Searching for Sterile Neutrinos and CP Violation: The IsoDAR and DaeΔalus Experiments

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Daeðalus 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)

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

- **H$_2^+$ Ion Source**
- **Daeδalus 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.

- **Multimegawat Daeδalus Cyclotron for Neutrino Physics**

*arXiv:1207.4895*
Current 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 currently being characterized at Best Cyclotrons, Inc, Vancouver
IsoDAR Experiment

Isotope Decay-at-Rest Neutrino Source ( $\bar{\nu}_e$ Disappearance )
to Search for Sterile Neutrinos
Many Experimental Hints for Sterile Neutrinos

- MiniBooNE/LSND $\nu_e / \bar{\nu}_e$ appearance signals

![Diagram showing $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transition]

- Reactor Anomaly: $\bar{\nu}_e$ disappearance signals?

![Diagram showing $\bar{\nu}_e \rightarrow \bar{\nu}_s$]

Data sets indicate a high $\Delta m^2$

Can be fit by introducing a new $\nu$, ...but it must be non-interacting (sterile!)

$\Delta m^2_{\text{sterile}} \sim 1 \text{eV}^2$

These signals are at the 2-4$\sigma$ level $\Rightarrow$ Need new “definitive” experiments

*Establishing the existence of sterile neutrinos would be a major result for particle physics*
Probing $\Delta m^2 \sim 1 \text{ eV}^2$ Oscillations
Short and Very-short Baseline Oscillation Experiments

**\(\nu\) - Source**
- Radioactive Source
- Isotope Source
- Reactor Source
- Proton into Dump Source

**\(\nu\) - Detector**

- Many ideas and neutrino sources:
  - Reactor sources
  - Radioactive sources
  - Isotope sources
  - $\pi / K$ decay-at-rest sources
  - $\pi$ decay-in-flight sources
  - Low-energy $\nu$-Factory source

- Need definitive experiments
  - Significance at the $> 5\sigma$ level
  - Smoking gun: Observation of oscillatory behavior within detector

- Several directions for next generation accelerator experiments
  - Multi-detector accelerator neutrino beam experiments
  - Very short baseline (VSBL) experiments with compact neutrino sources

Light Sterile Neutrinos: A White Paper
Overview IsoDAR $\bar{\nu}_e$ Disappearance Exp

- High intensity $\bar{\nu}_e$ source using $\beta$-decay at rest of $^8\text{Li}$ isotope \(\Rightarrow\) IsoDAR

- $^8\text{Li}$ produced by high intensity (10ma) proton beam from 60 MeV cyclotron \(\Rightarrow\) being developed as prototype injector for DAE\(\delta\)ALUS 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….

- Physics measurements:
  - $\bar{\nu}_e$ disappearance measurement in the region of the LSND and reactor-neutrino anomalies.
  - Measure oscillatory behavior within the detector as a function of $L$ and $E$.

arXiv:1205.4419
IsoDAR Neutrino Source and Events

- \( p \ (60 \text{ MeV}) + ^9\text{Be} \rightarrow ^8\text{Li} + 2p \)
  - plus many neutrons since low binding energy

- \( n + ^7\text{Li} \) (shielding) \( \rightarrow ^8\text{Li} \)

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

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

arXiv:1205.4419
Currently working with the Kamland collaboration on the details of siting and installation of the cyclotron, beamline, and neutrino source.
IsoDAR $\bar{\nu}_e$ Disappearance Oscillation Sensitivity (3+1)
IsoDAR Measurement Sensitivity

\[ \Delta m^2 \text{ (eV}^2) \]

95\% CL Allowed Regions

IsoDAR 5\% Limit

IsoDAR 1\% and 5\% contours

Cribier et al. 5\% Limit

\[ \sin^2 2\theta_{\text{new}} \]
IsoDAR’s high statistics and good L/E resolution has potential to distinguish (3+1) and (3+2) oscillation models.
IsoDAR Also Has Excellent Electroweak Measurement Sensitivity \( (\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-)\)

- 5yr data \(\Rightarrow\) 7200 evts with \(E_{\text{vis}}>3\text{MeV}\)
  \(\Rightarrow\) IsoDAR@Kamland:
  \[\delta\sin^2\theta_W = 0.0075\ (\sim 3\%)\]
  - Would be the best \(\bar{\nu}_e e\) (or \(\nu_e e\)) elastic scattering measurement

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

\[
g_L \rightarrow g_L + \epsilon_{ee}^L \quad g_R \rightarrow g_R + \epsilon_{ee}^R
\]
DAEδDALUS Experiment

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

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

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
Osc. maximum

\[ \delta = \pi/2 \]

\[ \delta = 0 \]

Constrains rise of probability wave

Constrains flux

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

Near Neutrino Source

Mid-distance Neutrino Source

Far Neutrino Source

\(8 \text{ km}\)

\(20 \text{ km}\)
The diagram illustrates the neutrino oscillation probability as a function of oscillation parameters and distance from the neutrino source. The oscillation probability is shown on the y-axis, with δ = π/2 and δ = 0 as critical points.

- **Constrains Initial flux**:
  - Neutrino emission from the source.

- **Constrains rise of probability wave**:
  - The probability wave rises significantly.

- **Osc. maximum at ~40 MeV**:
  - Maximum oscillation probability.

The diagram also shows three identical beams from near, mid-distance, and far neutrino sources. The near source is at 8 km, mid-distance is at 10 km, and far is at 20 km. The flux is depicted on an energy scale, with ν_e and ν_μ waveforms.
Constrains
Initial flux

Constrains rise
of probability
wave

Osc. maximum

Near Neutrino Source

Mid-distance Neutrino Source

Far Neutrino Source

You need to know which one is providing the beam. So they have to turn on/off.

\[ \nu_\mu \rightarrow \nu_e \]
Where can DAEδALUS run?

Hyper-K (or initially, Super-K)

*Focus for current studies*

LENA - Scintillator Detector

MEMPHYS
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 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ which Daeδalus can provide
  - Daeδalus has no matter effects and can help remove ambiguities.
$\delta_{CP}$ Sensitivity Compared to Others
Comparison of $\delta_{CP}$ Measurement Uncertainties

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

Fraction of $\delta$

$\Delta \delta$[$^\circ$]

From: P. Huber
Globes 2013
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)

• Establishing the existence of sterile neutrinos would be a major result for particle physics
  – IsoDAR can make a definitive search for sterile neutrinos
    • Combined L and E analysis with good resolutions can isolate the oscillatory behavior and reduce backgrounds

• Daeðalus is another method to probe for CP violation in the ν-sector
  – Can provide high statistics $\bar{\nu}_e$ data with no matter effects and reduced systematic uncertainties
  – Can give enhanced sensitivity when combined with long baseline $\nu_e$ appearance data
Backup
$\delta_{\text{CP}}$ Discovery Potential
(exclude $0^0$ and $180^0$ with $\sigma$ significance in 10yrs)

(34 kton)
Elastic Scattering $\Rightarrow$ Measure $\sin^2 \theta_W$

- NuTeV weak mixing angle measurement using neutrino neutral current scattering differs from expectation by $3\sigma$
  - Is there something special with neutrinos or difficulty in NuTeV analysis?

$\Rightarrow$ Use IsoDAR/Kamland to measure $\sin^2 \theta_W$ with pure lepton process antineutrino-electron elastic scattering: $\bar{\nu}_e + e \rightarrow \bar{\nu}_e + e$
Detect $\bar{\nu}_e$ Events using Inverse Beta Decay (IBD)

- Scintillator or Gd-doped water detector
- prompt positron signal followed by neutron capture
- $E_{\bar{\nu}_e} \approx E_{\text{prompt}} + 0.78$ MeV
Kamland Backgrounds to $\bar{\nu}_e$e Signal

- Backgrounds are large since signal is single outgoing electron
- Visible energy is low since outgoing $\bar{\nu}_e$ takes away energy

From L. Winslow

Use large sample of IBD events to constrain normalization to 0.2%

Cuts:
- $E_{\text{vis}} > 3$ MeV
- $\theta$ (to source) < 25°
⇒ Reduce isotropic bkgnd by x2

$E_\nu = 8$ MeV