Janet Conrad, MIT
Frontiers in Neutrino Physics 2011
Outline:

1) The basic idea: low energy neutrinos for $\mathcal{CP}$ studies
2) What we want in a low energy Neutrino Source
3) Cyclotrons to produce the proton beam
4) SBL physics too!
Thinking about an ultra-large liquid detector program…

Whatever detector we decide to build, it needs a strong well-balanced scientific basis.
Thinking about an ultra-large liquid detector program…

Long Baseline:
Accelerator-based
Mostly Neutrinos
1 GeV to 20 GeV
Thinking about an ultra-large liquid detector program…

Particle Astrophysics: Natural Sources, 1 MeV to >100 GeV

Long Baseline: Accelerator-based Mostly Neutrinos 1 GeV to 20 GeV

~100 kt
Thinking about an ultra-large liquid detector program…

Particle Astrophysics: Natural Sources, 1 MeV to >100 GeV

Long Baseline: Accelerator-based Mostly Neutrinos 1 GeV to 20 GeV

NEW! DAEδALUS: Accelerator-based Antineutrinos 20 to 50 MeV
A $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search, exploiting the L/E dependence of the CP-interference term to extract $\delta$
A multiple-baseline, single-detector experiment

osc max ($\pi/2$) at 40 MeV

off max ($\pi/4$) at 40 MeV

Constrains flux

$\pi^+ \rightarrow \nu_\mu + \mu^+$

$\rightarrow e^+ \bar{\nu}_\mu \nu_e,$

$\nu_\mu \rightarrow \nu_e$ normalizes flux

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$\nu_e \rightarrow \nu_e$

$\nu_\mu \rightarrow \nu_\mu$

$\nu_\mu \rightarrow \nu_e$

$e^+$

$p$

$n$
We need the 2-fold signature in time…

The signal:
inverse beta decay, IBD

Even if The $\nu_e$ xsec is small…
there are a lot of $\nu_e$s in the beam!
SITE OPTIONS:
Large water detectors:
LBNE
MEMPHYS
Hyper-K

Or scintillation oil-based detectors:
LENA, Hano-Hano

Groups in Red have Already Expressed Interest
Measurement strategy:

Using near accelerator
measure absolute flux normalization with $\nu$-e events to $\sim 1\%$,
Also, measure the $\nu_eO$ event rate.

At far and mid accelerator,
Compare predicted to measured $\nu_eO$ event rates
to get the relative flux normalizations between 3 accelerators

In all three accelerators,
given the known flux, fit for the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal
with free parameters: $\theta_{13}$ and $\delta$
The fraction of “δ-space” where a measurement will be $>3\sigma$
The strength is in the signal to-background

With LBNE...
The Neutrino Source
What do we want? A very pure DAR beam

1) Produce a lot of $\pi^+$
2) While minimizing all other particles!
   $\pi^-$, kaons, neutrons…
3) Kill off $\pi^-$ by capture $\Rightarrow$ reduce DIF!
4) Minimize source size compared to $L_{osc}$
Production data on p+Be target…
(collected in MB technote by Shaevitz)

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<th>Produced Hadron</th>
<th>Exclusive Reaction</th>
<th>$M_X$ (GeV/c$^2$)</th>
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<th>$E_{\text{beam\ thresh}}$ (GeV)</th>
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<td>295</td>
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<td>$\pi^-$</td>
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We want to be well above threshold to produce a **lot of** $\pi^+$ but near or below threshold to produce **very little** $\pi^-$ and **no kaons**!

800 MeV will be a good choice…
Production data on p+Be target…
(collected in MB technote by Shaevitz)

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Kaons are especially problematic because once produced, they do not capture, like the $\pi^-$ …they stop and decay. The $\pi/K$ ratio is not well understood -- hard to predict.

Avoid Energies >1500 MeV
not enough energy to excite the $\Delta$ resonance

Energy goes into other processes, not just DAR: $> 1500$ MeV is not efficient.

We are Updating This plot Soon!
Two sets of results on C from N. Mohkov

$\frac{\pi^+}{\pi^-}$ ratio

800 MeV is close enough to the $\pi^-$ production threshold to strongly suppress production!

$> 1500$ MeV -- production ratios close to unity
Lighter targets are better.

Ratio at 1.6 GeV (didn’t have heavy data info at lower energy)
Remove the \( \pi^- \) that are produced -- Minimize DIF

- \( \pi^- \) capture when they stop
- all flavors of DIF neutrinos are a problem because they do not have a well defined spectrum

Solution: Light target embedded in a heavy target

Also, no upstream targets!!!
Minimize neutron production

- wastes beam energy
- increases $\pi^{-}$ background
  
  (if p knocks out n, n can produce $\Delta^0 \rightarrow\pi^- p$)
- fast neutrons may be a background to your experiment, depending on the physics/design (I’ll return to this)

Solutions: Use a light target (C, H$_2$O)
  
  Use a lot of shielding to absorb n’s

*Note that spallation sources produce neutrons on purpose, so they are not very efficient neutrino sources!*
Wanted: ~1 MW sources of protons, w/ energy ~800 MeV for a reasonable price

What helps:

1. No fancy beam structure -- CW is fine. (run 100 ms on and 400 ms off for CP violation, running longer periods may be fine for sbl)

2. No need to inject into another accelerator

3. Constant energy -- no need for an energy upgrade path

... Unlike Project-X or SNS, which need all of the above.
Luckily there are others looking for ~1 GeV Machines!

“ADS” -- accelerator driven systems for subcritical reactors.

“DTRA”-- Defense Threat Reduction Agency

Both applications & others are of interest to industry…

The world-wide cyclotron industry
DAEdALUS machines are being presented at this conference for ADS uses!
Among all of the types of accelerators out there…

**Why cyclotrons?**
- Inexpensive,
- Only practical below ~1 GeV (ok for us!)
- Only good if you don’t need timing structure (ok!)
- Typically single-energy (ok!)

**Taps into existing industry**

We do not rule out other options, but cyclotrons seem like a good fit.

Very interesting
R&D ongoing, but these machines are not yet proven

Cyclotrons
Synchrotrons
Linacs
FFAGs
etc.

Can do what we need right now, but are expensive.

Use linacs if you want a nice beam for transfer to another line and flexibility on energy (We don’t)
Approaches using cyclotrons:

The compact cyclotron with self-extraction

under development for DTRA at MIT

An H2+ accelerator for ADS applications

Under dev. by INFN, PSI, MIT Cockcroft Inst.

The stacked cyclotron:

7 cyclotrons in one flux return

Under dev. for ADS at TAMU
An H2+ accelerator
for ADS applications
Under dev.
by INFN, PSI, MIT Cockcroft Inst

The example design I will describe today
Cyclotrons 101

We employ an “isochronous cyclotron” design where the magnetic field changes with radius, but RF does not change with time. This can accelerate many bunches at once.
Our magnet design
The big issue...

If you inject a lot of charge here, it repells & “blows up”

As radii get closer together the bunches at different radii interact
We need to reduce “space charge” at the start…

H₂⁺ gives you 2 protons out for 1 unit of +1 charge in!

Simple to extract! Just strip the electron w/ a foil
The main cyclotron will be about the size of MiniBooNE, it is relatively easy to site this anywhere that interesting detectors are built.
Working examples of each component exist. Now we need to optimize.

The ion source: prototype built at Catania
The injector cyclotron: modest modification to off-shelf model from, *e.g.*, BEST Cyclotron Systems Inc.
The main cyclotron: smaller, simpler version of Riken (Japan)
The extraction foils: well tested at many cyclotron facilities, including PSI and TRIUMF
The target/dumps: At present we have multiple extraction lines but we think we can avoid this by spreading beam. We are investigating this at MIT this summer.
Some highlights of progress & plans

• We have a 1st generation design

• We have a prototype ion source, which produced 20 mA immediately

• The large magnet specifications are nearly complete, and we expect to go to engineers for costing within 3 months. This is the cost driver.
Short Baseline Physics
Non-oscillation Physics

1) Test/improve nuclear models

<table>
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<tr>
<th>inclusive $^{12}\text{C} \rightarrow ^{12}\text{N}_{gs}$</th>
<th>$(\nu_e, e^-)$DAR</th>
<th>$\langle\sigma_f\rangle, 10^{-42} \text{ cm}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPA</td>
<td>49.47</td>
<td></td>
</tr>
<tr>
<td>QRPA</td>
<td>42.92</td>
<td></td>
</tr>
<tr>
<td>SM(HF wi) $(0 + 1 + 2)\hbar\omega$</td>
<td>8.11</td>
<td></td>
</tr>
<tr>
<td>SM(WS wi) $(0 + 1 + 2)\hbar\omega$ [10]</td>
<td>8.4</td>
<td></td>
</tr>
<tr>
<td>Experiment</td>
<td>$10.5 \pm 1.0 \pm 1.0$ [22]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$9.1 \pm 0.4 \pm 0.9$ [23]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$9.1 \pm 0.5 \pm 0.8$ [24]</td>
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We only have data on C, H, Fe, I in 10 - 50 MeV range.

2. Use the cross section to study supernovae!

... but then we will need more cross sections!

Like Argon!

.. and water too

Calculations have big variations!

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Fig. 3. Total cross section $\sigma$ vs. $E$ for $\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^*$ reaction with Fermi function (solid line), modified effective momentum approximation (dashed line), Ormand et al. [12] (dashed-double dotted line) and Bueno et al. [13] (dotted line).

Coherent scattering has never been measured, DAR beams are wonderful for this.

Kate Scholberg

http://arxiv.org/abs/1103.4894
Josh Spitz, Tali Figueroa, et al

Interesting tests of SM, including nonstandard couplings…

Re-use Dark Matter designs!
CLEAN/CLEAR
GEODM

1350 events with a 50 kg.yr exposure!
For these studies assume:

100 kW cyclotron DAR source over 1-2 years ⇒ 4.0e21 νe and 4.0e21νµ
• Bin and fit $\bar{\nu}_e + p \rightarrow e^+ + n$ data as a function of $L/E$
  – Include normalization uncertainty of 10% mainly due to neutrino flux
  – Include intrinsic $\bar{\nu}_e$ background (4e-4 level) with 20% uncertainty

(3+1) $Fit$
Karagiorgi et al.
$\Delta m^2 41 = 0.57$
$\sin^2 2\theta_{\mu e} = 0.0097$

(3 + 2) $Fit$  Kopp, Maltoni, Schwetz (2011), 1103.4570.
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Sensitivity (3+1) at 5\(\sigma\)
LENA with DAR Source

DAR–LENA Sterile Sensitivity (App mode)

3+1 Type Model with simple two-neutrino

Results for:
100 kW, 4e21 nu’s
10 kW, 4e20 nu’s
and with various fiducial masses

A 5 kton scintillator detector combined with a small 10 kW source can test the MiniBooNE/LSND signal at 5 \(\sigma\)!
Our paper also studies disappearance,
And looks at NOvA as another possibility.

We are now working on a paper that compares
Water Cerenkov and LAr detectors
For the short baseline physics!

Coming soon to an arXiv near you!
DAEδALUS

Is motivated by CP violation
Requires high rate, low background DAR
Uses cyclotrons at ~ 800 MeV
There are also exciting sbl uses like…
cross section measurements
short baseline oscillations

DAEδALUS offers a broad & exciting physics program!
It adds great strength to the ultra-large detector program