New approach to antineutrino from muon decay at rest

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Interaction of a few GeV protons with the target produces charged pions in addition to the spallation neutrons

\[ p + X \rightarrow \pi^\pm + X' \]

\( \pi^- \) & daughter \( \mu^- \) are absorbed in thick, high-Z target

\( \pi^+ \) are brought to rest in a high-Z beam stop

\( \pi^+ \) decay produces mono-energetic 29.8 MeV \( \nu_\mu \) & \( \mu^+ \)

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]

\( \mu^+ \) decays at rest, providing Michel spectrum

\[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]
Provides an equal, high-intensity, isotropic, DAR $\nu_\mu$, $\nu_e$ and $\bar{\nu}_\mu$ beam with tiny $\bar{\nu}_e$ contamination ($\sim 10^{-4}$ to $10^{-5}$)
# DAR Source Facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>Power</th>
<th>Proton energy</th>
<th>Time structure</th>
<th>Repetition rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAMPF (USA)</td>
<td>56 kW</td>
<td>0.8 GeV</td>
<td>Continuous</td>
<td>N/A</td>
</tr>
<tr>
<td>ISIS (UK)</td>
<td>160 kW</td>
<td>0.8 GeV</td>
<td>200 ns</td>
<td>50 Hz</td>
</tr>
<tr>
<td>DAEδALUS (USA)</td>
<td>1 - 5 MW</td>
<td>0.8 GeV</td>
<td>Continuous</td>
<td>N/A</td>
</tr>
<tr>
<td>SNS (USA)</td>
<td>&gt; 1 MW</td>
<td>1 GeV</td>
<td>380 ns</td>
<td>60 Hz</td>
</tr>
<tr>
<td>JSNS (Japan)</td>
<td>1 MW</td>
<td>3 GeV</td>
<td>1 µs</td>
<td>25 Hz</td>
</tr>
<tr>
<td>SPL (CERN)</td>
<td>4 MW</td>
<td>3.5 GeV</td>
<td>0.76 ms</td>
<td>50 Hz</td>
</tr>
<tr>
<td>ESS (Sweden)</td>
<td>5 MW</td>
<td>1.3 GeV</td>
<td>2 ms (1.4 µs)</td>
<td>17 Hz (50 Hz)</td>
</tr>
</tbody>
</table>

Past, present, and future DAR Source Facilities in different regions of the world


- **LSND** (167 tons) at 30 m from LAMPF in Los Alamos
- **KARMEN** (65 tons) at 17.6 m from ISIS at RAL

Sanjib K. Agarwalla, 2011 Moriond – EW Session, Italy, 19/03/11
Main technological challenge is the production of a sufficiently intense proton beam with few GeV energy.

Superconducting Linacs: clean & proven technology, can provide multi-MW beams, very expensive & size is large.

Conrad and Shaevitz suggested that new low-cost, high-power proton cyclotrons can deliver multi-MW beams at a cost of 5% of a conventional proton accelerator.


DAEδALUS collaboration performing an extensive R&D for a new DAR neutrino source for large Gd-doped water Cherenkov detector at Homestake mine aka DUSEL.

Assume that a multi-MW proton beam is affordable

Key for high-intensity DAR neutrino source

- Test anomalies: LSND, MiniBooNE, Gallium...
  - High $\Delta m^2$ oscillation ($L \sim 20 - 50 \text{ m}$)

- Study CP violation in active neutrinos
  - Oscillation at atm. $\Delta m^2$ ($L \sim 20 \text{ km}$)

- EW precision physics ($\sin^2 \theta_W$ measurement)

- Searches for non-standard neutrino interactions

- Coherent $\nu$-nucleus scattering ($^{12}\text{C}$, $^{16}\text{O}$, $^{40}\text{Ar}$)
  - Supernova $\nu$ spectrum overlaps with DAR $\nu$
  - Calibration of $\nu$ detectors for supernova
Where do we stand today?

**LSND**: \( L = 30 \) m, \( < E_{\nu_\mu} > = 40 \) MeV

- 3.8 \( \sigma \) excess of \( \bar{\nu}_e \) events in a beam of \( \bar{\nu}_\mu \)

**MiniBooNE**: \( L = 541 \) m, \( < E_{\nu_\mu,\bar{\nu}_\mu} > = 700 \) MeV

- No oscillation in the \( \nu \)-mode for energies above 475 MeV
- An unexplained 3 \( \sigma \) excess of \( \nu_e \) events in the \( \nu \)-mode below 475 MeV
- A 2.8 \( \sigma \) excess of \( \bar{\nu}_e \) events in the anti-neutrino mode above 475 MeV, consistent with LSND

- \( L/E \) ratio very similar between LSND and MiniBooNE

- Both points to a \( \Delta m^2 \) of the order 0.1 – 10 eV\(^2\)
MiniBooNE is not conclusive w.r.t. LSND

Simple increase in statistics would not resolve the issue

How to address this problem?

We suggest to perform a modern version of LSND

LSND reloaded

SKA, Patrick Huber, arXiv:1007.3228
Place DAR source 20m away from the surface of SK, should provide sufficient shielding against neutrons

$\bar{\nu}_\mu$ from DAR source will oscillate into $\bar{\nu}_e$ & will be detected via inverse beta decay in Gd doped SK

Useful coincidence tag between the prompt positron and the delayed neutron capture in a Gd doped WC detector

Event rates will be very high in SK due to large fiducial mass of 22.5 kt vs. 167 t in LSND

300 kW proton beam power is sufficient to have $4 \times 10^{21}$ $\bar{\nu}_\mu$ per year from each cyclotron

Intrinsic $\bar{\nu}_e$ contamination small, $4 \times 10^{-4}$ (LSND value)
Gd doped Super-Kamiokande

- Gd doping allows efficient detection of neutron capture ($\Delta T \sim 30 \mu s, 8 \text{ MeV } \gamma$). 67% IBD detection efficiency.
- SK is deep (2,700 mwe) and thus has only very small cosmic background rate compared to LSND (120 mwe).
- In SK, the large dimensions of the fiducial volume a cylinder of 14 m radius with a height of 36 m allow to observe the characteristic L dependence of oscillation.
- Beam stop size 0.5 m & vertex resolution in SK 0.75 m added in quadrature yields $\Delta x = 0.9 \text{ m}$. We use 1 m bins.
- Energy range: 20 - 52 MeV with $\sigma(E) = 50\% \sqrt{E/\text{MeV}}$
- Baseline range: 20 - 56 m
- 38 equally size $L/E$ bins ranging $0.4 - 2.8 \text{ m MeV}^{-1}$
L & L/E pattern in SK

2 flav: $\sin^2 2\theta = 10^{-3}$, $\Delta m^2 = 2 \text{eV}^2$, $L^{osc} = 49.6 \text{ m (40 MeV)}$

- Black: Background (765), Red: Signal (1856 events)
- $L/E$ dependence: powerful handle to reject background and to cancel systematic errors among various bins
Sensitivity to Sterile neutrinos

We cover the whole 99% CL region from both MiniBooNE and LSND at more than 5σ CL in one year.

If a signal will be seen, we will know whether it is oscillation or something else from L-dependence.

It will return the final verdict on LSND.
Leptonic CP violation

The discovery of CP violation in the lepton sector would constitute a smoking gun for leptogenesis to explain the baryon asymmetry of the Universe

Can we study CPV using DAR neutrino sources?

The effort of DAEδALUS collaboration

arXiv:0912.4079, 1006.0260, 1008.4967, 1012.4853

LBNE and DAR neutrino source

SKA, Huber, Link, Mohapatra, arXiv:1005.4055
\[ P = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{13} \]
\[ + \sin \delta_{CP} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin^2 \Delta_{13} \sin \Delta_{12} \]
\[ + \cos \delta_{CP} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin \Delta_{13} \cos \Delta_{13} \sin \Delta_{12} \]
\[ + \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta_{12} \]

where \( \Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E_\nu} \)

- Want to measure \( \delta_{CP} \) but \( \theta_{13} \) and \( \text{sgn}(\Delta m_{31}^2) \) not known
- \( 1.27 \frac{\Delta m_{31}^2 L}{E} \sim \frac{\pi}{2} \) at \( E = 40 \text{ MeV}, L = 20 \text{ km} \) (Osc. max)
- \( 1.27 \frac{\Delta m_{31}^2 L}{E} \sim \frac{\pi}{4} \) at \( E = 40 \text{ MeV}, L = 10 \text{ km} \) (Off max)
- \( 1.27 \frac{\Delta m_{31}^2 L}{E} \sim 0 \) at \( E = 40 \text{ MeV}, L = 1.5 \text{ km} \) (flux)

Use the \( L/E \) dependence of the interference terms
DAE$\delta$ALUS setup

DAR $\bar{\nu}_\mu$ beam + 300 kt Gd-doped water detector @ DUSEL
No. of Cyclotrons: 10 (20 km), 4 (8 km), 2 (1.5 km)

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10 years run, NH, $\sin^2 2\theta_{13} = 0.04$, no matter effects
Signal to Background ratio is good at $L = 8$ and 20 km
Inner (outer) region is $1\sigma$ ($2\sigma$) assuming hierarchy is known

$[\delta_{cp} = x^\circ, \text{NH}]$ is equivalent to $[\delta_{cp} = (180 - x)^\circ, \text{IH}]$
What would happen if we combine \textit{DAE\textgreek{a}LUS + LBNE} experiment?

Why should we combine them?
Long Baseline Neutrino Experiment

- New, upgraded, intense wide band beam from FNAL towards 300 kt water Cerenkov detector at Homestake mine aka DUSEL at a distance of 1300 km

- LBNE has to run conventional neutrino (HFN) and anti-neutrino (HFA) beams based on the decay of horn focused pions to disentangle CP and matter effects

- Anti-neutrino run in a superbeam is difficult due to lower anti-neutrino production, lower detection cross-sections and large neutrino contamination in the anti-neutrino beam
New Approach

New Approach: DAR + HFN
LBNE: HFA + HFN

4 Proton Accelerators
1 MW, 1 GeV
Low-cost, High-power

DAR:
\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \]
20 – 55 MeV

20 km IBD

FNAL
Wide Band Beam
700 kW, 120 GeV
6.2 \times 10^{20} \text{ protons/year}

HFN:
\[ \nu_\mu \rightarrow \nu_e \]

HFA:
\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \]
0.5 – 6 GeV

1300 km CC QE

DUSEL
w/ Gd
100 – 300 kton

4 \times 10^{22} \text{ neutrinos/flavor/year/accelerator}

SKA, Huber, Link, Mohapatra, arXiv:1005.4055

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### Signal vs. Background

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$  Bkg  $$\nu_\mu \rightarrow \nu_e$$  Bkg

<table>
<thead>
<tr>
<th></th>
<th>DAR+HFN</th>
<th>hfa+hfn</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)</strong></td>
<td>1194</td>
<td>231</td>
</tr>
<tr>
<td><strong>(\nu_\mu \rightarrow \nu_e)</strong></td>
<td>217</td>
<td>158</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th></th>
<th>DAR+HFN</th>
<th>hfa+hfn</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)</strong></td>
<td>1532</td>
<td>766</td>
</tr>
<tr>
<td><strong>(\nu_\mu \rightarrow \nu_e)</strong></td>
<td>428</td>
<td>214</td>
</tr>
</tbody>
</table>

$$\sin^2 2\theta_{13} = 0.1, \quad \delta_{\text{CP}} = 0^\circ, \quad \text{NH and total 6 years run}$$

**DAR+HFN:** 6 years of *simultaneous* running of neutrinos and anti-neutrinos

**HFA+HFN:** 3 years of *consecutive* running of neutrinos and anti-neutrinos

**DAR+HFN:** *twice* the statistics in the neutrino mode and *five times* as much statistics with a five times better sig/bkg ratio in the anti-neutrino mode

SKA, Huber, Link, Mohapatra, arXiv:1005.4055

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**300 kton & NH**

\[ \delta_{cp} \text{ (true)} \]

\[ \sin^2 2\theta_{13} \text{ (true)} \]

\[ \sin^2 2\theta_{13} \text{ (true)} \]

**\( \theta_{13} \) discovery**

**MH discovery**

**CPV discovery**

SKA, Huber, Link, Mohapatra, arXiv:1005.4055

**Discovery reaches at 3 \( \sigma \) confidence level**

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Concluding Remarks

- A stopped pion source provides neutrino beams with energy of a few tens of MeV from pion and muon decay-at-rest
- A rich physics program can be accomplished with such a neutrino source
- Low-cost, multi-MW proton cyclotrons needed
- 300kW proton beam + Gd-doped SK can test LSND, MiniBooNE anomalies in one year at more than 5σ CL
- DAR neutrino sources together with LBNE can accelerate the discovery reach of CP violation

For applications in EW precision physics, see SKA, Patrick Huber, arXiv:1005.1254
Our proposed experiment will provide a $\simeq 0.24\%$ measurement of $\sin^2 \theta_W$

This configuration can be a natural part of the proposed physics program for DUSEL

Discovery reaches at 3 $\sigma$ confidence level

Discovery reaches at 3\(\sigma\) confidence level
CP fraction for which a discovery at $3\sigma$ confidence level is possible as a function of $\sin^2 2\theta_{13}(\text{true})$

CP fraction for which a discovery at $3\sigma$ confidence level is possible as a function of $\sin^2 2\theta_{13}^{\text{true}}$
Technologies explored

Linacs
- Cleanest of technologies,
  but there are issues of size and cost

Cyclotrons
- Compact Superconducting (proton) Cyclotron
- Stacked (proton) Cyclotron
- $\text{H}_2^+$ Cyclotron -- reduces many problems related to beam loss and extraction compared to other designs
Cyclotron Options

- PSI is best in the world
  - 590 MeV protons
  - 2.2 mA
  - 1.3 MW
Backup Slides

H$_2^+$ Ring Cyclotron
Promising Design from 1990’s

- Concept proposed by Carlo Rubbia ~1994
- Initial designs done by Luciano Calabretta, Catania
  - Reports in European Particle Accelerator Conference
    - Calabretta et al: PAC 99 & EPAC 2000
- 1 GeV, ~6 mA
- High rigidity for H$_2^+$
  - Superconducting magnets reduce consequences
- Clean extraction (via stripping)