Low Energy Accelerator Neutrino Experiments

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Low Energy Accelerator Neutrino Experiments are DAEδALUS-like experiments.

What are the DAEδALUS-like experiments? Those that use decay-at-rest sources of (anti)neutrinos i.e. pion/muon decay-at-rest or isotope decay-at-rest.

**Pion/muon decay-at-rest**

Search for \( \overline{\nu}_\mu \rightarrow \overline{\nu}_e \)

Protons \( \rightarrow \pi^+ \) (stop) \( \rightarrow \mu^+ + \nu_\mu \)

\( \mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu \)

\( \rightarrow \pi^- \) (captures before decay)

**Isotope decay-at-rest**

Example: \(^8\text{Li}\) decay

\(^8\text{Li} \rightarrow ^8\text{Be} + e^- + \overline{\nu}_e \)

But only a few isotopes have endpoints > 3MeV above environmental backgrounds.
The DAR beams can be detected via Inverse Beta Decay

• Scintillator or Gd-doped water detector
• prompt positron signal followed by neutron capture
• $E_{\nu_e} \cong E_{\text{prompt}} + 0.78 \text{ MeV}$
DAEδALUS approach to determine $\delta_{CP}$

- Use $\bar{\nu}_\mu \to \bar{\nu}_e$ and exploit the L/E dependence in absolute event rates.

Oscillation probability $P(\nu_\mu \to \nu_e)$ in a vacuum (modified in matter):

$$P = \frac{1}{2} \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{31}$$

$$+ \sin \delta \left( \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \right) \sin^2 \Delta_{31} \sin \Delta_{21}$$

$$+ \cos \delta \left( \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \right) \sin \Delta_{31} \cos \Delta_{31} \sin \Delta_{21}$$

$$+ \left( \cos^2 \theta_{23} \sin^2 2\theta_{12} \right) \sin^2 \Delta_{21}.$$}

Want to find If $\delta_{CP} \neq 0$

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

Details: arXiv:1006.0260

$$\Delta_{ij} = \Delta m^2_{ij} L / 4E_\nu$$

-Different from conventional long-baseline neutrino beam approach.
Proton Source for DAEδDALUS: Cyclotron System

- Under Development.

H$_2^+$ Ion Source

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.
Osc. maximum at ~40 MeV

Constrains rise of probability wave

Constrains Initial flux

DAEδALUS Concept

$\delta_{CP} = \pi/2$

$= 0$

Use a planned >50 kton detector (LENA, HyperK, MEMPHYS…)

Kilometers
Three identical pion/muon decay-at-rest at three different distances. Only need to know relative normalization.
-Use this low-energy pure $\bar{\nu}_e$ source to search for sterile neutrinos (as a part of staged approach).

-Potential locations: KamLAND, SNO+, Daya BayII.

Details: arXiv:1205.4419
General Instrumentation Issues for DAEδALUS/isoDAR

-The detectors need to be underground because we don't have beam timing to reject cosmic rays (use CW mode of operation).
The idea of pairing with an underground detector presents unique issues for beams.

-Proximity – DAR sources are isotropic, though you are helped by a signal that rises with L

\[ P = \sin^2 2\theta \ \sin^2(1.27\Delta m^2 (L/E)) \]

Nevertheless, these are 10 m to few km experiments

-Space – if the accelerator goes underground, space is a limitation.

-Infrastructure – though many mines and tunnels have a lot of power and water, MW of beam will be an issue.

-Radiation – always an issue with beams, but even harder when not located at an accelerator laboratory site!
Detector Instrumentation Issues

Water Cerenkov Detector for DAEδALUS:

-For water Cerenkov detector one needs similar PMT coverage as for the solar studies (~40%, or more) in order to see the Cerenkov light from the electrons from the Gd photon Compton scattering.

-IBD interactions are identified via a coincidence signal: IBD $\bar{\nu}_e + p \rightarrow e^+ + n$ process. Prompt signal is from $e^+$’s Cerenkov ring. The second signal is from n capture on proton.

-The signal from n capture on p is a single 2.2 MeV gamma, and is usually too faint to be efficiently observed in a large Cerenkov detector => needs doping water with gadolinium (Gd) to see the Cerenkov light from the electrons from the Gd photon (total ~8 MeV) Compton scattering, and provide a high capture rate and a short n capture time (~30 μs). SK studies indicate that multiple photons with a total ~8MeV energy may be observed with 67% efficiency, with 40% PMT coverage.

-Related to the PMT-coverage are issues of energy threshold and energy resolution. For example, when extracting $\nu_e + e^- \rightarrow \nu_e + e^-$ sample with $E_\nu>10$ MeV one introduces a 1% error on flux normalization assuming 2.1% energy resolution in SK example.

-Examples of proposed water Cerenkov detectors are SK with Gd, Hyper-K, MEMPHYS.
Detector Instrumentation Issues

Hyper-Kamiokande detector, arXiv:1109.3262

<table>
<thead>
<tr>
<th>Detector type</th>
<th>Ring-imaging water Cherenkov detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Candidate site</td>
<td>Tohohura mine</td>
</tr>
<tr>
<td>Address</td>
<td>Kamioka town, Gifu, JAPAN</td>
</tr>
<tr>
<td>Lat.</td>
<td>36°21′08.928″N</td>
</tr>
<tr>
<td>Long.</td>
<td>137°18′49.668″E</td>
</tr>
<tr>
<td>Alt.</td>
<td>508 m</td>
</tr>
<tr>
<td>Overburden</td>
<td>688 m rock (1,750 m water equivalent)</td>
</tr>
<tr>
<td>Cosmic Ray Muon flux</td>
<td>1.0 × 10^{-6} sec^{-1}cm^{-2}</td>
</tr>
<tr>
<td>Off-axis angle for the J-PARC ν</td>
<td>2.5° (same as Super-Kamiokande)</td>
</tr>
<tr>
<td>Distance from the J-PARC</td>
<td>295 km (same as Super-Kamiokande)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Detector geometry</th>
<th>Total Volume</th>
<th>0.98 Megaton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Volume (fiducial Volume)</td>
<td>0.74 (0.56) Megaton</td>
<td></td>
</tr>
<tr>
<td>Outer Volume</td>
<td>0.2 Megaton</td>
<td></td>
</tr>
<tr>
<td>Photo-multiplier Tubes Inner detector</td>
<td>90,000 20-inch φ PMTs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20% photo-coverage</td>
<td></td>
</tr>
<tr>
<td>Outer detector</td>
<td>25,000 8-inch φ PMTs</td>
<td></td>
</tr>
<tr>
<td>Water quality</td>
<td>Light attenuation length</td>
<td>&gt; 100 m @ 400 nm</td>
</tr>
<tr>
<td></td>
<td>Rs concentration</td>
<td>&lt; 1 mBq/m³</td>
</tr>
</tbody>
</table>

**Resolution or Efficiency**

<table>
<thead>
<tr>
<th></th>
<th>Resolution @ 500MeV/c</th>
<th>28 cm (electron) / 23 cm (muon)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>@ 5GeV/c</td>
<td>27 cm (electron) / 32 cm (muon)</td>
</tr>
<tr>
<td>Particle ID @ 500MeV/c</td>
<td></td>
<td>98.5 ± 0.6 % (electron) / 99.0 ± 0.2 % (muon)</td>
</tr>
<tr>
<td></td>
<td>@ 5GeV/c</td>
<td>99.8 ± 0.2 % (electron) / 100% (muon)</td>
</tr>
<tr>
<td>Momentum resolution @ 500MeV/c</td>
<td></td>
<td>5.6 % (electron) / 3.6 % (muon)</td>
</tr>
<tr>
<td></td>
<td>@ 5GeV/c</td>
<td>2.0 % (electron) / 1.6 % (muon)</td>
</tr>
<tr>
<td>Electron tagging from 500MeV/c μ⁺ decays</td>
<td></td>
<td>98 %</td>
</tr>
<tr>
<td></td>
<td>from 5GeV/c μ⁺ decays</td>
<td>58 %</td>
</tr>
<tr>
<td>J-PARC νμ signal efficiency</td>
<td></td>
<td>64 % (nominal) / 50 % (tight)</td>
</tr>
<tr>
<td>J-PARC νμ CC background rejection</td>
<td></td>
<td>&gt;99.9 %</td>
</tr>
<tr>
<td>J-PARC νπ background rejection</td>
<td></td>
<td>95 % (nominal) / 97.6 % (tight)</td>
</tr>
<tr>
<td>p → e⁺ + π⁰ efficiency (w/ π⁰ intra-nuclear scattering)</td>
<td></td>
<td>45 %</td>
</tr>
<tr>
<td>atmospheric ν background</td>
<td></td>
<td>1.6 events/Mton/year</td>
</tr>
<tr>
<td>p → ν + K⁺ efficiency by prompt γ tagging method</td>
<td></td>
<td>7.1 %</td>
</tr>
<tr>
<td>atmospheric ν background</td>
<td></td>
<td>1.6 events/Mton/year</td>
</tr>
<tr>
<td>p → ν + K⁺, K⁺ → π⁺ + π⁰ efficiency</td>
<td></td>
<td>6.7 %</td>
</tr>
<tr>
<td>atmospheric ν background</td>
<td></td>
<td>6.7 events/Mton/year</td>
</tr>
</tbody>
</table>

| Vertex resolution for 10 MeV electrons | 90 cm |
| Angular resolution for 10 MeV electrons | 30° |
| Energy resolution for 10 MeV electrons | 20% |
Detector Instrumentation Issues

Liquid Scintillator Detector for DAEδALUS:

- An optimal detector would be LSND-like (lightly doped scintillator). In this case the experiment may use about a factor of 3 less tonnage than water because there is no invisible muon background (from atmospheric muon neutrinos). In the same time one can reconstruct Cerenkov rings which is a benefit.

- Example of planned large liquid scintillator detector is LENA (highly doped scintillator for enhanced light yield). The detector is optimized for low energy neutrinos (geo-neutrinos and astro-physical neutrinos) it would be a highly efficient (~90%) for detection of 2.2 MeV gamma ray from IBD \( \nu_e + p \rightarrow e^+ + n \) process. In addition one may use it for an efficient detection of process \( \nu_e + ^{12}\text{C} \rightarrow e^- + ^{12}\text{N}_{\text{g.s.}} \) process (important for a short-baseline of ~10m accelerator based experiment).
Detector Instrumentation Issues

- Proposed LENA (Low Energy Neutrino Astronomy) detector, see arXiv:1104.5620.

**Cavern**
- height: 115 m, diameter: 50 m
- shielding from cosmic rays: \( \sim 4,000 \) m.w.e.

**Muon Veto**
- plastic scintillator panels (on top)
- Water Cherenkov Detector
- 3,000 phototubes
- 100 kt of water
- reduction of fast neutron background

**Steel Cylinder**
- height: 100 m, diameter: 30 m
- 70 kt of organic liquid
- 30,000 – 50,000 phototubes

**Buffer**
- thickness: 2 m
- non-scintillating organic liquid shielding from external radioactivity

**Nylon Vessel**
- separating buffer liquid and liquid scintillator

**Target Volume**
- height: 100 m, diameter: 26 m
- 50 kt of liquid scintillator
Detector Instrumentation Issues

IsoDAR experiment (intermediate step in DAEDALUS program):
- Liquid scintillator is optimal. Gd doping would be an addition but isn't necessary for a
detector a high light yield with low background.
- Prosed detector (LENA) would do the job, but also existing detectors such as KamLAND
would be optimal.

\[ \nu_e \xrightarrow[\text{e}^+]{p, n} \]

Inverse Beta Decay Permits
Well- reconstructed \( E_\nu \)
is essential, …

\[ P = \sin^2 2\theta \sin^2(1.27\Delta m^2 (L/E)) \]

... along with spatial resolution.

<table>
<thead>
<tr>
<th>Detector</th>
<th>KamLAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial mass</td>
<td>897 tons</td>
</tr>
<tr>
<td>Target face to detector center</td>
<td>16 m</td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>92%</td>
</tr>
<tr>
<td>Vertex resolution</td>
<td>12 cm/\sqrt{E} (MeV)</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>6.4%/\sqrt{E} (MeV)</td>
</tr>
<tr>
<td>Prompt energy threshold</td>
<td>3 MeV</td>
</tr>
<tr>
<td>IBD event total</td>
<td>( 8.2 \times 10^5 )</td>
</tr>
<tr>
<td>( \bar{\nu}_e )-electron event total</td>
<td>7200</td>
</tr>
</tbody>
</table>

The next generation of oscillation experiments
Should demonstrate the oscillation “wave”
Detector Instrumentation Issues

-IsoDAR experiment at KamLAND site

Letter of Collaboration

IsoDAR provides a source of neutrinos that expands the physics reach of a scintillator-based detector like KamLAND. The sensitivity to sterile neutrinos is particularly motivating. The KamLAND Experiment has exchanged information with the IsoDAR group already, and will continue providing input to enable the development of a Baseline Design Report.

Sincerely,

Kunio Inoue
Research Center for Neutrino Science,
Tohoku University
-IsoDAR paper appeared in PRL and it was chosen as a “highlight”.

Synopsis: In Search of Sterile Neutrinos

Proposal for an Electron Antineutrino Disappearance Search Using High-Rate $^{8}$Li Production and Decay


Published October 4, 2012
Conclusion

- A brief overview of the low energy accelerator experiments i.e. those that use either pion/muon decay-at-rest or isotope decay-at-rest is provided.
- DAEδALUS/isoDAR are examples of the concept.
- Other DAR (decay-at-rest) concepts and detectors: mostly short-baseline sterile neutrino searches. Examples are OscSNS at Oak Ridge and an DAR accelerator at Gd-loaded SK.

- All detectors for the low energy accelerator experiments require:
  - large detector mass (~1kT up to ~1MT).
  - high PMT coverage (translates into enhanced energy resolution and optimal reconstruction capabilities for identifying signal and rejecting backgrounds).
  - reasonable low cost (dictates use of water or liquid scintillator equipped with photo-multiplier tubes).

- These requirements are the major challenges: getting an efficient massive detector requires effective light collection so the advances in the area of the photon-detection are expected to make performance/cost ratio more optimal.
Backup Slides
Neutrino Beam Production Time Sequence

1.5 km Accelerator
- 1.5 km Accelerator
- 100µs
- 400µs
- Beam Off
- 100µs
- 400µs
- Beam Off
- 100µs

8 km Accelerators
- 8 km Accelerators
- 100µs
- 400µs
- 100µs
- 400µs
- 100µs

20 km Accelerators
- 20 km Accelerators
- 100µs
- 400µs
- 100µs
- 400µs
- 100µs

Constrains Initial flux
Constrains rise of probability wave
Osc. maximum

One needs to know which source is providing the beam. So they have to turn on/off.
The duty factor is flexible, But beam-off time is needed.
How can we know the normalization?

Along with the signal:

We will also have scattering from electrons:

The $\nu$-$e$ cross section is known to $<1\%$ due to precision measurements of weak interaction parameters.

Extract normalization from $\nu$-$e$ rate.
Where can one run such beam? Large proton-based detectors w/ neutron detection exist

These detectors are deep underground, So reducing cosmic background by duty factor will not be necessary.
Other DAR (decay-at-rest) concepts and detectors: mostly short-baseline sterile neutrino Searches. Examples are OscSNS at Oak Ridge and an DAR accelerator at Gd-loaded SK.

-OscSNS experiment, see arXivL1211.5199.
-as mentioned already neutrinos from pion/muon decay-at-rest with well known spectrum provide a source for an oscillation search.
-in past LSND experiment deployed this concept in $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation search at a short baseline (~30 m) proving L/E~1 m/MeV, and resulted in 3.8σ signal excess consistent with $\bar{\nu}_e$ appearance.

-Spallation Neutron Source at Oak Ridge National Laboratory is 1MW pion and muon DAR source. It may be combined with a LSND-style detector to directly probe the LSND signal excess with lower background and higher beam power.

-Such experiment could reconstruct appearance and disappearance oscillation waves across a long detector.
-OscSNS detector with ~3000 8-inch phototubes, based on the LSND and MiniBooNE detectors, can be built for ~ $20M (or < $20M if the MiniBooNE oil and phototubes are reused).
Detector Instrumentation Issues

-Potential oscSNS detector shares common neutrino detector issues: need large detector mass, high PMT coverage (enhanced energy resolution and reconstruction capabilities), low cost.

~800 tons, 25% PMT coverage

Design still being finalized
- 8 m diameter (x 20 m length)
- LS (+Gd?)
- +b-PBD?

Hamamatsu R5912 assumed 60 rows (6°) of 54 each PMTs located 14” (.356m) center to center. Tube center located 3.4m radially from detector tank center line (3240 tubes)