Abstract

DAEδALUS is an experiment to measure the CP-violation angle in the neutrino sector by producing multiple, intense beams of neutrinos from pion- and muon-decays-at-rest near an ultra-large water Cerenkov detector. In this talk, a design for the proposed Deep Underground Science and Engineering Laboratory in the U.S. was presented. DAEδALUS will be statistics-limited and have different systematic errors than long baseline CP-violation searches. When the data from both searches are combined, the sensitivity exceeds proton-driver designs. In this proceeding, we briefly describe one of several alternative cyclotron designs under consideration for DAEδALUS, as an example.

Keywords: CP-violation, cyclotron

1. Introduction to the Physics

The physics community has placed the search for evidence for CP-violation in the neutrino sector at the highest priority [1, 2, 3]. A primary reason is that CP-violation in the light neutrino sector is considered a key piece of evidence for the theory of leptogenesis [4]. In this theory, the light neutrinos are Majorana and have GUT-scale partners. The matter-antimatter asymmetry of the universe is explained through CP-violating decays of the heavy partners. It is widely thought unlikely that CP-violation could appear in the heavy sector without the occurrence in the light neutrinos [4]. Thus, CP-violation in the neutrino sector is considered an important “smoking gun.”

Beyond this, the search for CP-violation in the leptons is motivated by the experimental observation of CP-violation in quarks. In many broad aspects, including flavor mixing, the leptons weak interactions seem to mirror the quarks. So it would, therefore, be very surprising that CP-violation would be exactly zero in the heavy sector while non-zero in quarks. But the quark-lepton correspondence is like a fun-house mirror – the actual value of the parameters in the two sectors are very different. For example, mixing in the neutrinos is very large compared to mixing in the quarks, but the neutrino masses are very small compared to quarks. It is important to ask if the CP violating parameter in neutrinos is similarly much larger than in quarks. Understanding the patterns can give us bottoms-up clues to the underlying theory of mass and flavor mixing in particle physics. The value of the leptonic CP-violation parameter is a key missing clue.

The search for a nonzero CP violation parameter, δ, requires a neutrino oscillation appearance experiment. At this point, the only viable appearance experiment is muon flavor neutrinos oscillating to electron flavor. If we say that \( \Delta_{ij} = \Delta m^2_{ij} L / 4E_\nu \), are the squared mass splittings and \( \theta_{ij} \) are the mixing angles parameterizing the oscillation, then, neglecting matter effects, the oscillation probability is given by [5]:

\[
P = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{13} \pm \sin \delta_c \sin \theta_{13} \cos \theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \times \sin^2 \Delta_{13} \sin \Delta_{12} \]

\[
+ \cos \delta_c \sin \theta_{13} \cos \theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \times \sin \Delta_{13} \cos \Delta_{13} \sin \Delta_{12} 
+ \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta_{12},
\]  

(1)

In this equation, \((-+)\) refers to neutrinos (antineutrinos).

With the exceptions of \( \theta_{13} \) and \( \delta \), the parameters
2. Introduction to DAE\(\delta\)ALUS

The DAE\(\delta\)ALUS design is described in Refs. \cite{11, 12} and Fig. \ref{fig:layout}. Cyclotrons are used to produce pion and muon decay-at-rest neutrino beams. The search is for \(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\tau}\) oscillations, exploiting the length-dependence of the \(CP\)-violating interference terms in the oscillation formula, Eq. \ref{eq:osc} to isolate \(\delta\). Three cyclotron sources are used to map the oscillation as a function of \(L\).

We propose to run this experiment at the new Deep Underground Science and Engineering Laboratory (DUSEL) in South Dakota, although in principle it can be installed near any ultra-large detector with free protons. The 1.5 km location is on the surface above the water Cerenkov detector located at the 4850 level. The other two sites are at 8 km and 20 km. Given the low beam energy, this preserves the \(L/E\) necessary to be sensitive to the atmospheric \(\Delta m^2\).

This design relies on the fact that the weak decay chain produces beams with identical energy dependence at each location. Cyclotrons are planned as a cost-effective, high-intensity method of producing protons to create pions that lead to these decay-at-rest neutrino beams. The 800 MeV protons impinge on a carbon target producing pions from the \(\Delta\) resonance. These come to a stop in the target and subsequently decay via the chain: \(\pi^+ \rightarrow \nu_\mu\mu^+\) followed by \(\mu^+ \rightarrow e^+\bar{\nu}_e\nu_\mu\). The resulting flux, shown in Fig. \ref{fig:energy}, is isotropic with a well known energy dependence for each of the three flavors. Because almost all \(\pi^-\) capture before decay, the \(\bar{\nu}_e\) fraction in the beam is \(\sim 4 \times 10^{-4}\).

The \(CP\)-violation search utilizes the \(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\) channel. The \(\bar{\nu}_e\) flux is peaked towards the endpoint of 52.8 MeV. At the atmospheric \(\Delta m^2\), a 50 MeV beam yields oscillation maximum at 20 km. We will use three neutrino sources located at 1.5 km (near), 8 km (mid) and 20 km (far). The cyclotrons at the three sites are run in alternating periods, so that the \(L\) for any given is event known by the timing. The neutrinos impinge on a single ultra-large detector with free-proton targets. This allows us to use the inverse beta decay interactions (IBD), \(\bar{\nu}_e + p \rightarrow n + e^+,\) to identify \(\bar{\nu}_e\) in the beam. The \(e^-\) electron and \(\nu_e\)-oxygen scatters are used to determine the relative normalization between sites.

To observe the \(n\) capture in the IBD events with high efficiency, the water Cerenkov detector would need to

![Figure 1: Schematic of the layout of DAE\(\delta\)ALUS. The powers at the respective sites, are, on average over the 10 year run, 1 MW, 2 MW and 5 MW in this equation are known now, with improvements expected in the near future \cite{6, 7, 8}. Global fits to \(\sin^2(2\theta_{13})\) yield, at present, \(0.06 \pm 0.04\). Reactor experiments in the near future \cite{9, 10} will push the uncertainty down to 0.005. The value of \(\delta\) is entirely unconstrained and measurement of this parameter is the goal of DAE\(\delta\)ALUS.

Sensitivity to \(\delta\) can arise in two ways. One can take data with neutrino and antineutrino beams and use the sign flip in Eq. \ref{eq:osc} to isolate \(\delta\). Or one can exploit the \(L/E\) dependence of the interference terms (\(\sin^2\Delta_{13} \sin \Delta_{12}\) and \(\sin \Delta_{13} \cos \Delta_{13} \sin \Delta_{12}\)). This second method allows sensitivity with either a neutrino or an antineutrino beam. Conventional searches use the former, while DAE\(\delta\)ALUS makes use of the latter, and combined searches use both.

The above oscillation probability is valid in a vacuum or for a short-baseline experiment, like DAE\(\delta\)ALUS. Long baseline experiments, such as those which use conventional neutrino beams, face the complication of matter effects which depend on the unknown sign of the mass hierarchy \cite{5}.

![Figure 2: Energy distribution for each flavor of neutrino in a decay-at-rest beam.](image-url)
be Gd-doped. Gd offers two essential advantages over the competing process of hydrogen capture: it reduces the capture time for the neutron generated in the IBD interaction from 200 \( \mu s \) to about 30 \( \mu s \), and the energy of the \( \gamma \)s released from the capture interaction is higher - \( \sim 8 \) MeV total (with about \( \sim 5 \) MeV converted to observable Cerenkov light from Compton-scattered electrons) compared with a 2.2 MeV \( \gamma \) for hydrogen.

The capability for measuring \( \delta \) as a function of \( \sin^2 2\theta_{13} \) is presented in Fig. 3. DAE\( \delta \)ALUS has an inherent ambiguity between the hierarchies because of its short baseline, and this is indicated by the left and right y-axis scales which correspond to normal and inverted hierarchies, respectively. For making a discovery of \( CP \)-violation (\( \delta \) not equal to 0° or 180°) this ambiguity is not important. The capability of the experiment depends upon the tonnage of the H\( _2 \)O detector. Ref. [13] presents a study of DAE\( \delta \)ALUS capability as a function of Gd-doped water Cerenkov detector mass. Here, we present results for 300 kt.

**3. Combining DAE\( \delta \)ALUS with a Conventional Beam**

The DAE\( \delta \)ALUS data complements data from conventional-beam searches for \( CP \)-violation, yielding high sensitivity when the data sets are combined. As an example, here we consider the LBNE neutrino beam, which has a 1300 km baseline [14][15] initiated at Fermi National Accelerator Laboratory. This beam is produced by 120 GeV protons impinging on a target to produce pions and kaons. These mesons are magnetically focused, and subsequently decay to neutrinos or antineutrinos, depending on the sign of the focusing field. The beam energy extends from about 300 MeV to above 10 GeV, and so is sensitive to the same \( L/E \) range as DAE\( \delta \)ALUS.

We consider four variations of beams impinging on the 300 kt water target, with 10 year running-periods:

- **LBNE alone** – which is \( 3 \times 10^{20} \) protons on target (POT) in neutrino mode followed by \( 3 \times 10^{20} \) POT in antineutrino mode. This is the standard 10-year run-plan for LBNE [16][17] prior to the startup of
“Project X.”

- **DAEδALUS alone** – which is strictly antineutrino running, as described above and following the plan described in Ref. [11].

- **Combined** – which is the standard plan for DAEδALUS antineutrino running combined with only-neutrino running of LBNE for the full 10 years. This design builds on the strength of conventional beams, which is to produce pure and powerful neutrinos beams. Conventional antineutrino beams can produce only about one-third the neutrino intensity and suffer from a high neutrino contamination [14]. The DAEδALUS and LBNE programs can take data simultaneously.

- **Project X** – which is a proposal for an upgrade to a “proton driver” which will yield ultra-high numbers of protons on target [18, 19]. A standard expectation assumes the LBNE conventional beam with $10^{22}$ POT in 5 years in neutrino mode and $10^{22}$ POT for 5 years in antineutrino mode.

As an example of the relative capabilities, Fig. 4 shows the fraction of $\delta$-space determined to be non-zero covered in the various scenarios. LBNE alone (green) and DAEδALUS alone (brown) have roughly the same capability, by design. What is particularly impressive is that the combined capability (red) exceeds that of Project X [18, 19] (black), as was also shown in Ref. [20], and reaches to very low values of $\sin^2 2\theta_{13}$.

LBNE is sensitive to the mass hierarchy. Fig. 4 assumes a known normal hierarchy, which seems plausible by the time these experiments run. However, if the hierarchy is unknown then LBNE sensitivity is degraded, while DAEδALUS sensitivity is not. Using an underlying normal hierarchy as an example, Fig. 5 shows the effect of an unknown hierarchy on the sensitivity for the four scenarios.

4. The Cyclotrons: An Example Design

While superconducting linacs provide the most conservative accelerator technology option, space and cost constraints suggest that it would be best to develop high-power cyclotrons to meet our goals. Several desirable aspects inherent to cyclotrons attract us to this option. First is compactness, minimizing costs for shielding and space, of particular value for the near site where footprint will be an important consideration. Second is that the fixed-energy and continuous beam character of cyclotrons are desirable features, reducing peak-power loads on targets.

Three potential cyclotron designs under consideration for DAEδALUS were presented at the Cyclotrons 2010 conference [21, 22]. Here we focus on only one of the three designs, for lack of space in these proceedings. This is a design which is particularly powerful and which is under development as an technology for Accelerator Driven Systems (ADS) for Thorium Reactors.

The Multi-MegaWatt Cyclotron (MMC) design consists of an injector and a booster cyclotron. Specifics of the two components are given in Table 1. This machine accelerates $H_2^+$ ions which provides advantages with respect to space charge effects and very clean extraction through stripping foils. The extraction goal is > 99.9% efficiency, as has been achieved at PSI. The design goal of this machine is 12 mA of beam at 800 MeV, which can be compared to the PSI experiment, which operates at 2.3 mA and 590 MeV. This very high instantaneous power is necessary for ADS operations. However, for DAEδALUS application, the near accelerator will run 67 ms of 500 ms, the mid accelerator will run 133 ms of 500 ms and the far accelerator runs 100 ms of 500 ms. Thus the average power is similar to PSI. There are two extraction lines per accelerator. Fig. 6 shows the cyclotron, with the beam injected from the right, accelerated and stripped with two extraction paths.

An important goal is a cost-effective design which, as much as possible, uses commercially available equipment. The ion source is expected to be adapted for the ECR Visible Ion Source at Catania, while the injector cyclotron is expected to be a modified commercial model. The booster cyclotron will be a custom design with economy in its simplicity. Dumps are also expected to be simple graphite targets, as described in Ref. [11]. Several aspects of the overall design keep costs low compared to existing machines of similar energy range, including: no need for a bunch structure, a single-energy design, and no need to extract to secondary beams or accelerators.

5. Conclusion

The DAEδALUS experiment provides a new approach to the search for CP violation in the light neutrino sector, using $\nu_\mu \rightarrow \bar{\nu}_e$ oscillations at short baselines. The beam is produced by high-power cyclotrons. The signal is inverse beta decay interactions in the 300 kt fiducial-volume Gd-doped water Cerenkov neutrino detector proposed for the Deep Underground Science
and Engineering Laboratory. This design could be employed at other underground laboratories with ultralarge detectors.

DAEoALUS provides a high-statistics, low-background complement to conventional long-baseline neutrino experiments, like LBNE. Because of the complementary designs, when DAEoALUS antineutrino data are combined with LBNE neutrino data, the sensitivity of the CP-violation search has sensitivity beyond the proposal for Project X.

The experiment relies on beams produced by high-power cyclotrons which are under development for commercial purposes. Cyclotrons have the advantage of being compact and low-cost compared to linacs. Three designs are presently under consideration. The example presented here accelerates H_2^+ ions, which allows for very clean extraction to multiple lines through electron stripping. The consensus among cyclotron physicists is that DAEoALUS is a challenging and interesting project, with high return on investment for both the accelerator and neutrino communities.

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