IsoDAR: Neutrino Physics Using a High Current Cyclotron

Joe Smolsky for the IsoDAR collaboration
Overview

Motivation
  • Standard model
  • Neutrino oscillations
  • Anomalies
  • Sterile neutrinos

IsoDAR
  • Setup
  • Physics
  • Current Status
  • Beyond IsoDAR
Standard Model

Quarks
up, charm, top
down, strange, charm

Leptons
electron, muon, tau
$\nu_e, \nu_\mu, \nu_\tau$

Force carriers
photon
gluon
W, Z

Mass
Higgs
Neutrino oscillations

- Interact in flavor eigenstates
- Propagate in mass eigenstates

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[
P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4 \sum_{j>i} U_{\alpha i} U_{\beta i} U_{\alpha j}^* U_{\beta j}^* \sin^2 \left( 1.27 \Delta m^2_{ij} \frac{L}{E} \right)
\]

\[ P_{\nu_\alpha \to \nu_\beta} = \sin^2(2\theta) \sin^2 \left( 1.27 \Delta m^2 \frac{L}{E} \right) \]

- \( \sin^2 2\theta \to \) statistics
- \( \frac{L}{E} \to \) experiment setup
- \( \sin^2 2\theta \) vs. \( \Delta m^2 \)
- Allow/exclude regions

Example plot from \( \nu_{\text{fit}} \):
http://arxiv.org/abs/1811.05487
http://www.nu-fit.org/
Sterile neutrinos

- Additional neutrino flavors
- Sterile flavors don’t interact through weak force
- Active neutrinos can oscillate into sterile neutrinos

Oscillation Experiments

MiniBooNE: $\nu_\mu \rightarrow \nu_e$ excess $4.8\sigma$

DANSS Results and allowed regions

More oscillation experiments

| Neutrino | MiniBooNE | MiniBooNE | NEOS *
|----------|-----------|-----------|---------
| Antineutrino | LENA | KATRIN | DANSS *

\[ \nu_e \rightarrow \nu_e \]

\text{Bugey}

\text{NEOS}

\text{DANSS *}

\text{PROSPECT}
IsoDAR @ KamLAND: as a definitive $\nu_s$ search

- $5\sigma$ experiment for allowed regions
- Distinguish between models
IsoDAR: Isotope Decay-At-Rest
## 5 years @ KamLAND

<table>
<thead>
<tr>
<th></th>
<th>KamLAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector</td>
<td>16.1 m</td>
</tr>
<tr>
<td>Distance between face of target and center of detector</td>
<td>897 metric tons</td>
</tr>
<tr>
<td>Fiducial mass</td>
<td>6.5 m</td>
</tr>
<tr>
<td>Fiducial radius</td>
<td>13 m</td>
</tr>
<tr>
<td>Total detector radius</td>
<td>92%</td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>12 cm/√E (MeV)</td>
</tr>
<tr>
<td>Vertex resolution</td>
<td>6.4%/√E (MeV)</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>3 MeV</td>
</tr>
<tr>
<td>Visible energy threshold (IBD and $\bar{\nu}_e$-electron)</td>
<td>$8.2 \times 10^5$</td>
</tr>
<tr>
<td>IBD event total</td>
<td>2600</td>
</tr>
<tr>
<td>$\bar{\nu}_e$-electron event total</td>
<td></td>
</tr>
<tr>
<td>Expected $\bar{\nu}_e$ disappearance sensitivity</td>
<td>$\sin^2 2\theta_{\text{new}} &gt; 0.005$ @ $\Delta m^2 = 1\text{eV}^2$</td>
</tr>
<tr>
<td>Expected $\sin^2 \theta_W$ 1σ precision</td>
<td>3.2%</td>
</tr>
</tbody>
</table>
5 years @ KamLAND

| Accelerator | 60 MeV/amu of H$_2^+$ |
| Beam Current | 10 mA of protons on target |
| Beam Power (CW) | 600 kW |
| Duty cycle | 90% |
| Protons/year of live time | $1.97 \times 10^{24}$ |
| Run period | 5 years |
| Live time | 5 years \times 0.90 = 4.5 years |
| Target | 5 years |
| Sleeve diameter and length | 9$^9$Be with FLiBe sleeve (99.995% pure $^7$Li) |
| $\bar{\nu}$ source | 100 cm and 190 cm |
| Fraction of $^8$Li produced in target | $^8$Li $\beta$ decay (6.4 MeV mean energy flux) |
| $\bar{\nu}$ flux during 4.5 years of live time | 10% |
| $\bar{\nu}$ flux uncertainty | $1.3 \times 10^{23}$ $\bar{\nu}_e$ |
| | 5% (shape-only is also considered) |
RFQ – Direct Injection Project (RFQ-DIP)

- $H_2^+$ to reduce space-charge effects
- RFQ for bunching, sorting, accelerating
- Inflector for axial injection

$H_2^+$ ion source

Spiral inflector and central region
$H_2^+$ production

- Hot tungsten filament ionizes hydrogen molecules
- Plasma is confined by SmCo magnets
- Small aperture allows ions to drift into extraction system
- Current output 35 mA/cm$^2$ (Sufficient for IsoDAR)
MIST-1
Extraction system
RFQ: 4-vane, split-coaxial design
RFQ Simulations

Re-bunching cell

- w/ rebuncher
- w/o re-buncher

Graph:
- E / 1000 [rel]
- Length [mm]

Graph 2:
- Divergence [mrad]
- Beam size [cm]
- 32.8 MHz phase [degree]
Spiral Inflector

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode voltages</td>
<td>±12</td>
<td>kV</td>
</tr>
<tr>
<td>Input energy</td>
<td>70</td>
<td>keV</td>
</tr>
<tr>
<td>Electrode width</td>
<td>1.0</td>
<td>cm</td>
</tr>
<tr>
<td>Gap distance</td>
<td>1.8</td>
<td>cm</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Tilt angle</td>
<td>27</td>
<td>deg</td>
</tr>
</tbody>
</table>
Spiral inflector simulation

Kinetic energy [keV]
Central region

- Collimators to escape halo particles
- VP inserts for vertical focusing

INFN-Catania
Central region

- Preliminary study by AIMA Developpement
- RFQ-DIP: 1 MeV cyclotron
Cyclotron extraction

- Septum at last turn for $H_2^+$ extraction

- Use stripper foil to minimize septum activation

- Second foil to transport protons in MEBT
IsoDAR $\bar{\nu}_e$ production

• Protons impinge on $^9$Be target producing neutrons

• Surrounding $^7$Li sleeve captures neutrons producing $^8$Li

• $^8$Li $\beta$-decays yielding a localized, isotropic $\bar{\nu}_e$ source with known energy distribution
Concurrent research for IsoDAR

• Target designed for high power beam

• Injection of Li-Be mixture into sleeve pressure vessel

• Graphite, steel, concrete for neutron shielding
Isotope production

• ~50 μA of protons extracted to protect septum
• Up to 4 stripping locations possible
• Protons can be used to produce medical isotopes
• Or also build machine dedicated to isotope production
Imaging: $^{68}$Ge/$^{68}$Ga

- $^{69}$Ga/$^{71}$Ga + p $\rightarrow$ $^{68}$Ge $\rightarrow$ $^{68}$Ga
- Similar uses as $^{99}$Mo $\rightarrow$ $^{99m}$Tc
- Longer parent half-life: 270 days vs. 66 hours
- Shorter emitter half-life: 68 minutes vs. 6 hours
- $1000 / mCi$ of $^{68}$Ga
- IsoDAR $\rightarrow$ 50 Ci / week

Image from: Semantic Scholar
Therapy: $^{225}$Ac

- $p + ^{229}$Th $\rightarrow ^{225}$Ac $\rightarrow 4\alpha + ^{209}$Bi
- Current targets $^{226}$Ra from purified reactor waste
- BLIP, LANCE at 100 $\mu$A $\rightarrow$ 60x world supply
- $1300 / mCi$
- IsoDAR at 10 mA $\rightarrow$ 200 mCi/hr

Medical isotopes with IsoDAR: [https://arxiv.org/abs/1807.06627](https://arxiv.org/abs/1807.06627)
Nature Reviews Physics: DOI : 10.1038/s42254-019-0095-6NATREVPHYS-19-343V1
DAEδALUS

- IsoDAR as injector for 800 MeV cyclotron
- Decay-at-rest pions as neutrino source
- Make three of these setups

200+ kiloton detector
\( \delta_{CP} \) measurement

- \( \pi^+ \) decay-at-rest produces: \( \bar{\nu}_\mu, \nu_\mu \)

- Sensitive to \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \) oscillation wave

- 3 accelerators at different distances
Summary

• IsoDAR can definitively answer the $\nu_s$ question with 5 years of runtime at KamLAND

• RFQ-DIP is developing technology for 10 mA, 60 MeV cyclotrons

• Target, sleeve, and shielding research is well underway

• IsoDAR cyclotrons have other potential uses such as $DAE\deltaALUS$ and medical isotope production
Resources

- IsoDAR: https://www.nevis.columbia.edu/daedalus/docs/publications.html

Acknowledgements
Cyclotron design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion accelerated</td>
<td>$\text{H}_2^+$</td>
</tr>
<tr>
<td>Max Energy</td>
<td>60 MeV/amu</td>
</tr>
<tr>
<td>Extraction radius</td>
<td>1.99 meters</td>
</tr>
<tr>
<td>Average magnetic field</td>
<td>1.16 tesla</td>
</tr>
<tr>
<td>Number of sectors</td>
<td>4</td>
</tr>
<tr>
<td>RF frequency</td>
<td>32.8 MHz</td>
</tr>
<tr>
<td>Accel. Voltage</td>
<td>70 – 240 kV</td>
</tr>
<tr>
<td>$\Delta E$/turn</td>
<td>(ave) 1.7 MeV</td>
</tr>
<tr>
<td>Turns</td>
<td>95</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>6.2 meters</td>
</tr>
<tr>
<td>Iron weight</td>
<td>450 tons</td>
</tr>
</tbody>
</table>

Segmentation

• Designed for assembly within Kamioka mine
• Size limited by mining tunnels
• Weight restrictions due to transportation
Split-coil design

- Coils come in two pieces
- No winding in mine
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (nominal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma chamber length</td>
<td>6.5 cm</td>
</tr>
<tr>
<td>Plasma chamber diameter</td>
<td>15 cm</td>
</tr>
<tr>
<td>Permanent magnet material</td>
<td>Sm$<em>2$Co$</em>{17}$</td>
</tr>
<tr>
<td>Permanent magnet strength</td>
<td>1.05 T on surface</td>
</tr>
<tr>
<td>Front plate magnets</td>
<td>12 bars (star shape)</td>
</tr>
<tr>
<td>Radial magnets</td>
<td>12 bars</td>
</tr>
<tr>
<td>Back plate magnets</td>
<td>4 bars, 3 parallel rows</td>
</tr>
<tr>
<td>Front plate cooling</td>
<td>embedded steel tube</td>
</tr>
<tr>
<td>Back plate cooling</td>
<td>embedded copper tube</td>
</tr>
<tr>
<td>Chamber cooling</td>
<td>water jacket</td>
</tr>
<tr>
<td>Water flow (both)</td>
<td>(1.5 l/min)</td>
</tr>
<tr>
<td>Filament feedthrough cooling</td>
<td>air cooled heat sink</td>
</tr>
<tr>
<td>Filament material</td>
<td>98% W, 2% Th</td>
</tr>
<tr>
<td>Filament diameter</td>
<td>$\approx$ 1.5 mm</td>
</tr>
<tr>
<td>Discharge voltage</td>
<td>max. 150 V</td>
</tr>
<tr>
<td>Discharge current</td>
<td>max. 24 A</td>
</tr>
<tr>
<td>Filament heating voltage</td>
<td>max. 8 V</td>
</tr>
<tr>
<td>Filament heating current</td>
<td>max. 100 A</td>
</tr>
</tbody>
</table>
Table 5: RFQ cavity geometrical parameters. Select parameters are also shown in Figure 8.

<table>
<thead>
<tr>
<th>Parameter (description)</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (cavity radius)</td>
<td>120.00</td>
<td>mm</td>
</tr>
<tr>
<td>r (electrode radius)</td>
<td>9.30</td>
<td>mm</td>
</tr>
<tr>
<td>d (electrode distance)</td>
<td>18.60</td>
<td>mm</td>
</tr>
<tr>
<td>g1 (gap vert. vane ↔ end plate)</td>
<td>25.62</td>
<td>mm</td>
</tr>
<tr>
<td>g2 (gap horz. vane ↔ end plate)</td>
<td>8.35</td>
<td>mm</td>
</tr>
<tr>
<td>p (vane skirt position)</td>
<td>60.0</td>
<td>mm</td>
</tr>
<tr>
<td>l1 (horizontal vane length)</td>
<td>1353.07</td>
<td>mm</td>
</tr>
<tr>
<td>l2 (vertical vane length)</td>
<td>1370.34</td>
<td>mm</td>
</tr>
<tr>
<td>L (cavity length)</td>
<td>1378.69</td>
<td>mm</td>
</tr>
<tr>
<td>t (cavity thickness)</td>
<td>20.0</td>
<td>mm</td>
</tr>
<tr>
<td>s (vane skirt max. thickness)</td>
<td>30.0</td>
<td>mm</td>
</tr>
<tr>
<td>h (vane skirt min. thickness)</td>
<td>10.0</td>
<td>mm</td>
</tr>
</tbody>
</table>
Rebunching cell

• Longitudinal focusing at end of RFQ
• Adjustable parameter in design
RFQ longitudinal E-field

![Graph showing RFQ longitudinal E-field with and without rebuncher](image)

- w/ rebuncher
- w/o re-buncher

Re-bunching cell
Beam dynamics with re-buncher

- w/o re-buncher: ±20 deg, 44.57%
- w/ re-buncher: ±2%, 55.17%
Rebunching cell effects

Without rebunching

With rebunching
Rebunching cell effects

Without rebunching

With rebunching
Target is the <2cm thick circular dome of Be here.

Boiling and forced convection happen at this surface.
Production in target and sleeve

![Graph showing isotopes and proton counts for 1.7 cm Be target and FLiBe sleeve]
\bar{\nu} \text{ production}

Figure 4.28: Distributions for the antineutrino \( \bar{\nu} \) production points in the IsoDAR target.