:

- Multiple neutrino sources at different baselines
- Single neutrino detector
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Constrains Initial flux

Constrains rise of probability wave

Osc. maximum

Near Neutrino Source

Mid-distance Neutrino Source

Far Neutrino Source

Single Ultra-large Detector With Free Protons as IBD ($\bar{\nu}_e + p \rightarrow e^+ + n$) Targets (Oil or Water)
The DAEδALUS Neutrino Source

$\pi^+$ decay-at-rest (DAR) beam:

$$p + C \rightarrow \pi^+ \rightarrow \nu_\mu + \mu^+ \leftrightarrow e^+ \bar{\nu}_\mu \nu_e,$$

Shape driven by nature!

Only the normalization varies from beam to beam

A great place to search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
Constrains Initial flux

Constrains rise of probability wave

Osc. maximum at ~40 MeV

8 km

20 km

Near Neutrino Source

Mid-distance Neutrino Source

Far Neutrino Source

Three Identical Beams

$\delta = \pi/2$

$\delta = 0$
You need to know which One is providing the beam. So they have to turn on/off. The duty factor is flexible, But beam-off time is needed.
Measurement strategy:

Using the near neutrino source measure **absolute flux normalization** with $\nu_e$-e events to ~1%, Also, measure the $\nu_e$C event rate.

At far and mid-distance neutrino source, Compare predicted to measured $\nu_e$C event rates to get the **relative flux normalizations between 3 sites**

For all three neutrino sources, given the known flux, **fit for the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal** with $\delta$ as a free parameter
We use multiple “Accelerator Units” to produce our DAR beam, Constructed out of Cyclotrons, Which accelerate $H_2^+$ to 800 MeV/amu

The result is a decay-at-rest-flux That can be used for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ searches
Multimegawatt DAEδALUS Cyclotrons for Neutrino Physics

M. Abs\textsuperscript{a}, A. Adelmann\textsuperscript{b,\ast}, J.R. Alonso\textsuperscript{c}, W.A. Barletta\textsuperscript{c}, R. Barlow\textsuperscript{h}, L. Calabretta\textsuperscript{f}, A. Calanna\textsuperscript{c}, D. Campo\textsuperscript{c}, L. Celona\textsuperscript{f}, J.M. Conrad\textsuperscript{c}, S. Gammino\textsuperscript{f}, W. Kleeven\textsuperscript{j}, T. Koeth\textsuperscript{a}, M. Maggiore\textsuperscript{e}, H. Okuno\textsuperscript{g}, L.A.C. Piazza\textsuperscript{e}, M. Seidel\textsuperscript{b}, M. H. Shaevitz\textsuperscript{d}, L. Stingelin\textsuperscript{b}, J. J. Yang\textsuperscript{c}, J. Yeck\textsuperscript{j}

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\textsuperscript{d}Columbia University
\textsuperscript{e}Istituto Nazionale di Fisica Nucleare - LNL
\textsuperscript{f}Istituto Nazionale di Fisica Nucleare - LNS
\textsuperscript{g}Riken
\textsuperscript{h}Huddersfield University, Queensgate Campus, Huddersfield, HD1 3DH, UK
\textsuperscript{j}IceCube Research Center, University of Wisconsin, Madison, Wisconsin 53706
\textsuperscript{j}IBA-Research

In this paper we address the most challenging questions regarding a cyclotron-based high-power proton driver in the megawatt range with a kinetic energy of 800 MeV. Aspects of important subsystems like the ion source and injection chain, the magnet design and radio frequency system will be addressed.

Precise beam dynamics simulations, including space charge and the \textsuperscript{2}H\textsuperscript{+} stripping process, are the base for the characterization and quantification of the beam halo—one of the most limiting processes in high-power particle accelerators.

Submitted to NIM
Where can DAEδALUS run?

LENA is an outstanding possibility!

Coverage of CP violation parameter at LENA, 10 years

This gets even better if it can be played against a conventional beam!

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A two-part talk:

1. The experimental design for the flagship measurement:

   **CP Violation**

2. Implementing a phased approach with rich physics, highlighting:

   **The IsoDAR sterile neutrino program (Phase II)**
Design Principle: “Plug-and-play”

**DAEδALUS**

**Near Site**

- Ion source
- Injector Cyclotron
- Superconducting Ring Cyclotron
- Target/
  Dump

**Mid Site**

- Ion source
- Injector Cyclotron
- Superconducting Ring Cyclotron
- Target/
  Dump

- Ion source
- Injector Cyclotron
- Superconducting Ring Cyclotron
- Target/
  Dump

**Far Site**

- Ion source
- Injector Cyclotron
- Superconducting Ring Cyclotron
- Target/
  Dump

- Ion source
- Injector Cyclotron
- Superconducting Ring Cyclotron
- Target/
  Dump

- Ion source
- Injector Cyclotron
- Superconducting Ring Cyclotron
- Target/
  Dump

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The “plug-and-play design” of what we are building

Leads to an obvious multiphase development plan
Phase I: The Ion Source

- Ion Source
- Injector
- Superconducting Ring Cyclotron
- Target/Dump
The big issue… Space Charge Effects

If you inject a lot of charge here, it repels & beam “blows up”

As radii get closer together, bunches at different radii interact

To reduce the “space charge” at injection… we use $\text{H}_2^+$

Two options for extraction:
- Stripping foil
- “Classical” Electrostatic Septum

2 protons per unit of +1 charge
**Ion Source:**
By our collaborators at INFN Catania.
→ Produces sufficient H$_2^+$!

Beam to be characterized at
Best Cyclotrons, Inc, Vancouver
This winter  (NSF funded)
Test results to be available by
Cyclotrons’13 Conference, Sept 2013, Vancouver
Open Issue: Lorentz stripping
Can induce unacceptable losses of $\text{H}_2^+$ beam in the 800 MeV SRC

Should be OK as long as high vibrational states are eliminated

We are doing tests at Oakridge to study vibrational states from ion sources
So: some important questions remain for DAEδALUS, but we have a workable ion source for a Phase II

Ion source → Injector → Superconducting Ring Cyclotron → Target/Dump

IsoDAR: A sterile neutrino experiment
So: some important questions remain for DAEδALUS,
But we have a workable ion source for a

Phase II

Ion source  →  Injector  →  Superconducting Ring Cyclotron  →  Target/Dump

IsoDAR: A sterile neutrino experiment

Accepted for publication in PRL
Base Design Injector:
60 MeV/n @ 5 mA of H$_2^+$

Industry (IBA, BEST) produces ~1 mA $p$ machines for isotope production:

<table>
<thead>
<tr>
<th>Isotope</th>
<th>half-life</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{52}$Fe</td>
<td>8.3 h</td>
<td>The parent of the PET isotope $^{52}$Mn and iron tracer for red-blood-cell formation and brain uptake studies.</td>
</tr>
<tr>
<td>$^{122}$Xe</td>
<td>20.1 h</td>
<td>The parent of PET isotope $^{122}$I used to study blood brain-flow.</td>
</tr>
<tr>
<td>$^{28}$Mg</td>
<td>21 h</td>
<td>A tracer that can be used for bone studies, analogous to calcium</td>
</tr>
<tr>
<td>$^{128}$Ba</td>
<td>2.43 d</td>
<td>The parent of positron emitter $^{128}$Cs. As a potassium analog, this is used for heart and blood-flow imaging.</td>
</tr>
<tr>
<td>$^{97}$Ru</td>
<td>2.79 d</td>
<td>A $\gamma$-emitter used for spinal fluid and liver studies.</td>
</tr>
<tr>
<td>$^{117m}$Sn</td>
<td>13.6 d</td>
<td>A $\gamma$-emitter potentially useful for bone studies.</td>
</tr>
<tr>
<td>$^{82}$Sr</td>
<td>25.4 d</td>
<td>The parent of positron emitter $^{81}$Rb, a potassium analogue. This isotope is also directly used as a PET isotope for heart imaging.</td>
</tr>
</tbody>
</table>
At 60 MeV/n, we can use this to make isotopes that beta-decay-at-rest…

**IsoDAR**

\[ ^{8}\text{Li} \rightarrow ^{8}\text{Be} + \text{e}^- + \bar{\nu}_e \]

In liquid scintillator

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

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Use this low-energy pure $\bar{\nu}_e$ source to search for sterile neutrinos!

Potential locations: KamLAND, SNO+, Borexino
Outstanding sensitivity to sterile neutrinos à la the reactor neutrino anomaly…

…can be ruled out at $> 5\sigma$
in 4 months of running!

Ability to discriminate between models!

3+1

3+2

(3+1) Model with $\Delta m^2 = 1.0 \text{ eV}^2$ and $\sin^2 2\theta = 0.1$

(3+2) with Kopp/Maltoni/Schwetz Parameters

(5 years of running)
Along with sterile neutrino searches…
Searches for new particles produced in dump
Studies of antineutrino-electron scattering
More ideas welcome!

The science capability is outstanding.
This is of interest to the medical isotope industry!
This moves DAEδALUS forward!
Phases III and IV

Establish the “standard” system
And the high-power system
Many exciting possibilities for a near accelerator physics program:

- **Short-baseline neutrino oscillation waves in ultra-large liquid scintillator detectors**
  *Agarwalla, S. et. al. JHEP 12 (2011), 85*

- **Coherent neutrino scattering in dark matter detectors**

- **Active-to-sterile neutrino oscillations with neutral current coherent neutrino scattering**

- **Measurement of the weak mixing angle with neutrino-electron scattering at low energy**
  *Agarwalla, S. and P. Huber JHEP 8 (2011), 59*
Phase III: SRC & Target/Dump; Near Accelerator Physics Program

Phase IV: Modifications to SRC for high-power running at mid & far sites; CP violation Program
Summary...

Existing Prototype, Tests Funded & Ongoing.

Advanced Design, Proposing A physics Program: IsoDAR

1st Engineering Design soon to undergo external review

Least Advanced, But based On past designs
Conclusions

\[ \text{DAE} \delta \text{ALUS} \]

Is…

A phased program with strong physics along the way
(especially the IsoDAR sterile neutrino search!)

Being brought to you by an international collaboration
of accelerator and particle physicists,
with input from Industry
Other Slides
We will use 1 MW targets (we can use multiple targets). Design is well understood from past DAR experiments…

Light target embedded in a heavy target

Also, no upstream targets!!!
Our proposed 800 MeV cyclotron is very similar to the existing Riken, Japan, cyclotron:

Our first engineering design from MIT-PFSC Technology and Engineering Division...

...will be available this autumn

<table>
<thead>
<tr>
<th>Basic Parameters</th>
<th>DSRC</th>
<th>RIKEN-SRC</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum field on the hill</td>
<td>6.05</td>
<td>3.8</td>
<td>T</td>
</tr>
<tr>
<td>Maximum field on the coil</td>
<td>6.18</td>
<td>4.2</td>
<td>T</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>280</td>
<td>235</td>
<td>MJ</td>
</tr>
<tr>
<td>Coil size</td>
<td>30×24 or 15×48</td>
<td>21×28</td>
<td>cm²</td>
</tr>
<tr>
<td>Coil Circumference</td>
<td>9.8</td>
<td>10.86</td>
<td>m</td>
</tr>
<tr>
<td>Magnetomotive force</td>
<td>4.9</td>
<td>4</td>
<td>MAtot/sector</td>
</tr>
<tr>
<td>Current density</td>
<td>34</td>
<td>34</td>
<td>A/m²</td>
</tr>
<tr>
<td>Height</td>
<td>3.6</td>
<td>6.0</td>
<td>m</td>
</tr>
<tr>
<td>Length</td>
<td>6.9</td>
<td>7.2</td>
<td>m</td>
</tr>
<tr>
<td>Weight</td>
<td>≤450</td>
<td>900</td>
<td>ton</td>
</tr>
<tr>
<td>Additional magnetic shield</td>
<td>0</td>
<td>3000</td>
<td>ton/total</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Magnetic Forces</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansion</td>
<td>1.87 or 1.8</td>
<td>2.6</td>
<td>MN/m</td>
</tr>
<tr>
<td>Vertical</td>
<td>3.7</td>
<td>3.3</td>
<td>MN</td>
</tr>
<tr>
<td>Radial shifting</td>
<td>2.7</td>
<td>0.36</td>
<td>MN</td>
</tr>
<tr>
<td>Azimuthal shifting</td>
<td>0.2</td>
<td>0</td>
<td>MN</td>
</tr>
<tr>
<td>Force on the pole</td>
<td>TBD</td>
<td>630</td>
<td>MN</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Main Coil</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational current</td>
<td>5000</td>
<td>5000</td>
<td>A</td>
</tr>
<tr>
<td>Layer × turn</td>
<td>31×16</td>
<td>22×18</td>
<td></td>
</tr>
<tr>
<td>Cooling</td>
<td>Bath cooling</td>
<td>Bath cooling</td>
<td></td>
</tr>
<tr>
<td>Mudderock Stabilized Current</td>
<td>6345</td>
<td>6665</td>
<td>A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Other Components</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SC trim</td>
<td>no</td>
<td>4</td>
<td>sets</td>
</tr>
<tr>
<td>NC trim× turn</td>
<td>no</td>
<td>22</td>
<td>pairs</td>
</tr>
<tr>
<td>Stray field in the SRC valley region</td>
<td>0.01</td>
<td>0.04</td>
<td>T</td>
</tr>
<tr>
<td>Gap for thermal insulation</td>
<td>40</td>
<td>900</td>
<td>min, mm</td>
</tr>
<tr>
<td>Extraction method</td>
<td>Stripper foil</td>
<td>Electrostatic channel</td>
<td></td>
</tr>
</tbody>
</table>
Some other useful articles (beyond those already highlighted)…

arXiv:1205.5790 [pdf, ps, other]

**Target Studies for the Production of Lithium-8 for Neutrino Physics Using a Low Energy Cyclotron**
Adriana Bungau, Roger Barlow, Michael Shaevitz, Janet Conrad, Joshua Spitz
Comments: 3 pages, 6 figures, IPAC 2012
Subjects: Accelerator Physics (physics.acc-ph); Nuclear Experiment (nucl-ex)

arXiv:1205.5528 [pdf, ps, other]

**Simulations of Pion Production in the DAE5ALUS Target**
Adriana Bungau (1), Roger Barlow (1), Mike Shaevitz (2), Janet Conrad (3), Joshua Spitz (3), Tess Smidt (3) 
(1) University of Huddersfield, (2) Columbia University, (3) Massachusetts Institute of Technology), for the DAE5ALUS Collaboration
Comments: 3 pages, 3 figures, IPAC 2012
Subjects: Instrumentation and Detectors (physics.ins-det); High Energy Physics – Experiment (hep-ex); Nuclear Theory (nucl-th)

arXiv:1107.0052 [pdf]

**Preliminary Design Study of High-Power H2+ Cyclotrons for the DAEedALUS Experiment**
Subjects: Accelerator Physics (physics.acc-ph); High Energy Physics – Experiment (hep-ex)
What proton energy is required?

There is a “Delta plateau” where you can trade energy for current to get the same rate of $\nu$/MW.

- **<600 MeV**
  - too little $\pi^+$ production

- **>1500 MeV**
  - energy goes into producing other particles besides $\pi^+$ at a significant level
Beam envelope,
No energy spread,
1% spread

Design work
By A. Calanna
To produce the 800 MeV protons, we use **Cyclotrons:**

- Inexpensive,
- Practical below \( \sim 1 \) GeV
- Good if you don’t need short timing structure
- Typically single energy
- **Taps into existing industry**

---

We use an “isochronous cyclotron” design (magnetic field changes with radius) → Allows multi-bunch acceleration
The most challenging aspect:
The Superconducting Ring Cyclotron

Multi Megawatt DAEδALUS Cyclotrons for Neutrino Physics

M. Abs\textsuperscript{j}, A. Adelmann\textsuperscript{a,b}, J.R. Alonso\textsuperscript{c}, W.A. Barletta\textsuperscript{c}, R. Barlow\textsuperscript{a}, L. Calabretta\textsuperscript{f}, A. Calanna\textsuperscript{c}, D. Campo\textsuperscript{c}, L. Celona\textsuperscript{f}, J. M. Conrad\textsuperscript{c}, S. Gammino\textsuperscript{f}, W. Kleeven\textsuperscript{j}, T. Koeth\textsuperscript{a}, M. Maggiore\textsuperscript{e}, H. Okuno\textsuperscript{g}, L.A.C. Piazza\textsuperscript{e}, M. Seidel\textsuperscript{b}, M. Shaevitz\textsuperscript{d}, L. Stingelin\textsuperscript{b}, J. J. Yang\textsuperscript{c}, J. Yeck\textsuperscript{j}

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\textsuperscript{e}National Institute of Nuclear Physics - LNL
\textsuperscript{f}National Institute of Nuclear Physics - LNS
\textsuperscript{g}Riken
\textsuperscript{h}Huddersfield University, Queensgate Campus, Huddersfield HD1 3DH, UK
\textsuperscript{i}IceCube Research Center, University of Wisconsin, Madison, Wisconsin 53706
\textsuperscript{j}IBA-Research

For ADS/thorium reactor applications, see web for our talk at
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