The DAEδALUS at Hyper-K Experiment:
Searching for CP Violation

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for the DAEδALUS Collaboration

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DAEδALUS / IsoDAR Program

• DAEδALUS is a program to develop a new resource for Neutrino Physics.
  – The goal is to produce small sized and relatively inexpensive cyclotron-based decay-at-rest neutrino sources.

• This frees the program from being forced to match detectors to accelerator sites and opens up interesting new physics opportunities.

• This is a phased program with physics output at each stage
  – IsoDAR experiment is the second phase.
  – Full DAEδALUS for CP measurements as the final phase

The DAEδDALUS Collaboration

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2Argonne National Laboratory, Argonne IL, U.S.
3Bartoszek Engineering, Aurora IL, U.S.
4Best Cyclotron System, Inc., Vancouver BC, Canada
5University of California, Los Angeles, CA, U.S.
6University of California, Irvine, CA, U.S.
7Columbia University, New York NY, U.S.
8Duke University, Durham NC, U.S.
9University of Huddersfield, Huddersfield, U.K.
10INFN-LNS, Catania, Italy
11Institute for the Physics and Mathematics of the Universe, Kashiwa, Japan
12Massachusetts Institute of Technology, Cambridge MA, U.S.
13New Mexico State University, Las Cruces NM, U.S.
14Northwestern University, Evanston IL, U.S.
15Paul Scherrer Institute, Villigen, Switzerland
16RIKEN, Wako, Japan
17University of Tennessee, Knoxville TN, U.S.
18Tohoku University, Sendai, Japan

Composed of particle, accelerator, and engineering physicists from universities, companies, and national labs.
Dædalus and IsoDAR Experiments
(“Cyclotrons as Drivers for Precision Neutrino Measurements” - arXiv:1307.6465)

IsoDAR Setup:
Very short baseline search for sterile neutrinos
A. Bungau et al., PRL 109, 141802 (2012)

Dædalus Setup:
A new way to search for CP violation in the $\nu$-sector
DAEδDALUS High Power (~1 MW) 800 MeV Cyclotron System (Under Development with Lab and Industrial Partners)

- Daeδalus DAR Target-Dump (about 6x6x9 m³)
- IsoDAR Cyclotron (Resistive Isochronous)
- Superconducting Ring Cyclotron (SRC)

“Isochronous cyclotron” where mag. field changes with radius, but RF does not change with time. This can accelerate many bunches at once.

H₂⁺ Ion Source

Multimegawat Daeδalus Cyclotron for Neutrino Physics

arXiv:1207.4895
Phase I

Produce 50 mA H2+ source, inflect, capture 5 mA and accelerate

Best Inc. Teststand, Catania Experiment

Physics Output at Each Stage

Accelerator Science
Physics: 2014-15

Phase II

IsoDAR

Build the injector cyclotron, extract, produce antinu flux via 8Li

KamLAND (WATCHMAN)

SBL $\bar{\nu}_e$ physics
Engineering, 2015
Start of run, 2018

Phase III

Build the first SRC,
Run this as a “near accel.” at existing large detector

Super K, NOvA

SBL $\bar{\nu}_\mu$ physics
Engineering, 2017
Start of run 2021

Phase IV

DAEδALUS

Build the high power SRC, Construct DAEδALUS

HyperK

CP
Eng: 2020
Start 2025

We are here
DAEδDALUS Cyclotron Accomplishments and Status

International Partnership Between Universities, Labs, and Industry

• Ion source developed by collaborators at INFN Catania
  – Reached adequate intensities for the system

• Ion Source Beam and capture currently being characterized at Best Cyclotrons, Inc, Vancouver with INFN-Catania and MIT

• Engineering study of SRC magnet completed
  – Engineering design, Assembly plan, Structural analysis, Cryo system design (see arXiv:1209.4886)
The DAEδDALUS Experiment

Search for CP Violation using $\bar{\nu}_e$ Appearance with Pion Decay-at-Rest Neutrino Beams
Use L/E Dependence of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ to Measure $\delta_{CP}$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (\sin^2 \theta_{23} \sin^2 2\theta_{13}) (\sin^2 \Delta_{31})$$
$$\mp \sin \delta (\sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12}) (\sin^2 \Delta_{31} \sin \Delta_{21})$$
$$+ \cos \delta (\sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12}) (\sin \Delta_{31} \cos \Delta_{31} \sin \Delta_{21})$$
$$+ (\cos^2 \theta_{23} \sin^2 2\theta_{12}) (\sin^2 \Delta_{21}).$$

We want to see if $\delta$ is nonzero

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

$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$
Use Multiple Neutrino Sources at Different Distances to Map Out $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance Rate

Each source produces a pure $\pi/\mu$ decay-at-rest beam at a different distances to the detector

Very small $\bar{\nu}_e$ contamination in the beam so ideal to search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations
Detect $\bar{\nu}_e$ Events using Inverse Beta Decay (IBD)

Inverse $\beta$ Decay (IBD)

$\bar{\nu}_e$ → $e^+$ + p + n

- Prompt positron followed by delayed coincidence from n capture
  ⇒ For water detector need Gd doping
- Antineutrino energy well measured
  ⇒ $E_{\bar{\nu}_e} = E_{\text{prompt}} + 0.78$ MeV

- IBD Cross section known very accurately
- Very small systematic uncertainty for a neutrino oscillation analysis
Osc. maximum

\[ \delta = \pi/2 \]

\[ \delta = 0 \]

Constrains rise of probability wave

\[ \delta = \pi/2 \]

\[ \delta = 0 \]

Single Ultra-large Water Detector (Hyper-K with Gd)

With Free Protons as IBD (\( \bar{\nu}_e + p \rightarrow e^+ + n \)) Targets
Oscillation Probability

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

\( \delta = \pi/2 \)

\( \delta = 0 \)

1.5 km

Constrains Initial flux

8 km

Constrains rise of probability wave

20 km

Osc. maximum at \( \sim 40 \) MeV

Near Neutrino Source

Mid-distance Neutrino Source

Far Neutrino Source

Three Identical Beams to a single detector

\[ \delta = \pi/2 \]

\[ \delta = 0 \]
Need to know which source produced a given event ⇒ Use timing with sources turning on/off.
DAEδALUS Measurement Strategy

Using the near neutrino source measure absolute flux normalization with $\nu_e$-e events to $\sim$1%, Also, measure the ($\nu_e O$) event rate.

At far and mid-distance neutrino source, Compare predicted to measured $\nu_e O$ 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
### DAEδALUS at Hyper-K  Event Statistics for 10 yrs

<table>
<thead>
<tr>
<th>Event Type</th>
<th>1.5 km</th>
<th>8 km</th>
<th>20 km</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IBD Oscillation Events (E_{vis} &gt; 20 MeV)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta_{CP} = 0^0$, Normal Hierarchy</td>
<td>2660</td>
<td>4456</td>
<td>4417</td>
</tr>
<tr>
<td>”, Inverted Hierarchy</td>
<td>1838</td>
<td>3268</td>
<td>4338</td>
</tr>
<tr>
<td>$\delta_{CP} = 90^0$, Normal Hierarchy</td>
<td>2301</td>
<td>4322</td>
<td>5506</td>
</tr>
<tr>
<td>”, Inverted Hierarchy</td>
<td>2301</td>
<td>4328</td>
<td>5556</td>
</tr>
<tr>
<td>$\delta_{CP} = 180^0$, Normal Hierarchy</td>
<td>1838</td>
<td>3263</td>
<td>4295</td>
</tr>
<tr>
<td>”, Inverted Hierarchy</td>
<td>2660</td>
<td>4462</td>
<td>4460</td>
</tr>
<tr>
<td>$\delta_{CP} = 270^0$, Normal Hierarchy</td>
<td>2197</td>
<td>3397</td>
<td>3206</td>
</tr>
<tr>
<td>”, Inverted Hierarchy</td>
<td>2197</td>
<td>3402</td>
<td>3242</td>
</tr>
<tr>
<td><strong>IBD from Intrinsic $\bar{\nu}<em>e$ (E</em>{vis} &gt; 20 MeV)</strong></td>
<td>1119</td>
<td>79</td>
<td>31</td>
</tr>
<tr>
<td><strong>IBD Non-Beam (E_{vis} &gt; 20 MeV)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>atmospheric $\nu_\mu p$ “invisible muons”</td>
<td>505</td>
<td>505</td>
<td>505</td>
</tr>
<tr>
<td>atmospheric IBD</td>
<td>103</td>
<td>103</td>
<td>103</td>
</tr>
<tr>
<td>diffuse SN neutrinos</td>
<td>43</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>$\nu-e$ Elastic (E_{vis} &gt; 10 MeV)</td>
<td>40025</td>
<td>2813</td>
<td>1123</td>
</tr>
<tr>
<td>$\nu_e$-oxygen (E_{vis} &gt; 20 MeV)</td>
<td>188939</td>
<td>13281</td>
<td>5305</td>
</tr>
</tbody>
</table>

$\sin^2 2\theta_{13} = 0.10$
DAEδALUS at Hyper-K  Event vs Energy for 10 yrs

Near

Middle

Far

\[ \sin^2 2\theta_{13} = 0.10 \]
# Configurations Considered for $\delta_{CP}$ Sensitivity Studies

<table>
<thead>
<tr>
<th>Configuration Name</th>
<th>Source(s)</th>
<th>Average Long Baseline Beam Power</th>
<th>Detector</th>
<th>Fiducial Volume</th>
<th>Run Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAE$\delta$ALUS@Hyper-K</td>
<td>DAE$\delta$ALUS only</td>
<td>N/A</td>
<td>Hyper-K</td>
<td>560 kt</td>
<td>10 years</td>
</tr>
<tr>
<td>DAE$\delta$ALUS/JPARC (nu only)@Hyper-K</td>
<td>DAE$\delta$ALUS &amp; JPARC</td>
<td>750 kW</td>
<td>Hyper-K</td>
<td>560 kt</td>
<td>10 yrs $\bar{\nu}$ DAE$\delta$ALUS + 10 yrs $\nu$-only JPARC</td>
</tr>
<tr>
<td>JPARC@Hyper-K</td>
<td>JPARC</td>
<td>750 kW</td>
<td>Hyper-K</td>
<td>560 kt</td>
<td>3 years $\nu$ + 7 years $\bar{\nu}$ [106]</td>
</tr>
<tr>
<td>LBNE</td>
<td>FNAL</td>
<td>850 kW</td>
<td>LBNE</td>
<td>35 kt</td>
<td>5 years $\nu$ 5 years $\bar{\nu}$ [100]</td>
</tr>
</tbody>
</table>
CP Violation Sensitivity

- Daeδalus has good CP sensitivity as a stand-alone experiment.
  - Small cross section, flux, and efficiency uncertainties
- Daeδalus can also be combined with Hyper-K ν-only data to give enhanced δ_{CP} sensitivity
  - Long baseline experiments have difficulty obtaining good statistics for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ which Daeδalus can provide
  - Daeδalus has no matter effects so can help remove ambiguities.
$\delta_{CP}$ Sensitivity Compared to Others

![Graph showing $\delta_{CP}$ sensitivity compared to others.](image-url)
\( \delta_{CP} \)Discovery Potential
(exclude 0° and 180° with \( \sigma \) significance in 10yrs)

Diagram showing the discovery potential for different experiments, with 3\( \sigma \) and 5\( \sigma \) significance levels indicated.
Comparison of $\delta_{CP}$ Measurement Uncertainties

\[ \Delta \delta \text{ at } 1\sigma \]
\[ \theta_{23} = 40^\circ \]

- LBNE10 (0.7MW, 10kt)
- LBNE (0.7MW, 34kt)
- LBNE + Project X (2.3MW, 34kt)
- T2HK (0.7MW, 560kt)
- Daedalus (8MW) + T2HK
- NuMAX to SURF (1MW, 10kt)
- NuMAX+ to SURF (3MW, 34kt)

From: P. Huber
Globes 2013
DAEδALUS Top Level Cost Estimate

- $130M near accelerator plus $320M for 2nd and 3rd sites.
  - Includes various contingencies from 20% to 50%.
  - Assumes component costs drop by 50% after prod. of 1st item.
  - Does not include site specific cost (buildings)

- The cyclotron magnet is the cost driver.
  - For this we have: Engineering Study for Daedalus Sector Magnet; Minervini, et al., arXiv:1209.4886

- The RF is based on the PSI design and scaled from those costs.

- The strong similarity to RIKEN cyclotron allows cost cross check.

- All targets are ~1 MW (similar to existing targets), note each cyclotron can have more than one target to maintain the power level on each.
Final Comments

• High-power (~1MW) class cyclotrons are becoming a reality
  – For physics, they can provide high intensity neutrino sources
  – Important industrial interest for medical isotope production
  – Other applications in connection with accelerator driven reactors (ADS)

• IsoDAR using the Phase I DAEδALUS injector cyclotron can make a definitive search for sterile neutrinos at KamLAND

• DAEδALUS is another method to probe for CP violation in the ν-sector
  – Can provide high statistics $\bar{\nu}_e$ appearance data with no matter effects and reduced systematic uncertainties
  – Can give enhanced sensitivity when combined with Hyper-K long baseline $\nu_e$ appearance data
Backup
Method Uses $\Delta \chi^2$ with Pull Terms
(Inspired by previous Hyper-K studies)

Assumptions for studies:

$\Delta m^2 = 2.4 \pm 0.05 \times 10^{-3} \text{ eV}^2$  Systematic $\sigma = 5\%$

$\sin^2 2\theta_{13} = 0.10 \pm 0.005$

$\sin^2 \theta_{23} = 0.57 \pm 0.01$
Accelerator Technologies
Where can DAEδALUS run?

Hyper-K (or initially, Super-K)  
*(Focus for current studies)*

LENA - Scintillator Detector

MEMPHYS

Detector needs to have free protons to capture neutrons from IBD ⇒ liquid argon is not an option