DAEδALUS: A Phased Neutrino Physics Program Using Cyclotron Decay-at-Rest Neutrino Sources

M. Toups, on behalf of the DAEδALUS collaboration

Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Abstract
DAEδALUS is a proposed phased neutrino physics program consisting of two flagship experiments: a search for CP violation in the neutrino sector and a definitive search for sterile neutrinos. Ultimately, DAEδALUS will comprise several accelerator-based modules located at three different distances from a single, large underground detector such as LENA, MEMPHYS, or Hyper-K. Each of these modules will employ new low cost, high power cyclotrons to produce pion decay-at-rest neutrino beams, which can be used to search for evidence of CP violation in the oscillation probability of muon antineutrinos to electron antineutrinos over baselines of ~20 km. However, at an early phase of the program, the high power DAEδALUS injector cyclotron can also be used to produce an intense isotope decay-at-rest neutrino beam. IsoDAR is a proposed experiment, which uses a 8Li decay-at-rest neutrino beam to perform a definitive search for sterile neutrinos by installing the DAEδALUS injector cyclotron in an underground lab close to a large liquid scintillator detector such as KamLAND. IsoDAR can rule out the parameter space allowed by global fits to the Reactor, SAGE, and GALLEX anomalies at 20σ in 5 years. These two flagship searches make a compelling case for the DAEδALUS phased neutrino physics program.

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1. Introduction

Two of the “big questions” confronting neutrino physics in the coming decade [1] are whether there is CP violation in the lepton sector and whether the LSND [2], MiniBooNE [3, 4], Reactor [5], and GALLEX/SAGE [6] anomalies are pointing to the existence of a light sterile neutrino. The DAEδALUS [7, 8] neutrino physics program addresses these two questions in a phased approach using new low cost, high power cyclotrons to produce intense decay–at–rest neutrino beams.

2. DAEδALUS CP Violation Search

The probability for a muon neutrino with energy $E_\nu$ to be detected as an electron neutrino after propagating a distance $L$ in a vacuum is given by:
\[ P(\nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{31} \]
\[ - \sin \delta_{CP} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin^2 \Delta_{31} \sin \Delta_{21} \]
\[ + \cos \delta_{CP} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin \Delta_{31} \cos \Delta_{31} \sin \Delta_{21} \]
\[ + \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta_{21}, \]

where \( \Delta_{ij} = \Delta m_{ij}^2 L/4E \), \( \Delta m_{ij}^2 = m_i^2 - m_j^2 \), and the corresponding oscillation probability for antineutrinos is obtained by reversing the sign of the second term. Typically, the first term driven by \( \Delta m_{31}^2 \) dominates the oscillation probability in neutrino experiments looking for CP violation, and the last term driven by \( \Delta m_{21}^2 \) is sub-dominant. The second and third terms are interference terms, which depend on the CP violating phase \( \delta_{CP} \) as well as the propagation distance \( L \) and the energy \( E \) of the neutrinos. The size of the second interference term is maximized by choosing \( L \) and \( E \) such that \( \Delta_{31} \) is an odd multiple of \( \pi/2 \).

The standard “long baseline” approach to determine the CP violating phase \( \delta_{CP} \) is to measure the oscillation probability with a single neutrino source and multiple neutrino detectors at different baselines. The novel approach DAE\( \delta \)ALUS takes is to measure the oscillation probability with multiple neutrino sources at different baselines from a single large underground detector. Both approaches address the fact that in order to observe oscillations from \( \nu_\mu \) (\( \bar{\nu}_\mu \)) to \( \nu_e \) (\( \bar{\nu}_e \)) over some distance, the initial \( \nu_e \) (\( \bar{\nu}_e \)) flux in the beam must be known. Long baseline experiments measure the initial \( \nu_e \) (\( \bar{\nu}_e \)) contamination in the beam with a “near detector”, while in the case of DAE\( \delta \)ALUS the unoscillated neutrino flux is measured with a “near accelerator”. Similarly, long baseline experiments compare the initial \( \nu_e \) (\( \bar{\nu}_e \)) beam content to the final \( \nu_e \) (\( \bar{\nu}_e \)) beam content seen by a “far detector”, while in the case of DAE\( \delta \)ALUS, the unoscillated flux is compared to the oscillated flux seen from the “far accelerator”. However, unlike long baseline experiments DAE\( \delta \)ALUS also constrains the dependence of the oscillation probability on other parameters (such as \( \theta_{13} \)) with a “mid-distance” neutrino source.

Each DAE\( \delta \)ALUS neutrino source is driven by one or more “accelerator units” consisting of a low energy, compact injector cyclotron and a high energy, super-conducting ring cyclotron (SRC) [9]. The injector cyclotron captures and accelerates 10 mA of protons in the form of an \( H_2^+ \) beam to 60 MeV/n, where it is then injected into the SRC, accelerated up to 800 MeV/n, and made to collide with a target producing large quantities of pions. Positively charged pions quickly lose energy in the target, come to rest, and produce a flux of neutrinos according to decay chain \( \pi^+ \rightarrow \mu^+ \nu_\mu, \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \). The weak interaction determines the well-known energy distribution of the \( \pi^+ \) and subsequent \( \mu^+ \) decay-at-rest neutrino flux, which extends up to 52.8 MeV. Negatively charged pions are also produced, quickly lose energy in the target, and come to rest. However, negatively charged pions and muons are efficiently captured by target atoms so that the \( \bar{\nu}_e \) contamination is at the level of \( \sim 5 \times 10^{-4} \) of the \( \bar{\nu}_\mu \) flux. Thus, the DAE\( \delta \)ALUS sources naturally lend themselves to a precise measurement \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \) oscillations over distances of \( \sim 20 \) km.

DAE\( \delta \)ALUS uses the inverse beta decay (IBD) interaction \( \bar{\nu}_e + p \rightarrow e^+ + n \) to detect \( \bar{\nu}_e \) events via the coincidence of the prompt positron and the delayed neutron capture. IBD is an ideal detection channel because it is a coincidence signal with very low backgrounds, it has a large, precisely-known cross section, and it allows the neutrino energy to be reconstructed on an event-by-event basis. However, the IBD interaction only occurs on free protons, and so DAE\( \delta \)ALUS can be paired with a large underground liquid scintillator detector or Gd-doped water Cerenkov detector such as LENA [10], Hyper-K [11], or MEMPHYS [12], but not with a large underground liquid argon detector such as the LBNE far detector [13].

In order to associate each IBD interaction in the detector with a given neutrino source, DAE\( \delta \)ALUS staggers the running periods for the three neutrino sources, which are located above ground and at distances of 1.5 km, 8 km, and 20 km from the large underground detector, respectively. The beam structure for the 3 neutrinos sources is somewhat flexible, but there should be sufficient beam-off time to measure the beam-off backgrounds. The average beam powers for the near, mid-distance, and far neutrino sources, are 1 MW, 2 MW, and 5 MW, respectively. The relative normalization between the 3 neutrino sources is determined from the relative rates of \( \nu_e \)-oxygen (or \( \nu_e \)-carbon) events, while the absolute normalization is determined from the number of \( \nu_e \)-electron events from the near neutrino source.
Table 1. Configurations considered in the various CP violation sensitivity studies. Reproduced from Ref. [15].

| Configuration Name                   | Source(s)          | Average Long Baseline Beam Power | Detector | Fiducial Volume | Run Length |
|-------------------------------------|--------------------|---------------------------------|----------|-----------------|------------|
| DAEδALUS@LENA                       | DAEδALUS only      | N/A                             | LENA     | 50 kt           | 10 years   |
| DAEδALUS@Hyper-K                    | DAEδALUS only      | N/A                             | Hyper-K  | 560 kt          | 10 years   |
| DAEδALUS/JPARC (nu only)@Hyper-K    | DAEδALUS & JPARC   | 750 kW                          | Hyper-K  | 560 kt          | 10 years   |
| JPARC@Hyper-K                       | JPARC              | 750 kW                          | Hyper-K  | 560 kt          | 3 years ν + 7 years ¯ν [11] |
| LBNE                                | FNAL               | 850 kW                          | LBNE     | 35 kt           | 5 years ν 5 years ¯ν [14] |

The CP violation sensitivities for the experiment configurations given in Table 1 are shown in Figure 1. The most powerful configuration combines the DAEδALUS source with the Hyper-K detector, which can run in parallel with a 750 kW traditional neutrino-only long baseline beam from JPARC. A ten year run with this combination gives a 1σ measurement uncertainty of less than 5° for certain values of δ_{CP}.

![Graph showing CP violation sensitivity estimates for various experiment configurations. See Table 1 for the description of each configuration. Reproduced from Ref. [15].](image-url)

3. A Phased Neutrino Physics Program

The “accelerator units” that drive each of the DAEδALUS neutrino sources consist of four main components: the ion source, the injector cyclotron, the SRC, and the target/dump. This modularity of this design allows the DAEδALUS neutrino physics program to be phased in a natural way.

3.1. Phase I: Ion Source

The first phase of the DAEδALUS neutrino physics program is to capture and accelerate 10 mA protons in the form of H^+_2. Commercial cyclotrons can reliably capture and accelerate 2 mA of protons at an injection energy of 30 keV. Space charge forces at injection can cause unacceptable beam losses in the cyclotron if the intensity of the proton beam is increased to 10 mA. The generalized perveance \( K = qI/(2\pi\epsilon_0m\gamma^3\beta^3) \) is a measure of this effect. However, if instead one injects 10 mA of protons in the form of H^+_2 at an energy of 35 keV/n, the generalized perveance is equivalent to that of a 2 mA proton beam injected at 30 keV, and so the space charge forces should be comparable.

The DAEδALUS injector cyclotron is expected to have an RF phase acceptance of \( \sim 10\% \). Therefore, in order to capture and accelerate 10 mA of H^+_2 in the injector cyclotron, the DAEδALS ion source needs to deliver a continuous-wave (CW) beam with between 25 – 50 mA of H^+_2, depending on whether a buncher can
be used to increase the injection efficiency into the cyclotron. Space charge may again limit this efficiency and so it is important that experimental tests of this be performed.

Though CW ion sources delivering 50 mA of protons are not unusual, this is at the edge of what has been achieved for $H_2^+$ sources. A test stand to study and optimize the ion source and injection system for the DAEδALUS injector cyclotron has been assembled at Best® Cyclotron Systems, Inc. (BCSI) in Vancouver, Canada. A 2.45 GHz non-resonant electron cyclotron resonance (ECR) source [16] capable of producing 40 mA of proton current and 15 mA of $H_2^+$ was shipped from LNS-INFN (Catania) to BCSI for this purpose [17]. Preliminary tests demonstrated good separation of proton and $H_2^+$ beams using a focusing solenoid (see Fig. 2). Further studies of the ion source and injection system will resume in Summer 2014.

![Beam stop current vs. Solenoid current](image)

Fig. 2. BCSI test stand beam stop current vs. focusing solenoid current for 1200 W of microwave power and a 40 kV extraction voltage. The beam stop is located behind a collimator with a 2 cm diameter. The proton beam from the ion source peaks at a solenoid current of 190 A, and the $H_2^+$ peaks at a solenoid current of 280 A.

3.2. Phase II: IsoDAR

The second phase of the DAEδALUS neutrino physics program is to use the DAEδALUS injector cyclotron to produce an intense beam of neutrinos from radioactive isotope decay-at-rest. The Isotope Decay-At-Rest (IsoDAR) experiment proposes to collide the 60 MeV/n, 10 mA $H_2^+$ beam from the DAEδALUS injector cyclotron into a $^8$Be target surrounded by 99.99% isotopically pure $^7$Li sleeve to produce $^8$Li [18].

If the target is installed 16 m away from a kiloton-scale liquid scintillator detector such as KamLAND, the isotropic neutrino flux from $^8$Li $\beta$ decay can produce over $8 \times 10^5$ IBD events in the detector over 5 years. This data set can be used to perform a definitive sterile neutrino search, which can rule out the parameter space allowed by global fits to the Reactor, SAGE, and GALLEX anomalies at 20$\sigma$ and can also discriminate between different sterile neutrino models. IsoDAR will also produce more than $7 \times 10^3$ $\nu_e$–electron events in the KamLAND detector. These events can be used as a sensitive probe of electroweak parameters and to search for new physics such as neutrino nonstandard interactions (NSIs) [19].
3.3. Phases III & IV: Near accelerator and full system

The third phase of the DAEδALUS neutrino physics program is to build the SRC and target/dump so that the first complete “accelerator unit” for the near neutrino source can be constructed. The construction of this neutrino source enables a broad “near accelerator” physics program, which includes sterile neutrino searches [21], searches for coherent neutrino scattering [22], sterile neutrino searches using neutral current coherent neutrino scattering [23], and measurements of the weak mixing angle with neutrino electron scattering [20].

Finally, the fourth phase of the DAEδALUS neutrino physics program is to complete the high power mid-distance and far neutrino sources, which enables the CP violation search described above.

4. Conclusion

DAEδALUS is a proposed neutrino physics program employing new low cost, high power cyclotrons to produce intense decay-at-rest neutrino beams. By following a phased approach, the DAEδALUS program can produce compelling physics results at each stage in the development of these high power cyclotrons. The program is punctuated by two world-class experiments: a search for CP violation in the neutrino sector with sensitivities down to 5° and IsoDAR, a definitive search for sterile neutrinos.

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References

[1] A. de Gouvea, et al., Working Group Report: Neutrinos, 1310.4340.

[2] A. Aguilar, et al., Evidence for neutrino oscillations from the observation of $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam, Phys. Rev. D 64 (2001) 112007. doi:10.1103/PhysRevD.64.112007. URL http://link.aps.org/doi/10.1103/PhysRevD.64.112007

[3] Aguilar-Arevalo, et al., Search for electron neutrino appearance at the $\delta m^2 \sim 1 eV^2$ scale, Phys. Rev. Lett. 98 (2007) 231801. doi:10.1103/PhysRevLett.98.231801.

[4] Aguilar-Arevalo, et al., Search for electron antineutrino appearance at the $\delta m^2 \sim 1 eV^2$ scale, Phys. Rev. Lett. 103 (2009) 111801. doi:10.1103/PhysRevLett.103.111801.

[5] G. Mention, M. Fechner, T. Lasserre, T. Mueller, D. Lhuillier, et al., The Reactor Antineutrino Anomaly, Phys.Rev. D83 (2011) 073006. arXiv:1101.2755, doi:10.1103/PhysRevD.83.073006.

[6] C. Giunti, M. Laveder, Statistical Significance of the Gallium Anomaly, Phys.Rev. C83 (2011) 065504. arXiv:1006.3244, doi:10.1103/PhysRevC.83.065504.

[7] J. M. Conrad, M. H. Shaevitz, Multiple cyclotron method to search for cp violation in the neutrino sector, Phys. Rev. Lett. 104 (2010) 141802. doi:10.1103/PhysRevLett.104.141802.

[8] J. Alonso, F. Avignone, W. Barletta, R. Barlow, H. Baumgartner, et al., Expression of Interest for a Novel Search for CP Violation in the Neutrino Sector: DAEdALUS, 1207.4895.

[9] M. Abs, A. Adelmann, J. Alonso, W. Barletta, R. Barlow, et al., Multimegawatt DAEδALUS Cyclotrons for Neutrino Physics, 1006.0260.

[10] M. Wurm, et al., The next-generation liquid-scintillator neutrino observatory LENA, Astropart.Phys. 35 (2012) 685–732. arXiv:1104.5620, doi:10.1016/j.astropartphys.2012.02.011.

[11] K. Abe, et al., Letter of Intent: The Hyper-Kamiokande Experiment — Detector Design and Physics Potential —, 1109.3262.

[12] A. de Bellefon, et al., Memphys: A large scale water cerenkov detector at frejus, hep-ex/0607026.

[13] T. Akiri, et al., The 2010 Interim Report of the Long-Baseline Neutrino Experiment Collaboration Physics Working Groups, arXiv:1110.6249 [hep-ex].

[14] M. Bishai, M. Diwan, S. Kettel, J. Stewart, R. Tschirhart, et al., Precision Neutrino Oscillation Measurements using Simultaneous High-Power, Low-Energy Project-X Beams, arXiv:1307.0807 [hep-ex].

[15] A. Adelmann, J. Alonso, W. Barletta, J. Conrad, M. Shaevitz, et al., Cyclotrons as Drivers for Precision Neutrino Measurements, Adv.High Energy Phys. 2014 (2014) 347097. arXiv:1307.6465, doi:10.1155/2014/347097.

[16] F. Mainone, L. Celona, F. Chines, G. Ciavola, G. Gallo, et al., Status of the Versatile Ion Source VIS, Conf.Proc. C0806233 (2008) MOPC151.
[17] J. R. Alonso, L. Calabretta, D. Campo, L. Celona, J. Conrad, R. G. Martinez, R. Johnson, F. Labrecque, M. H. Toups, D. Winckler, L. Winslow, Characterization of the Catania VIS for H$_2^+$, Rev.Sci.Instrum. 85 (2014) 02A7A2. doi:10.1063/1.4850736.
[18] A. Bungau, A. Adelmann, J. R. Alonso, W. Barletta, R. Barlow, L. Bartoszek, L. Calabretta, A. Calanna, D. Campo, J. M. Conrad, Z. Djurcic, Y. Kamyschkov, M. H. Shaevitz, I. Shimizu, T. Smidt, J. Spitz, M. Wascko, L. A. Winslow, J. J. Yang, Proposal for an electron antineutrino disappearance search using high-rate li8 production and decay, Phys. Rev. Lett. 109 (2012) 141802. doi:10.1103/PhysRevLett.109.141802.
URL http://link.aps.org/doi/10.1103/PhysRevLett.109.141802
[19] J. Conrad, M. Shaevitz, I. Shimizu, J. Spitz, M. Toups, et al., Precision $\bar{\nu}_e$-electron Scattering Measurements with IsoDAR to Search for New Physics, Phys.Rev. D89 (2014) 072010. arXiv:1307.5081, doi:10.1103/PhysRevD.89.072010.
[20] S. K. Agarwalla, P. Huber, Potential measurement of the weak mixing angle with neutrino-electron scattering at low energy, JHEP 1108 (2011) 059. arXiv:1005.1254, doi:10.1007/JHEP08(2011)059.
[21] S. Agarwalla, J. Conrad, M. Shaevitz, Short-baseline Neutrino Oscillation Waves in Ultra-large Liquid Scintillator Detectors, JHEP 1112 (2011) 085. doi:10.1007/JHEP12(2011)085.
[22] A. Anderson, J. Conrad, E. Figueroa-Feliciano, K. Scholberg, J. Spitz, Coherent Neutrino Scattering in Dark Matter Detectors, Phys. Rev. D 84 (2011) 013008. doi:10.1103/PhysRevD.84.013008.
[23] A. Anderson, et al., Measuring Active-to-Sterile Neutrino Oscillations with Neutral Current Coherent Neutrino-Nucleus Scattering, Phys. Rev. D 86 (2012) 013004. doi:10.1103/PhysRevD.86.013004.