Daeðalus and IsoDAR Experiments

(“Cyclotrons as Drivers for Precision Neutrino Measurements” - arXiv:1307.6465
Snowmass Whitepaper on the DAEdALUS Program - arXiv: 1307.2949)

**IsoDAR Setup:**
Very short baseline search for sterile neutrinos

*PRL 109, 141802 (2012)*

**Daeðalus Setup:**
A new way to search for CP violation in the ν-sector

*PRL 104, 141802 (2010)*
DAEδALUS / IsoDAR Summary

• 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.
  – Therefore, the development of these new, smaller sources should be a priority for our field.

• 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

• We request that P5 endorse our development program with the goal to move rapidly forward with a
  1. A first demonstration IsoDAR system built before the end of this decade
  2. A full DAEδALUS set-up potentially installed in the 2020's.
IsoDAR Cyclotron

Injectors

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.

Daeδalus DAR Target-Dump (about 6x6x9 m³)

Multimegawat Daeδalus Cyclotron for Neutrino Physics

arXiv: 1207.4895
Phase I

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

Phase II

IsoDAR

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

Phase III

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

Phase IV

DAEδALUS

We are here

Best Inc. Teststand, Catania Experiment

Accelerator Science
Physics: 2014-15

WATCHMAN, KamLAND, JUNO

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

NOvA, LENA, Super K

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

HyperK, LENA

CP
Eng: 2020
Start 2025

Question 1: “Notional Timeline” (Technically driven)
IsoDAR $\bar{\nu}_e$ Disappearance Search

- **IsoDAR**: Isotope Decay-at-rest beam (high intensity $\bar{\nu}_e$ source)

  - $p$ (60 MeV@10ma) into target $\rightarrow ^8$Li
  - $^8$Li $\rightarrow ^8$Be + e$^-$ + $\bar{\nu}_e$
    - Known $\bar{\nu}_e$ energy spectrum (mean event energy of 8.5 MeV)
    - Use shape analysis with very small systematic uncertainties
    - Observe changes in the event rate as a function of L/E
    - $\sim$160,000 IBD events / yr in 1kton

- Update options since Snowmass (see “Update on the IsoDAR Program For P5”)
  - Watchman 1kton Gd-doped water (or scintillator) detector in old IMB cavern
  - IsoDAR at JUNO (Daya Bay II) 20 kton liquid scintillator

Can also isolate 3+1 vs 3+2
IsoDAR Combinations with Various Detectors

- IsoDAR @ Watchman or KamLAND
  - Full coverage of “Global Fit region” and “Reactor Anomaly” for $\Delta m^2 < 10\text{eV}^2$

- IsoDAR @ JUNO
  - Full coverage of “Global $\bar{\nu}_e$ Appearance” region
IsoDAR Also Has Excellent Electroweak Measurement Sensivity ($\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$)

- 5yr data $\Rightarrow$ ~7200 evts with $E_{\text{vis}} > 3\text{MeV}$

$\Rightarrow$ IsoDAR@ Watchman:

$\delta \sin^2 \theta_W = 0.0044$ (~1.7%)

- Would be, by far, the world’s best electron-flavor, pure leptonic measurement

Precision neutrino-electron scattering can also probe Non-Standard Interactions (NSI) since it is a well-understood Standard Model process

$$g_L \rightarrow g_L + \epsilon_{ee}^{e_L}, \quad g_R \rightarrow g_R + \epsilon_{ee}^{e_R}$$
DAEδALUS Experiment
Search for CP Violation using $\bar{\nu}_e$ Appearance with a Pion Decay-at-Rest Neutrino Beam

- Pion decay-at-rest neutrino source produced by high-intensity 800 MeV cyclotron
  - Very high-intensity $\bar{\nu}_\mu$ source with known spectrum

- Look for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations
- Single large water (with Gd) or scintillator
  - Need free hydrogen to use inverse-beta-decay (IBD) detection

- Neutrino sources at three different distances
  - Use IBD interactions to isolate a pure sample of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations

- Can combine DAEδALUS antineutrino data set with long baseline neutrino-only data for much improved CP violation search
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 long baseline ν-only data to give enhanced sensitivity, i.e. Hyper-K
  – Long baseline experiments have difficulty obtaining good statistics for $\bar{\nu}_\mu \to \bar{\nu}_e$ which DAEδALUS can provide
  – Daeδalus has no matter effects and can help remove ambiguities.
$\delta_{CP}$ Sensitivity Compared to Others
Question 1: “What makes this program unique?”

These programs are quite different from all other proposals

IsoDAR

1. Known flux shape since single beta decay (unlike reactors)
2. Higher energy than sources or reactors (endpoint 13 MeV)
   • Well above the 3 MeV environmental backgrounds
   • Very low systematic uncertainties
   • High flux and low systematics allows precision $\bar{\nu}_e - e$ scattering
3. Flexible location
   – Can bring source to detector (unlike reactors)
   – Combined with higher energy gives better L/E coverage
4. Long runs are possible (unlike sources) with no interfacing with company or lab schedules
Question 1: “What makes this program unique?”

DAEδALUS

1. Tracing the oscillation wave is a unique approach to CP studies.
2. Beam energy and flavor content well defined
3. Very low $\bar{\nu}_e$ intrinsic background
   - Due to compact target/dump design with little $\pi^-$ decay-in-flight backgrounds
   - Energy implies no Kaon production
   - Better geometry than DAR setups at spallation facilities
4. Very short baseline $\Rightarrow$ no matter effects
   - No mass hierarchy dependence
   - Unaffected by propagation NSI effects
5. The complementary nature is what makes combining with conventional beam data so powerful
Questions 2 & 4: Collaborating Institutions and Labs

US
Amherst College
Bartoszek Engineering
Columbia University
Duke University
Lawrence Livermore National Lab.
Los Alamos National Laboratory
Massachusetts Institute of Technology*
Michigan State University*
New Mexico State University
UC Berkeley (Nuc. Eng.)*
UC Irvine
UCLA
University of Maryland*
University of Tennessee

Very Active, Ramping Up, Low Level, but interested

Foreign
The Cockcroft Institute for Accelerator Science*
University of Huddersfield*
Imperial College London
University of Manchester*
Tohoku University*

Cyclotron Labs
LNS-INFN (Catania)*
Paul Scherrer Institut*
RIKEN*

* group includes experienced accelerator scientists
## Questions 2 & 4: Collaboration Cyclotron Companies

<table>
<thead>
<tr>
<th>Cyclotron Company</th>
<th>Location</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIMA</td>
<td>European</td>
<td>General interest</td>
</tr>
<tr>
<td>Best Cyclotron Systems, Inc.</td>
<td>US &amp; Worldwide</td>
<td></td>
</tr>
<tr>
<td>IBA</td>
<td>US &amp; Worldwide</td>
<td></td>
</tr>
<tr>
<td>Sumitomo Heavy Industries</td>
<td>Japan</td>
<td>Interest is in IsoDAR@KamLAND</td>
</tr>
</tbody>
</table>

So far the role of these companies has been as collaboration members, not as contractors.
Questions 3: IsoDAR Present Top Level Cost Estimates

**Cost-effective Design Options for IsoDAR**
A. Aldelmann et al.; arxiv: 1210.4454

1st source constructed --
$30M base cost (2013 $)

recommended contingency
as of now: 50%
after 1st eng. design: 20%

If more sources are
constructed – ~$15M each.

We need funding for engineering to make improved cost estimates.

<table>
<thead>
<tr>
<th>Assessment</th>
<th>60 MeV Compact Cyclotron</th>
<th>RFQ/Separated Sector Cyclotron</th>
<th>LINAC, 30 MeV, 40 mA</th>
<th>Modified Beta Beam Design</th>
<th>New Detector at Existing Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Cost</td>
<td>Good</td>
<td>Moderate</td>
<td>Bad</td>
<td>Good</td>
<td>Moderate</td>
</tr>
<tr>
<td>2. (\bar{\nu}) rate</td>
<td>Good</td>
<td>Moderate</td>
<td>Bad</td>
<td>Good</td>
<td>Moderate</td>
</tr>
<tr>
<td>3. Backgrounds low</td>
<td>Good</td>
<td>Moderate</td>
<td>Bad</td>
<td>Good</td>
<td>Moderate</td>
</tr>
<tr>
<td>4. Technical risk</td>
<td>Moderate</td>
<td>Good</td>
<td>Bad</td>
<td>Moderate</td>
<td>Good</td>
</tr>
<tr>
<td>5. Compactness</td>
<td>Moderate</td>
<td>Good</td>
<td>Bad</td>
<td>Moderate</td>
<td>Good</td>
</tr>
<tr>
<td>6. Simplicity u’ground</td>
<td>Moderate</td>
<td>Good</td>
<td>Bad</td>
<td>Moderate</td>
<td>Good</td>
</tr>
<tr>
<td>7. Reliability</td>
<td>Good</td>
<td>Moderate</td>
<td>Bad</td>
<td>Good</td>
<td>Moderate</td>
</tr>
<tr>
<td>8. Value to other exps</td>
<td>Good</td>
<td>Moderate</td>
<td>Bad</td>
<td>Good</td>
<td>Moderate</td>
</tr>
<tr>
<td>9. Value to Industry</td>
<td>Good</td>
<td>Moderate</td>
<td>Bad</td>
<td>Good</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
Questions 3: DAEδALUS Present Top Level Cost Estimates

DAEδALUS – $130M near accelerator, $450M for the 3 sites. Includes various contingency 20% to 50%. Assumes component costs drop by 50% after prod. of 1st item. Does not include site specific cost (buildings)

1. The SRC magnet is the cost driver. For this we have:
   Engineering Study for Daedalus Sector Magnet; Minervini, et al., arXiv:1209.4886
   (Minervini received the 2013 award for Continuing and Significant Contributions in the Field of Applied Superconductivity)

2. The RF is based on the PSI design, for which we have a cost.

3. The strong similarity to RIKEN allows a sanity check, and we have the costs for this.

4. 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.

We need funding for engineering to make improved cost estimates.
Final Comment: Cyclotron Development as Value to Society

1. IsoDAR design would give enhanced medical isotope production - much industry interest

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{52}\text{Fe}$</td>
<td>8.3 h</td>
<td>The parent of the PET isotope $^{52}\text{Mn}$ and iron tracer for red-blood-cell formation and brain uptake</td>
</tr>
<tr>
<td>$^{122}\text{Xe}$</td>
<td>20.1 h</td>
<td>The parent of PET isotope $^{122}\text{I}$ used to study brain blood flow</td>
</tr>
<tr>
<td>$^{28}\text{Mg}$</td>
<td>21 h</td>
<td>A tracer that can be used for bone studies, analogous to $^{51}\text{Cr}$</td>
</tr>
<tr>
<td>$^{128}\text{Ba}$</td>
<td>2.43 d</td>
<td>The parent of positron emitter $^{128}\text{Cs}$. As a potassium analog, this is used for heart and blood-flow studies</td>
</tr>
<tr>
<td>$^{97}\text{Ru}$</td>
<td>2.79 d</td>
<td>A $\gamma$-emitter used for spinal fluid and liver studies</td>
</tr>
<tr>
<td>$^{117}\text{mSn}$</td>
<td>13.6 d</td>
<td>A $\gamma$-emitter potentially useful for bone studies</td>
</tr>
<tr>
<td>$^{82}\text{Sr}$</td>
<td>25.4 d</td>
<td>The parent of positron emitter $^{82}\text{Rb}$, a potassium analog. This isotope is also directly used as a PET isotope for heart studies</td>
</tr>
</tbody>
</table>

2. DAE$\delta$ALUS design applicable to Accelerator Driven Systems (ADS) Reactors

MW-CLASS 800 MeV/n $H_2^+$ SC-CYCLOTRON FOR ADS APPLICATION, DESIGN STUDY AND GOALS*

F. Méot, T. Roser, W. Weng, BNL, Upton, Long Island, New York, USA
L. Calabretta, INFN/LNS, Catania, Italy; A. Calanna, CSFNSM, Catania, Italy

 Thorium reactor community interested in DAE$\delta$ALUS development.

⇒ Cyclotrons are practical and cheap compared to linacs.
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Backup Slides
Questions 3: Cost - Supporting docs for IsoDAR

Ours will cost more because machine is larger, but this sets scale.

Obtaining ~3 tons of 99.99% pure 7Li -- molten salt reactor industry

Molten salt reactors: A new beginning for an old idea

David LeBlanc\textsuperscript{a,b,*}

100 m\textsuperscript{3} of flibe will contain about 30 tonnes of 99.995\% 7Li with previous cost estimates being from 120 to 800 \$/kg. Even several
Questions 3: DAEδALUS - Supporting Docs

Engineering Study of SRC, arXiv: 1209.4886

- Engineering design,
- Assembly Plan,
- Structural analysis,
- Cryo system design

Fig. 4-11A. Gravity, Pre-tension, 4K.

Fig. 4-9. Flux density on surface of coils with upper coil current zero.
Cyclotron Arrangements for DAEδALUS

The “standard” system:
* 1 will run at near site,
  \[ DF \sim 13\% \Rightarrow 10\text{ma@0.8GeV} \times 13\%DF = 1\text{MW} \]
* 1 will run at midsite
  \[ DF \sim 25\% \Rightarrow 10\text{ma@0.8GeV} \times 25\%DF = 2\text{MW} \]

The “high power system”
* 2 will run at far site
  \[ DF \sim 25\% \Rightarrow 2 \times 12.5\text{ma@0.8GeV} \times 25\%DF = 5\text{MW} \]

Note: Cyclotrons can have multiple dumps. All dumps will be identical at 1 MW
Three Identical Beams with Known Flux (Both Normalization and Shape)

- Use $\nu_e$-$e$ scattering events from near neutrino source to set the absolute normalization.
- Transfer this normalization to other sources using high statistics $\nu_e$ (or $\nu_e$C) events from three sources.
- Then given the known $\bar{\nu}_\mu$ flux from each source, fit the observed $\bar{\nu}_e$ events to extract $\delta$.

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

At far and mid-distance neutrino source, compare predicted to measured $\nu_eO (\nu_eC)$ 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.
IsoDAR Compared to Existing Similar Cyclotrons

We claim we will be able to produce
\(~10~\text{mA of protons} @ 60\text{ MeV}\)
when commercial machines (IBA, Best) produce
\(~1~\text{mA of protons} @ 60\text{ MeV}\)

How do we achieve this?

Rather than one single order-of-magnitude improvement, there are four issues to solve…

1. Space Charge  --- Solved by using H2+
2. Intensity of ion source -- Resolvable within 1 year
3. Inflection -- Resolvable within 2 years
4. Protection of the electrostatic septum  -- solved with foil
1) Accelerate more particles for same level of space charge effects

Present machines inject p or H$^-$
We inject H$_2^+$

A measure of the strength of space charge is the generalized perveance:

$$K = \frac{qI}{2\pi\varepsilon_0 m\gamma^3 \beta^3}$$

Comparing perveance at injection:
5 mA, 35 keV/n of H$_2^+$ = 2 mA, 30 keV of p
(already achieved in commercial cyclotrons)
2) Push the envelope of H$_2^+$ intensities from ion sources

Most ions are lost in the first “turn” because they hit material.
(Phase acceptance 20-30 degrees)

To capture 5 mA we will need between 35 and 50 mA injected.

This is not unusual for a p source, but is **high** for an H$_2^+$ source. This is at the edge of what has been done…
Ion sources that are close to what is needed:

Can run 50 mA but is pulsed, not CW. Interesting because design is similar to VIS source we have been using in our teststand.

Testing of a $\text{H}_2^+$-enriched ion source for deuterium simulation

M. D. Williams and K. N. Leung

*Lawrence Berkeley Laboratory, Berkeley, California 94720

G. M. Brennen and D. R. Burns

*McDonnell Douglas Astronautics Co., St. Louis, Missouri 63166

(Presented on 12 July 1989)

We have tested a McDonnell Douglas short multicusps plasma generator, designed to generate a positive hydrogen ion beam which is enriched with $\text{H}_2^+$ ions. Initial testing shows that the prototype source is capable of producing a positive hydrogen ion beam with $\text{H}_2^+$ percentage greater than 85%. The total ion-current density was 56 mA/cm². For a higher current density of 110 mA/cm², the percentage of $\text{H}_2^+$ ions is approximately 73% as measured by a magnetic deflection spectrometer. A comparison between tungsten and lanthanum hexaboride cathodes shows that tungsten filaments can provide better performance.

Most promising existing source?

Under study!
3) Develop an unusually large spiral inflector ($\text{H}_2^+$ rigidity)

The beam enters axially, through a conducting “spiral inflector”

Takes beam from vertical to the horizontal plane

Tricky to design:
• B field effects
• neutralization

This is an iterative R&D process

designed by MIT Postdoc Daniela Campo
Experiments ongoing now, and upgrades planned.
4) Avoid beam losses on the electrostatic extraction septum (protecting with a stripper foil, removing 5 µA of beam)

Without the foil:

In the final four turns…
Intensity vs. position

In the final two turns…
Beam spot vs. position
What do communities outside of the Neutrino Frontier think?

From the Snowmass Accelerator Capabilities Executive Summary:

Our study heard exciting possibilities for capabilities of narrower experimental scope than Project X. The DAEδALUS collaboration proposes multiple sources of decay-at-rest anti-neutrinos for short baseline oscillation experiments. DAEδALUS would use three multi-MW H2+ cyclotrons and target stations located ~2-20km from a large hydrogenous detector to measure CP violation as a complement to the LBNE experiment. The first stage of DAEδALUS is IsoDAR, a compact 60 MeV cyclotron located only 15m from the KamLAND detector to make a definitive search for one or two sterile neutrinos. This international collaboration has engaged commercial industries to address the challenges of cost-optimization and reliable operation of multi-MW cyclotrons.
From Section 3 of the Accelerator Capability Report:

DAEdALUS [10] is a neutrino research program based on "decay-at-rest" sources. Pions are produced by interaction of 800 MeV protons on a suitable target. This energy is sufficiently above threshold for good pion yield, and low enough that pions will stop in the target before decaying. The DAEdALUS configuration consists of three sources of neutrinos as identical as possible. The highest power accelerator, located 20 km from the detector would provide 10 mA of protons at 800 MeV to the neutrino-generating targets. A current of 10 mA is approximately a factor of 5 over the highest achieved current at PSI, the world's leading high-power cyclotron today. Accelerating H2+ ions rather than protons has the potential for reducing space-charge issues at injection. Extraction of the beam at 800 MeV with a stripper foil minimizes the necessity for clean turn separation at the outer radii, only requiring an extraction channel (for the resulting protons) with sufficiently large momentum acceptance to allow for ions stripped from several overlapping turns. The use of H2+ acceleration represents a novel approach to reducing beam losses at extraction from the 800 MeV cyclotron.

To date, the DAEdALUS feasibility arguments are made by scaling from existing low-energy H- commercial cyclotrons as well as from the PSI high-power proton cyclotron. Since the high-power H2+ concept is quite novel, a systematic research is being conducted to address challenges of meeting the required performance. The most critical elements are 1) ion-source development to achieve very bright, vibrationally cold H2+ beams of at least 50 mA CW, 2) injection into cyclotrons with emphasis on bunching efficiency, space requirements and space-charge dynamics, 3) end-to-end simulations to evaluate beam stability and uncontrolled loss, and 4) atomic physics experiments of stripping and vacuum cross sections and possibly techniques for Lorentz dissociation of vibrational states in high-field (<25T) magnets in transport line between the injection and the second-stage cyclotrons. As is the case for Project X, target systems are challenging and will require sustained research.

The first phase of DAEdALUS is IsoDAR [11], a compact 600 kW cyclotron proposed to be located 15 m from the KamLAND detector for a 5 sigma search for one or two sterile neutrinos. The IsoDAR cyclotron would also be a prototypical injector for the superconducting ring cyclotron of DAEdALUS. Presently space charge effects at injection are being studied experimentally in collaboration with industrial partners.
From Accelerators for America’s Future:

“The United States, which has traditionally led the development and application of accelerator technology, now lags behind other nations in many cases, and the gap is growing. To achieve the potential of particle accelerators to address national challenges will require sustained focus on developing transformative technological opportunities...."

This is quite true for cyclotrons!
We can pair with other types of detectors…

e.g. Coherent Neutrino Scattering:

Coherent Neutrino Scattering in Dark Matter Detectors

Measuring Active-to-Stereile Neutrino Oscillations with Neutral Current Coherent Neutrino-Nucleus Scattering

From the Snowmass summary talk on Underground Capability:

…use of cyclotrons, intense sources or small modular reactors would increase the number of potential facilities for neutrino experiments in the U.S. and worldwide.
Comparison of $\delta_{CP}$ Measurement Uncertainties

From: P. Huber
Globes 2013

$\Delta\delta$ at $1\sigma$
$\theta_{23}=40^\circ$

Fraction of $\delta$

$\Delta\delta[\circ]$

- LBNE10 (0.7MW, 10kt)
- LBNE (0.7MW, 34kt)
- LBNE + Project X (2.3MW, 34kt)
- T2HK (0.7MW, 560kt)
- Daedalus (8MW) + T2HK$
u$
- NuMAX to SURF (1MW, 10kt)
- NuMAX+ to SURF (3MW, 34kt)
Oscillation L/E Waves in IsoDAR

IsoDAR’s high statistics and good L/E resolution has potential to distinguish (3+1) and (3+2) oscillation models
ISODAR@WATCHMAN

Sterile Neutrino Search

You want a convincing shape (L/E) analysis, not just rate.
Comparison of Future $\bar{\nu}_e$ Disappearance Proposals