High Current $\text{H}_2^+$ Cyclotrons for Neutrino Physics: The IsoDAR and DAEδALUS Projects

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Outline

• Neutrino oscillations and CP violation are very hot topics!
  – Background
  – Decay-at-rest (DAR) program
• The DAEδALUS experiment
  – Requirements
  – Cyclotron designs
• The IsoDAR experiment
  – Requirements
  – Cyclotron designs
  – Siting options
• Status and ongoing developments
Background...

- Neutrino representations in 2 sets of eigenstates:
  - Flavor ($\nu_e$, $\nu_\mu$, $\nu_\tau$) related to production reaction
  - Mass ($\nu_1$, $\nu_2$, $\nu_3$)
- Coupling between determined by “mixing angles”
- Example (2-state system):

\[
\begin{pmatrix}
\nu_\theta \\
\nu_\mu
\end{pmatrix}
= \begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]
Background...

- 3-state system coupling is a “simple” extrapolation

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

Flavor eigenstates

Mass eigenstates
Background...

- $U_{ij}$ are sin/cos function of mixing angles
  - All now measured
  - $\theta_{13}$ latest to be measured
- Some elements also contain CP violation terms $e^{i\delta}$
Oscillations (for 2-state system)

\[ P_{\text{osc}} = \sin^2 2\theta \sin^2 (1.27 \Delta m^2 L/E) \]

- \( P \): oscillation probability
- \( \sin^2 2\theta \): mixing strength
- \( \Delta m^2 \): mass difference (squared) for mass eigenstates (eV^2)
- \( L \): baseline length (km)
- \( E \): neutrino energy (GeV)

Start with a pure \( \nu_e \) beam

\( \nu_e \) Disappearance

\( \nu_\mu \) Appearance

(assuming you can produce and see \( \mu \)'s)
Oscillations (for 2-state system)

\[ P_{\text{osc}} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E) \]

- \( P \) = oscillation probability
- \( \sin^2 2\theta \) = mixing strength
- \( \Delta m^2 \) = mass difference (squared) for mass eigenstates (eV²)
- \( L \) = baseline length (km)
- \( E \) = neutrino energy (GeV)

For \( \Delta m^2 \sim 2.4 \times 10^{-3} \text{ eV}^2 \), \( E \sim 1 \text{ GeV} \),
\( \Delta L \sim 1000 \text{ km} \)
(optimized Long Baseline conditions)
Oscillations  (for 3-state system)

\[
P = (\sin^2 \theta_{23} \sin^2 2\theta_{13}) (\sin^2 \Delta_{31}) \\
\mp \sin \delta (\sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12}) (\sin^2 \Delta_{31} \sin \Delta_{21}) \\
+ \cos \delta (\sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12}) (\sin \Delta_{31} \cos \Delta_{31} \sin \Delta_{21}) \\
+ (\cos^2 \theta_{23} \sin^2 2\theta_{12}) (\sin^2 \Delta_{21}) .
\]
Oscillations (for 3-state system)

\[ P = \pm \sin \delta (\sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12}) (\sin^2 \Delta_{31} \sin \Delta_{21}) + \cos \delta (\sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12}) (\sin \Delta_{31} \cos \Delta_{31} \sin \Delta_{21}) + (\cos^2 \theta_{23} \sin^2 2\theta_{12}) (\sin^2 \Delta_{21}). \]

- Sign difference between \( \nu \) and \( \bar{\nu} \)
- CP violating terms
- Terms depending on mixing angles
- Terms depending on mass splittings

\[ \Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu \]
CP Violation

Option 1: Long-baseline configuration
(~1000 km, ~1 GeV neutrinos)
Changing between $\nu_\mu$ and $\bar{\nu}_\mu$ (- or +)

Option 2: Decay-at-rest configuration
(1-20 km, ~30 MeV neutrinos)
Changing baseline length (changing $\Delta$)

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NOTE: HUGE benefit from combining both measurements in same detector!
Decay-At-Rest

well understood spectrum, isotropic

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]  
2-body decay: monochromatic 29.9 MeV \( \nu_\mu \)

\[ \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \]  
3-body decay: range of energies between 0 and \( m_\mu/2 \) (2.2 \( \mu s \))

\( \bar{\nu}_e \) is \( \sim \)absent in the flux: look for its appearance
DAR Detection

• Look for appearance of $\bar{\nu}_e$
• Inverse beta decay (IBD) in detector with lots of free protons
  – Water Cherenkov or Liquid Scintillator
Oscillation Probability vs. Kilometers

- **$\delta = \pi/2$**
- **$\delta = 0$**

Constrains Initial flux

Constrains rise of probability wave

Osc. maximum at $\sim$40 MeV

- Near-site Accelerator Module, up to 1.5km, 0.8 MW
- Mid-site Accelerator Module, 8km, 1.6 MW
- Far-site Accelerator Module, 20km, 4.8 MW

Underground detector:
- Gd-doped water
- Or
- Liquid scintillator
You need to know which One is providing the beam. So they have to turn on/off.

The duty factor is flexible, But beam-off time is needed.
Six MW Target Concept

\[ r_0 = 20 \text{ cm} \]
\[ z_0 = 8 \text{ m} \]
weight = 55 tons
Accelerator Requirements

- Beam on target: ~800 MeV protons
- Beam power*:
  - 1.5 km site: 0.8 MW average
  - 8 km site: 1.6 MW average
  - 20 km site: 4.8 MW average
- Accelerator duty factor ~ 20%
  - Instantaneous power requirement is x5 average power

*Based on matching data rates in proposed 200 kTon Water Cherenkov counter, and LBNE beamline from FNAL to Homestake
Accelerator requirements in perspective

AVERAGE power

PEAK power
Cyclotrons: Viable technology?

- PSI is current world power leader in this energy range
  \(~ 1 \text{ MW average, 590 MeV protons}\)
- Extrapolation to higher power?

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- Problems:
  1. Capture of more ions… space-charge at injection
  2. Clean extraction… max loss 200 W \((\sim 10^{-4})\)
Proposed Solution: $\text{H}_2^+$ ions

- Two protons for every ion ($1 \text{ emA} = 2 \text{ pmA}$)
- Perverance of $5 \text{ emA} \text{ H}_2^+$ at $35 \text{ keV/amu}$
  - same as $2 \text{ emA}$ of $30 \text{ keV}$ protons
  - Axial injection of $2 \text{ emA}$ protons at $30 \text{ keV}$ is well within state of the art
- Extract with stripping foil
  - Clean turn separation is not needed, only high-acceptance extraction channel
Concept (Luciano Calabretta)
INFN-Catania
Injector Cyclotron

- 60 MeV/amu, 5 emA $\text{H}_2^+$
- Normal conducting coils ~ 4 meter coil diameter
- Axial injection (spiral inflector)
- Electrostatic extraction channel

arXiv: 1207.4895
Ring Cyclotron: Design #1

- $E_{\text{max}}$ 800 MeV/amu
- $B_{\text{max}}$ 6.1T
- Diameter 14 m
- Height 5.6 m
- Injection radius 1.8 m
  - passive magnetic channel
  - electrostatic inflector
- Extraction radius 4.8 m
  - stripper $\sim$2mg/cm$^2$
- 330 turns
- RF $\Delta E$/turn
  - 2 MeV inner radii
  - 4 MeV outer radii
Engineering “Existence Proof”

RIKEN K2600 SUPERCONDUCTING RING CYCLOTRON

Completed November 2005 - the 140-ton cold mass cooled to 4.5K.
Iron weight
8000 tons

RIKEN SRC
Beam Dynamics (for Design #1)

No space charge

Isochronicity
$(\pm 0.4\%)$
Space Charge Simulations

JJ Yang, MIT/PSI
Adelmann’s OPAL code

Energy Spread on the Stripper

2° initial phase

10° initial phase
Extraction Channel

Proton Extraction

- The proton beam experiences complicated bending fields (including nonlinear fringe fields)
- The proton beam is accelerated and decelerated during the gap crossing (4 times)
Extracted beam size

**Horizontal beam size along extraction channel (3% ΔE/E)**
- Max dia ~ 5 cm
- Essentially no space charge effect

**Extraction orbit length**
~ 17 meters

**Vertical beam size**
- Max dia ~ 9.5 mm
Problem with Design #1: Complex SC Coil Geometry

Non-uniform coil cross section

Difficult to build
Possible Solution

- Six-sector design
  - More similar to RIKEN
Possible Solution

- Six-sector design
  - More similar to RIKEN
- Preliminary beam dynamics ~ OK
  - Isochronicity, tune resonance avoidance
  - No injection/extraction/space-charge yet

\[ W_0/W-1 \]
Six-sector Cryostat
More manageable coil engineering
DAEδALUS SRC Status

• Much work still to do
  – Coordinating engineering and beam-dynamics designs
  – Other physics issues:
    • Vacuum system
    • Integration of RF system
    • Ion source and loosely-bound vibrational states of H$_2^+$

• To date no major show stoppers!
Development Strategy

• With highly-complex projects:
  – Develop phased approach
  – Design phases such that good physics can be done with each
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• In our case… Injector cyclotron can in itself be a “barn-burning” neutrino source
  – The IsoDAR Project
  – 10 pmA (CW) at 60 MeV/amu = 600 kW!
IsoDAR (Isotope Decay At Rest)

- Proton beam into neutron-producing target
- Secondary neutrons into ~50 kg pure $^7\text{Li}$ blanket
- $^8\text{Li}$ decay produces $\bar{\nu}_e$, high beta endpoint energy
  - Good for discriminating background
- As with DAEδALUS, use IBD in liquid scintillator
  - Good spatial, energy resolution

GOAL: STERILE NEUTRINO SEARCH
Sterile Neutrino

- Anomalies in $\nu$, $\bar{\nu}$ behaviors
  - LSND, MiniBooNE
  - Reactor flux anomaly
- Possible explanation:
  - New neutrinos that do not interact via weak force but still can oscillate with other neutrino states
  - Most likely $\Delta m^2 \sim 1 \text{ eV}^2$
- $\Delta L \sim$ few meters!
Oscillation L/E Waves in IsoDAR

IsoDAR’s high statistics and good L/E resolution gives good sensitivity to distinguish (3+1) and (3+2) oscillation models

Oscillations can be seen within detector!
IsoDAR at Kamland

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

SNO+ also encouraging IsoDAR
Beam Extraction in DIC
DAEδALUS Injector Cyclotron

Turn separation
Last 4 turns (OPAL sim)

Septum Protection:
- Place thin stripper foil in front of septum
- Beam that would strike septum is stripped and is bent inwards
- Power dissipated over larger area, or defined dump
Engineering Challenges for DIC

• Deliver components through narrow passageways or down shafts
  – 4-meter diameter coil will NOT fit!
    • KamLAND drive-in access, drift height < 4 meters
    • Creighton mine shaft (SNO+) is ~3.8 x 1.5 m
  – Pole pieces too heavy for hoist
    • Creighton hoist has 12 ton limit

• Power and cooling

• Neutron shielding
Project Status

- Central region tests being set up at BEST Cyclotrons (Vancouver)
Ground surface.
This is the beginning of the beam line.
Quote = 0

Insulator and acceleration column, 70 kV

VIS ion source

Wave guide for the microwave.

Wave guide enter from the bottom
Some beam line components (will be shipped from Catania)

RF Resonator and cyclotron model (to be built by BEST)
BEST tests... Buncher efficiency

Ion source output
- without buncher: ~10% effic
- with buncher: ~20% effic

Captured in Cyclotron

Cyclotron RF

Time
Goals and Schedule

• To benchmark ion source and buncher performance for $\text{H}_2^+$ ions
  – Input validation for simulation codes

• To explore space-charge effects and \{x,y\} coupling of space-charge dominated beams

• Components being built

• Catania shipment in February

• Run tests in late spring 2013.
On Other Fronts…

• Near-term funds being sought for further engineering design for IsoDAR
• Longer-range funding for engineering studies of DAEδALUS SRC
• Ion source development plans taking shape
  – Vibrational states not an issue for IsoDAR
  – Loosely-bound H$_2^+$ states will Lorentz dissociate in 6T at 800 MeV/amu
    • Must develop source that quenches these states
• Erice Workshops (12/2011, 11/2012) study design issues with cyclotron experts
Summary

- $\text{H}_2^+$ ions can be a key to high-power cyclotrons for many applications
- Compactness and relative cost of cyclotrons could open doors to several important neutrino experiments
- Exciting times ahead!