Searching for Sterile Neutrinos and CP Violation: The IsoDAR and DAE$\delta$ALUS Experiments

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Daeδalus 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)

Daeδalus Setup:
A new way to search for CP violation in the ν-sector
DAEδDALUS High Power (~1 MW) 800 MeV Cyclotron System

H$_2^+$ Ion Source

Daeδalus DAR Target-Dump (Antineutrino Source) (about 6x6x9 m$^3$)

IsoDAR 60 MeV Cyclotron

Injector Cyclotron (Resistive)

800 MeV Ring Cyclotron (Superconducting)

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

New Short and Very-short Baseline Oscillation Experiments

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

$v$ - Source

Radioactive Source or
Isotope Source or
Reactor Source or
Proton into Dump Source

$v$ - Detector

Establishing the existence of sterile neutrinos would be a major result for particle physics
**Overview IsoDAR $\bar{\nu}_e$ Disappearance Exp**

- 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
  - $p + ^9$Be $\rightarrow$ many n’s $\Rightarrow$ n + $^7$Li (shielding) $\rightarrow$ $^8$Li $\Rightarrow$ $^8$Li $\rightarrow$ $^8$Be + e$^- + \bar{\nu}_e$
  - Mean $\bar{\nu}_e$ energy = 6.5 MeV with $2.6 \times 10^{22}$ $\bar{\nu}_e$ / yr

- Put a cyclotron-isotope source near one of the large (kton size) liquid scintillator/water detectors such as KAMLAND or WATCHMAN

- 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
Possible IsoDAR Sites: KAMLAND or WATCHMAN

**KAMLAND Detector**
- Location available for cyclotron and $\nu$ source
- Pure scintillator with excellent energy resolution and low backgrounds
- 1 kton spherical fiducial vol.
  - 6.5m radius

**WATCHMAN Detector**
- To be located in old IMB site near Cleveland Ohio
- Gd-doped water Cerenkov detector either pure water or water doped with scintillator
- 1 kton cylindrical fiducial vol.
  - 5.4 m radius by 10.8m high
IsoDAR $\bar{\nu}_e$ Disappearance Oscillation Sensitivity (3+1)
IsoDAR at KAMLAND Measurement Sensitivity (5 yrs)
Oscillation L/E Waves in IsoDAR at KAMLAND

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

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

\[ \text{Observed/Predicted event ratio vs L/E including energy and position smearing} \]

\[ \bar{\nu}_e \rightarrow \bar{\nu}_e \text{ 5 yrs} \]

\[ \text{(3+2) with Kopp/Maltoni/Schwetz Parameters} \]

\[ \bar{\nu}_e \rightarrow \bar{\nu}_e \text{ 5 yrs} \]

IsoDAR’s high statistics and good L/E resolution has potential to distinguish (3+1) and (3+2) oscillation models.
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 $\delta_{CP}$

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

We want to see if $\delta$ is nonzero  

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

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

Pion/muon decay-at-rest beam
- Very small $\bar{\nu}_e$ cont.
- Flux normalization using $\nu_e$ - e events.

Neutrino beam flux vs energy fixed by the physics of muon decay
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)

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

\[\delta = \pi/2\]

\[\delta = 0\]

\(\bar{\nu}_e\)
Where can DAEδALUS run?

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

MEMPHYS

LENA - Scintillator Detector

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

• Daeðalus has good CP sensitivity as a stand-alone experiment.
  – Small cross section, flux, and efficiency uncertainties
• Daeðalus 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 Daeðalus can provide
  – Daeðalus has no matter effects and can help remove ambiguities.
$\delta_{CP}$ Sensitivity Compared to Others

![Graph showing $\delta_{CP}$ sensitivity compared to others with different projects and timeframes.](image)
Comparison of $\delta_{CP}$ Measurement Uncertainties

$\Delta \delta$ 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$
u$
- NuMAX to SURF (1MW, 10kt)
- NuMAX+ to SURF (3MW, 34kt)

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

• Dædalus 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 long baseline $\nu_e$ appearance data
Backup
IsoDAR Also Has Excellent Electroweak Measurement Sensitivity ( $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$ )

- 5yr data $\Rightarrow$ 7200 evts with $E_{\text{vis}} > 3$ MeV
  $\Rightarrow$ IsoDAR@Kamland: $\delta \sin^2 \theta_W = 0.0075$ (~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

$$g_L \rightarrow g_L + \epsilon^{eL}_{ee} \quad g_R \rightarrow g_R + \epsilon^{eR}_{ee}$$
IsoDAR Comparison to Other Proposals
$\delta_{\text{CP}}$ Discovery Potential
(exclude $0^0$ and $180^0$ with $\sigma$ significance in 10yrs)

$\delta_{\text{CP}}$ (degrees)

- LBNE (34 kton)
- JPARC@Hyper-K
- DAE$\delta$ALUS@Hyper-K
- DAE$\delta$ALUS/JPARC($\nu$-only)@Hyper-K
IsoDAR Neutrino Source and Events

- $p \ (60 \text{ MeV}) + {^9\text{Be}} \rightarrow {^8\text{Li}} + 2p$
  - plus many neutrons since low binding energy
- $n + {^7\text{Li}} \text{ (shielding)} \rightarrow {^8\text{Li}}$
- $^{8}\text{Li} \rightarrow ^{8}\text{Be} + e^- + \bar{\nu}_e$
  - 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
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
DAEδALUS Measurement Strategy

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

At far and mid-distance neutrino source,
Compare predicted to measured $\nu_e O (\nu_e C)$ 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