HIGH POWER, HIGH ENERGY CYCLOTRONS FOR MUON ANTINEUTRINO PRODUCTION: THE DAEδALUS PROJECT

Jose R. Alonso, Tess Smidt, MIT, Cambridge MA 02138
for the DAEδALUS Collaboration

Abstract

Neutrino physics is a forefront topic of today's research. Large detectors installed underground study neutrino properties using neutrino beams from muons decaying in flight. DAEδALUS looks at neutrinos from stopped muons, "decay at rest" (DAR) neutrinos. The DAR neutrino spectrum has no electron antineutrinos (all pi-minus are absorbed), so a detector with free protons is sensitive to appearance of nu-e-bar oscillating from nu-mu-bar via inverse-beta-decay (IBD). Oscillations are studied using sources relatively near the detector, but which explore the same physics as the high-energy neutrino beams from Fermilab. As the DAR spectrum is fixed, the baseline is varied: plans call for 3 accelerator-based neutrino sources at 1.5, 8 and 20 km with staggered beam-on times. Compact, cost-effective superconducting ring cyclotrons accelerating molecular hydrogen ions (H_2^+) to 800 MeV/n with stripping extraction are being designed by L. Calabretta and his group [1]. This revolutionary design could find application in many ADS-related fields.

INTRODUCTION

In the quest for "physics beyond the Standard Model", neutrinos are playing an important role. Observation of neutrino oscillations, which requires the neutrino to have mass, is not accommodated within the Standard Model. In addition, hints of CP violation through unanticipated differences in neutrino and antineutrino behavior is leading to development of new, sensitive experiments capable of precision measurements of neutrino properties. The Sanford Underground Laboratory in Lead, South Dakota (USA) has been proposed as the site for a new, large (300 kiloton) water-Cherenkov detector, to be installed at the 4850 foot level of the Lab. This detector, a factor of 6 over (the world's largest) SuperKamiokande, in Japan, would be the end-point of LBNE (Long Baseline Neutrino Experiment) from a new beam line at Fermilab.

The recent reneging of NSF on its commitment to fund the DUSEL project has caused delays in the originally-conceived timetables for construction of the larger installations at the Sanford Lab, however DOE and Fermilab remain committed to the LBNE experiment, though perhaps with a somewhat smaller detector.

Our Collaboration has recently proposed the DAEδALUS experiment [2] as a complement to LBNE, using the same detector to observe oscillation characteristics of neutrinos from nearby sources, located at carefully-calculated distances (from 1.5 to 20 km). By running both DAEδALUS and LBNE concurrently and combining the data sets, measurement sensitivity of the CP violating term δ can be substantially better than for either experiment alone.

This complementarity is generating considerable interest in the neutrino community, and encouragement to study further the technology requirements for mounting the DAEδALUS experiment.

Key to this experiment are compact, cost-effective neutrino sources based on proton beams of around 800 MeV striking low Z targets. To obtain adequate neutrino fluxes, average beam-power levels on target should be in the megawatt regime.

DAEδALUS CONCEPT

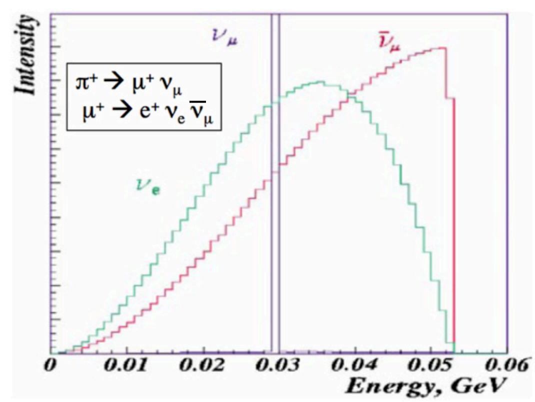

Figure 1: Decay-at-Rest neutrino spectrum from stopped pi-plus. Spectrum is devoid of nu-e-bar.

Protons strike the target producing π^+ mesons with low-enough kinetic energy that these stop before decaying to muons, yielding a "decay-at-rest" source; the spectrum of neutrinos is shown in Figure 1. A key element of this spectrum is the absence of electron antineutrinos.

Nu-e-bars *are* present in the decay sequence of pi-minus, however in the DAR configuration these pions are absorbed in nuclei prior to stopping. Proper selection of the proton beam energy and target material can reduce the contamination of pi-minus to less than 1 part in 10^4.

A large detector with a high fraction of free protons is ideal for detecting nu-e-bar through the inverse-beta-decay (IBD) process. In this reaction, which has a relatively high cross section (~10^{-38} cm^2), the initial absorption of the nu-e-bar produces a relativistic positron that emits a cone of Cherenkov radiation in the water. A short while later the free neutron from the IBD process is captured, producing a delayed-coincidence signal from the nuclear cascade associated with this capture. If the detector is doped with gadolinium to enhance the neutron capture, the energy release is higher, providing greater sensitivity to the detector. This two-level event provides a unique signature for the nu-e-bar that is very insensitive to background.

The DAEδALUS experiment looks for the appearance of nu-e-bar coming from the oscillation of nu-mu-bar that are well-represented in the DAR spectrum.

NEUTRINO OSCILLATION

Oscillation probability for muon going to electron neutrinos is governed by equations (1) and (2).

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) = & \sin^2\theta_{23} \sin^2 2\theta_{13} \quad \sin^2\Delta_{31} \\ & \pm \sin\delta \quad \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin^2\Delta_{31} \sin\Delta_{21} \\ & + \cos\delta \quad \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin\Delta_{31} \cos\Delta_{31} \sin\Delta_{21} \\ & + \quad \cos^2\theta_{23} \sin^2 2\theta_{12} \quad \sin^2\Delta_{21} \end{aligned} \quad (1)$$

$$\Delta_{ij} = \Delta m^2_{ij} L/4E. \quad (2)$$

Dependences are seen on mixing angles θ_{ij} between mass eigenstates, CP-violating term δ, and mass splitting, baseline length and neutrino energy. Two of the three mixing angles, θ_{12} and θ_{23} are well known from solar and atmospheric neutrino studies, and the corresponding Δm_{ij}^2 values are also known. Unknown still are the CP-violating term, mass hierarchy ("normal" or "inverted" depending on which Δm^2 is above the other), and θ_{13}. θ_{13} should be less uncertain when Double Chooz and Daya Bay experiments are completed.

Equation (1) shows two different approaches to measuring δ: LBNE in which the baseline and neutrino energy are fixed and one changes between neutrino and antineutrino modes (changing the sign of δ); and DAEδALUS where only the antineutrino mode is available, but one can change the baseline length L.

COMPLEMENTARITY WITH LBNE

Despite the great differences in the neutrino-source configurations, the oscillation physics is comparable for LBNE and DAEδALUS as the L/E ratios are quite similar. In the LBNE case L is ~1000 km and E is ~1 GeV, while for DAEδALUS the baseline is ~20 km and the energy is ~20 MeV. However, kinematic focusing of the LBNE beam allows the source to be far away, while the DAEδALUS beams are isotropic. The required proton beam power for the DAEδALUS sources is calculated to match the projected fluxes and reaction rates from LBNE.

The basic difference in the two experiments enhances measurement sensitivity; the strengths of one technique complement the weaknesses of the other. Also, running both experiments simultaneously using the same detector cancels systematic and calibration effects. Both can be taking data concurrently as timing is quite different. The DAEδALUS sources are essentially continuous, while the LBNE beam comes in a few microseconds once every 3 seconds. Overall, combining the data sets increases experimental sensitivity by almost a factor of 10.

DAEδALUS LAYOUT

Figure 2 shows the proposed layout for the DAEδALUS accelerator stations. The first, at 1.5 km is

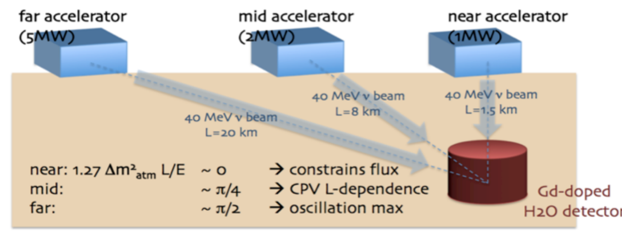

Figure 2: DAEδALUS configuration.

as close to the detector as possible (directly overhead), and serves as a flux calibrator. The second, at 8 km, represents the π/4 point in the oscillation spectrum, the third at 20 km is at the π/2 point. The (average) power-on-target needs are 1 MW, 2 MW and 5 MW respectively. Though the neutrino flux emanating from the target is isotropic, the ratio of powers is not $1/r^2$ because the oscillation maximum at the 20 km point requires a lower neutrino flux to achieve the same statistics.

An IBD event in the water-Cherenkov detector contains no directional information for the source of the neutrino, so the three DAEδALUS stations cannot be on at the same time. Their operation will be staggered so that an event can be time-tagged to determine its source. The duty factors for each station are 20%, with a 40% off time for all stations to assess backgrounds. This operations cycle will substantially impact accelerator requirements, as the peak power needs are then a factor of 5 higher than the average power. Note that the cycle time is relatively unimportant, the beam-on time can range from ~100 μsec to days. Optimizing the duty cycle can be based on engineering aspects such as RF, target thermal cycling, …

ACCELERATOR REQUIREMENTS

Table 1: DAEδALUS Accelerator Requirements

Beam on Target	Protons
Proton Energy	~800 MeV
Duty Factor	20%
Average Power	1/2/5 MW
Peak Power	5/10/25 MW
Acceptable beam loss	<200 W @>100 MeV

Protons are the most efficient way of producing pions. Threshold energy is 600 MeV, an incident energy of 800 MeV on a thick target maximizes π+ yield with low π-, and other contaminants from higher-energy production channels. Duty factor and power levels are determined by neutrino flux requirements and ability to identify the source of the neutrino.

Beam loss requirement results from PSI experience: their specification of 200 watts of high-energy beam loss inside a cyclotron vault maintains tolerable activation levels for hands-on maintenance. This level of beam loss ($\sim 10^{-4}$) is a huge challenge for high-power machines!

AVAILABLE TECHNOLOGIES

The requirements for the DAEδALUS accelerators represent a substantial leap over any existing machine. Can such a machine actually be built?

In fact, suitable accelerator technologies exist that could meet the energy and beam-power requirements: superconducting RF linacs and high-power cyclotrons.

Mature designs for CW, or even pulsed linacs in this parameter range are available, and beam-loss history for the SNS linac, for example, is excellent. However, costs are high and footprint for the accelerator and support systems is quite large. Optimization of cost and compactness seem to point to other system designs.

PSI offers an interesting alternate example. At 590 MeV and 2.2 mA CW beam, this normal-conducting ring cyclotron yields beam power of 1.3 MW, the world's leader in this energy range. In achieving the 99.98% extraction efficiency, it meets the beam-loss specification as well. The question is whether this technology can be extended to 800 MeV and the factor-of-ten power increases required for DAEδALUS. For one, the increase in radius between each turn gets smaller at higher energies, making clean turn separation for placement of an extraction septum more difficult. This can lead to unacceptable beam losses. Increased turn separation can be obtained by higher-power RF systems (increasing the energy-gain per turn), however it is difficult to imagine increasing what PSI has already been able to accomplish. Andreas Adelmann and his group [3] are exploring the feasibility of extrapolating PSI designs to the higher power and energy levels needed.

Luciano Calabretta and his group at LNS-Catania are working on a superconducting ring cyclotron (SRC) design in which the beam accelerated is molecular hydrogen instead of bare protons.

H_2^+ CONCEPT

The prime advantage of using H_2^+ is that extraction using a stripping foil becomes a practical means of getting the beam out of the machine with a hope of meeting the stringent beam-loss requirement. While accelerating H^- has revolutionized the low-energy cyclotron field, the H^- ion is not stable against Lorentz stripping in B fields of 2T above about 70 MeV. However, the H_2^+ ion is more tightly bound and is somewhat smaller, predicting survival at the highest field, ~6T, in our SRC. Foil stripping produces two protons that bend inwards, however extraction orbits snaking through the hills and valleys have been found which allow clean extraction.

Another area where H_2^+ ions will help is in the central region of the injector cyclotron where space-charge effects in high-current beams cause substantial inefficiencies in beam capture and emittance growth. The perveance of an H_2^+ beam is lower, due to the lower charge-to-mass ratio (two protons for every charge), indicating increased efficiency for capture of high-current beams.

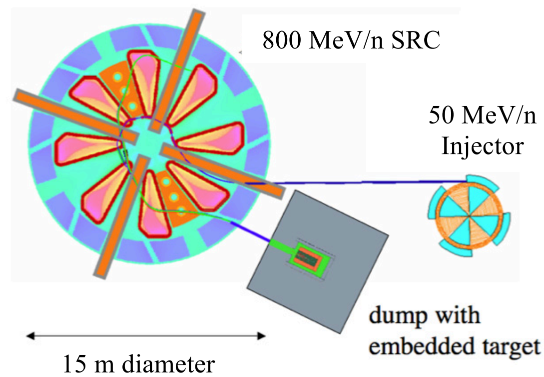

Figure 3: H_2^+ Superconducting Ring Cyclotron module.

STATUS OF DESIGN AND OUTLOOK

Preliminary design work by Calabretta et al [1], have demonstrated that the concept, shown schematically in Figure 3 is in principle feasible. Beam-dynamics work continues at LNS-Catania and PSI to optimize field configurations (isochronicity) and beam stability (emittance growth and resonance avoidance). Target design optimizing pion yield using the MARS code [4] is underway. An agreement has been entered into with BEST Cyclotrons [5] to collaborate on ion-source and central-region tests. An RFP is being prepared to conduct pre-preliminary engineering studies on the sector magnets for the SRC, to establish feasibility and fabrication costs. A Workshop is planned for later this year with cyclotron experts to evaluate design work, identify areas needing further research, develop an R&D program, and provide an overall assessment of feasibility and begin an evaluation of likely program costs for development and construction.

Goal of the DAEδALUS Collaboration is to have a reviewable preliminary design and cost study within a year.

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