DAEδALUS/IsoDAR Experiment(s)

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Argonne National Laboratory

International Symposium on Neutrino Physics and Beyond, Shenzhen, China.
23-26 September 2012
A Phased Physics Program Using Decay-at-Rest Neutrino Beams
Experimental design for the flagship measurement: CP-violation

DAEδALUS
Decay-At-rest Experiment for $\delta_{CP}$ studies
At the Laboratory for Underground Science

- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search, exploiting the L/E dependence of the CP-interference term to extract $\delta$.
- Complementary to long-baseline experiments with conventional beams (such as LBNE):
  - High Statistics
  - Low Background
  - No matter effects.
Neutrino Oscillations: Standard 3-Flavor Picture

\[ U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} \text{Big} & \text{Big} & \text{Small?} \\ \text{Big} & \text{Big} & \text{Big} \end{pmatrix} \]

Big question: what is the value of \( \delta_{\text{CP}} \)?

\[ \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\delta_{\text{CP}}} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\text{CP}}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \]

\( \theta_{12} \sim 30^\circ \)  \( \Theta_{13} \sim 9^\circ \)  \( \theta_{23} \sim 45^\circ \)

Measured by T2K, Double Chooz, Daya Bay, RENO.

Oscillation probability \( P(\nu_\mu \rightarrow \nu_e) \) in a vacuum (modified in matter):

\[ P = (\sin^2 \theta_{23} \sin^2 \theta_{13} - \Delta_m^2) \]

Want to find

If \( \delta_{\text{CP}} \neq 0 \)

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

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

\( \Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu \)
**DAEδALUS approach**

- Use $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ and exploit the L/E dependence in absolute event rates.

Oscillation probability $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$ in a vacuum (modified in matter):

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

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

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

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

Want to find \( \text{If } \delta_{\text{CP}} \neq 0 \)

- terms depending on mixing angles
- terms depending on mass splittings

$$\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu$$

-Different from conventional long-baseline neutrino beam approach.
Different Approach: Daedalus Experiment

- Multiple beam sources using high-power cyclotrons + single detector location.
- Cyclotron beam impinges on dump where produced $\pi^+$ and $\mu^+$ decay to neutrinos (almost all $\pi^-$ capture before decay).

  $\rightarrow$ Very few $\bar{\nu}_e$ produced so can do precise $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search.

- Have $L_v \sim 1.5-20$ km, $E_v \sim 10-50$ MeV.
Different Approach: Daedalus Experiment

Oscillation probability at ~40 MeV

Constraints rise of probability wave

Initial flux

Oscillation maximum at ~40 MeV

Single Ultra-large Detector With Free Protons as Targets (Oil or Water)
Different Approach: Daedalus Experiment

Three Identical Beams

Constrains Initial flux

Constrains rise of probability wave

Osc. maximum at ~40 MeV

\[ \delta = \pi/2 \]

\[ \delta = 0 \]

0 0.01 0.02 0.03 0.04 0.05 0.06

0 5 10 15 20 25

8 km 20 km

Kilometers

Oscillation Probability

\[ \delta = \pi/2 \]

\[ \delta = 0 \]

8

Energy [MeV]

Flux [Arb. units]
Neutrino Beam Production

Proton beam produces pions in a carbon plus copper beam dump:

Protons $\rightarrow \pi^+$ (stop) $\rightarrow \mu^+ + \nu_\mu$

$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

$\rightarrow \pi^-(\text{captures before decay})$

Detector is assumed to be a single ultra-large detector
With free protons as targets (Oil or Water)

Energy Spectrum for $\pi^+$ Decay-at-Rest Beam
(No uncertainty in energy spectrum)

Osc signal events are $\nu_e + p \rightarrow e^+ + n$
(IBD) which can be well identified by a two part delayed coincidence.
Neutrino Beam Production

One needs to know which source 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 accelerator**
measure **absolute flux normalization** with $\nu_e$-$e$ events to $\sim 1\%$,
Also, measure the $\nu_e C$ event rate.

At far and mid accelerator,
Compare predicted to measured $\nu_e C$ event rates
to get the **relative flux normalizations between 3 accelerators**.

In all three accelerators,
given the known flux, **fit for the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal**
with $\delta$ as free parameter.
Cyclotron as the proton source

- Use Cyclotrons to produce the 800 MeV protons.

Inexpensive
Only practical below \(~1\) GeV
(ok for DAE\(\delta\)ALUS!)
Only good if you don’t need short timing structure (ok!)
Typically single energy (ok!)
Taps into existing industry

An “isochronous cyclotron” design:
magnetic field changes with radius
Allowing multibunch acceleration

Beam Production

-Use multiple “Accelerator Units” to produce DAR beam, constructed out of cyclotrons, which accelerate $\text{H}_2^+$ to 800 MeV.

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

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\textsuperscript{j}\textit{IBA-Reasearch}

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 H\textsuperscript{2+} 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
Design Principle

**DAEδALUS**

**Near Site**

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

**Mid Site**

- (8 km)
- Ion source
- Injector Cyclotron
- Superconducting Ring Cyclotron
- Target / Dump

**Far Site**

- (20 km)
- Ion source
- Injector Cyclotron
- Superconducting Ring Cyclotron
- Target / Dump
- Ion source
- Injector Cyclotron
- Superconducting Ring Cyclotron
- Target / Dump
Example of $\delta_{CP}$ sensitivity

Where can DAE$\delta$ALUS run? LENA is an outstanding possibility.

Coverage of CP violation Parameter at LENA, 10 years

Sensitivity is further enhanced if it can be combined with a conventional long-baseline neutrino beam.
Initially …

… detailed $\delta_{CP}$ sensitivity study was done for a large water Cherenkov detector (300kton) previously considered as an option for LBNE in US.

-1 and 2 $\sigma$ sensitivities for DAE$\delta$ALUS + (LBNE $\nu - 10$ yr) scenario.

-Normal mass hierarchy assumed for LBNE.

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
 & \delta_{CP} & -160^\circ & -80^\circ & 0^\circ & 80^\circ & 160^\circ \\
\hline
\text{LBNE $\nu$ (5 yr) + $\bar{\nu}$ (5 yr)} & 24.5 & 31.6 & 21.3 & 30.8 & 21.6 \\
\text{DAE$\delta$ALUS Phase 1+2} & 17.7 & 25.3 & 19.6 & 23.6 & 27.2 \\
\text{DAE$\delta$ALUS+LBNE$\nu$ -5 yr} & 16.8 & 23.7 & 15.3 & 25.5 & 15.0 \\
\text{DAE$\delta$ALUS+LBNE$\nu$ -10 yr} & 10.6 & 16.2 & 10.1 & 17.3 & 10.4 \\
\hline
\end{array}
\]
IsoDAR: Isotope Decay-at-Rest Neutrino Program
-This is what we are building.

-This is leading to multiphase development plan.
Design Principle

Phase I: Ion source.
Phase I issues

-Space charge effects.

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

When radii get closer together, the bunches at different radii interact.

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

-$\text{H}^+_2$ gives 2 protons out for 1 unit of +1 charge -> space charge effects reduced.

-Two options for extraction:
  - Stripping foil.
  - “Classical” Electrostatic Septum.
Phase I: 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*
Phase I issues

-Lorentz stripping.
-May induce unacceptable losses of H\(^+\)\(_2\) beam in the 800 MeV SRC.

-We are doing tests at Oakridge to study vibrational states from ion sources.

Should be OK as long as high vibrational states are eliminated.

800 MeV, 6T
Phase II

-Some important questions remain for DAEdALUS, but we have a workable ion source for a

IsodAR: A sterile neutrino experiment
IsoDAR $\bar{\nu}_e$ Disappearance Experiment

- Use high intensity $\bar{\nu}_e$ source using $\beta$-decay at rest of $^8$Li isotope $\Rightarrow$ IsoDAR.

- $^8$Li produced by high intensity (10ma) proton beam from 60 MeV cyclotron
  $\Rightarrow$ being developed as prototype injector for DAEδALUS cyclotron system.

- Put a cyclotron-isotope source near one of the large (kton size) liquid scintillator/water detectors such as KamLAND, SNO+, Borexino, Super-K, Daya Bay II,…

- Physics measurements:
  - $\bar{\nu}_e$ disappearance measurement in the region of the LSND/MiniBooNE and reactor-neutrino anomalies.
  - Measure oscillatory behavior within the detector.
IsoDAR $\bar{\nu}_e$ Disappearance Experiment

Details:

Also accepted for publication in Phys. Rev. Letters:

Proposal for an electron antineutrino disappearance search using high-rate $^8$Li production and decay


Accepted Tuesday Sep 4, 2012

This paper introduces an experimental probe of the sterile neutrino with a novel, high-intensity source of electron antineutrinos from the production and subsequent decay of $^8$Li. When paired with an existing ~ 1 kton scintillator-based detector, this $E_n=6.4$ MeV source opens a wide range of possible searches for beyond standard model physics via studies of the inverse beta decay interaction $[^{(n)}]e + p \rightarrow e^+ + n$. In particular, the experimental design described here has unprecedented sensitivity to $[^{(n)}]e$ disappearance at $Dm^2 \sim 1$ eV$^2$ and features the ability to distinguish between the existence of zero, one, and two sterile neutrinos.
IsoDAR 60 MeV Proton Cyclotron

-Under Development.

Figure 3: Left: Layout of the injector cyclotron. Pastel colors indicate magnetic field map (pink is highest). The hill/valley structure is apparent. Extraction trajectory for H$_2^+$ is shown. Right: Illustration of the Opera3D finite element magnetic model showing one quarter of the cyclotron with the pole, the return yoke and the coil.

Table 1: Parameters of the DAEðALUS injector cyclotron

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{max}$</td>
<td>60 MeV/amu</td>
</tr>
<tr>
<td>$R_{ext}$</td>
<td>1.99 m</td>
</tr>
<tr>
<td>&lt;$B&gt;$ @ $R_{ext}$</td>
<td>1.16 T</td>
</tr>
<tr>
<td>Sectors</td>
<td>4</td>
</tr>
<tr>
<td>Valley gap</td>
<td>1800 mm</td>
</tr>
<tr>
<td>Outer Diameter</td>
<td>6.2 m</td>
</tr>
<tr>
<td>Cavities</td>
<td>4</td>
</tr>
<tr>
<td>$E_{inj}$</td>
<td>35 keV/amu</td>
</tr>
<tr>
<td>$R_{inj}$</td>
<td>55 mm</td>
</tr>
<tr>
<td>&lt;$B&gt;$ @ $R_{inj}$</td>
<td>0.97 T</td>
</tr>
<tr>
<td>Hill width</td>
<td>28 - 40 deg</td>
</tr>
<tr>
<td>Pole gap</td>
<td>100 mm</td>
</tr>
<tr>
<td>Full height</td>
<td>2.7 m</td>
</tr>
<tr>
<td>Cavity type</td>
<td>$\lambda/2$, double gap</td>
</tr>
</tbody>
</table>
DAEδDALUS 800 MeV Cyclotron System

- Under Development.

- H$_2^+$ Ion Source
- DAR Target-Dump (about 6x6x9 m$^3$)
- IsoDAR Cyclotron
- Injector Cyclotron (Resistive Isochronous)
- Ring Cyclotron (Superconducting)

“Isochronous cyclotron” where mag. field changes with radius, but RF does not change with time. This can accelerate many bunches at once.
-Use this low-energy pure $\bar{\nu}_e$ source to search for sterile neutrinos.

-Potential locations: KamLAND, SNO+, DBII.
IsoDAR at Kamland

Letter of Collaboration

IsoDAR provides a source of neutrinos that expands the physics reach of a scintillator-based detector like KamLAND. The sensitivity to sterile neutrinos is particularly motivating. The KamLAND Experiment has exchanged information with the IsoDAR group already, and will continue providing input to enable the development of a Baseline Design Report.

Sincerely,

Kunio Inoue
Research Center for Neutrino Science, Tohoku University
-p (60 MeV) + $^9$Be $\rightarrow$ $^8$Li + 2p
  plus many neutrons since low binding energy

-n + $^7$Li (shielding) $\rightarrow$ $^8$Li

$^{-8}$Li $\rightarrow$ $^8$Be + e$^-$ + $\overline{\nu}_e$
  Mean $\overline{\nu}_e$ energy = 6.5 MeV
  $2.6 \times 10^{22}$ $\overline{\nu}_e$ / yr

-Example detector: KamLAND (900 t)
  Use IBD $\overline{\nu}_e$ + p $\rightarrow$ e$^+$ + n process
  Detector center 16m from source
  ~160,000 IBD events / yr
  60 MeV protons @ 10ma rate
  Observe changes in the IBD rate as a function of L/E

IsoDAR Neutrino Source and Events

arXiv:1205.4419
IsoDAR $\overline{\nu}_e$ Disappearance Oscillation Sensitivity (3+1)
It could be Daya Bay II detector

- Mass = 20kton = 20 x KamLAND.

- IsoDAR sensitivity moves left by a factor of $\sqrt{20} = 4.5$.
  (statistics only considered).
- This moves the 95% CL sensitivity to ~0.0010-0.0015.
- Covers completely LSND allowed region at 95% CL.
Oscillation L/E Waves with IsoDAR

- Observed/Predicted event ratio vs L/E including energy and position smearing.

- IsoDAR’s high statistics and good L/E resolution gives good sensitivity to distinguish (3+1) and (3+2) oscillation models.
Additional Opportunities for isoDAR

- Along with sterile neutrino searches:
  - Searches for new particles produced in dump.
  - Studies of antineutrino-electron scattering.

- 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 the high-power system
Phases III and IV

DAEδALUS
Near Site

Mid Site
(8 km)

Far Site
(20 km)

Phase III: SRC & Target/Dump; \textit{Near Accelerator Physics Program}

Phase IV: Modifications to SRC for high-power running at mid & far sites; \textit{CP violation Program}
The most challenging aspect:
The Superconducting Ring Cyclotron

Multi Megawatt DAEδALUS Cyclotrons for Neutrino Physics

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For ADS/thorium reactor applications, see web for our talk at
800 MeV SRC magnet design study complete and posted Monday this week

**Engineering Study of Sector Magnet for the Daedalus Experiment**

Joseph Minervini, Mike Cheadle, Val Fishman, Craig Miller, Alexi Radovinsky, Brad Smith

*(Submitted on 21 Sep 2012)*

The Daedalus experiment seeks to evaluate neutrino scattering effects that go beyond the standard model. Modular accelerators are employed to produce 800 MeV proton beams at the megawatt power level directed toward a target, producing neutrinos. The Superconducting Ring Cyclotron (SRC) consists of identical sectors (currently 6) of superconducting dipole magnets with iron return frames. The Daedalus Collaboration has produced a conceptual design for the magnet, which, after several iterations, is the current best design that achieves the physics requirements of the experiment. The Technology and Engineering Division (T&ED) of the MIT Plasma Science and Fusion Center was awarded with a contract by the Daedalus team to further develop the magnet conceptual design. The resulting Engineering Study is reported here.

Subjects:  Accelerator Physics (physics.acc-ph); High Energy Physics – Experiment (hep-ex)

Cite as:  arXiv:1209.4886 [physics.acc-ph]
        (or arXiv:1209.4886v1 [physics.acc-ph] for this version)
Summary

Existing Prototype, Tests Funded & Ongoing.

Advanced Design, Proposing A physics Program: IsoDAR

Now undergoing 1st Engineering Design.

Least Advanced, But based On past designs
Conclusions

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.
Backup Slides
Event Types in Water Detector

\[ \bar{\nu}_\mu \rightarrow \nu_e \text{ then } \nu_e + p \rightarrow e^+ + n \text{ (IBD events)} \]

The signal:
(inverse beta decay, IBD)

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

\[ \nu_e \rightarrow e^- \]
\[ \bar{\nu}_e \rightarrow \nu_e \]

& other \( v_e \) scattering diagrams -- essential to normalization.
(Also \( v_\mu e \) and \( \bar{v}_\mu e \))

\[ \nu_e \rightarrow e^- \]
\[ O \rightarrow F \]

Lower than IBD by \( \times 10 \) because of binding, & no associated \( n \)
Used for relative normalization of different distances

\[ \bar{\nu} \rightarrow NC \]
\[ O, \quad \nu \rightarrow \nu \]

“debris”
(nucleon, nucleus, low \( E \gamma, \alpha \))

Will not reconstruct as an IBD event
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!!!
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