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Whitepaper on the DAEDALUS Program

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Whitepaper on the DAE δ ALUS Program

The DAE δ ALUS Collaboration, July 12, 2013

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Abstract: This whitepaper describes the status of the DAE δ ALUS program for development of high power cyclotrons as of the time of the final meeting of the Division of Particles and Fields 2013 Community Study (“Snowmass”). We report several new results, including a measurement capability between ~ 4 and 12 degrees on the CP violating parameter in the neutrino sector. Past results, including the capability of the IsoDAR high $\Delta m^2 \bar{\nu}_e$ disappearance search, are reviewed. A discussion of the R&D successes, including construction of a beamline teststand, and future plans are provided. This text incorporates short whitepapers written for subgroups in the Intensity Frontier and Frontier Capabilities Working Groups that are available on the Snowmass website.

1 Introduction

DAE δ ALUS (Decay-At-rest Experiment for δ_{CP} studies At the Laboratory for Underground Science) is a phased R&D program leading to a high-sensitivity search for CP -violation [1, 2]. This is a unique, cyclotron-driven $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search for a non-zero CP violation parameter, δ_{CP} , in the three-neutrino mixing matrix. DAE δ ALUS, when combined with Hyper K (with-JPARC beam), can achieve an uncertainty of 4 to 12 degrees on δ_{CP} —well beyond the sensitivity of LBNE or HyperK alone. The system consists of a two-cyclotron design. The smaller injector cyclotron, which will be developed first, also can be used as a driver to provide a very pure $\bar{\nu}_e$ flux. This can be paired with KamLAND to allow for a disappearance search, called IsoDAR, that is a factor of five times more sensitive to oscillations indicative of a sterile neutrino than other proposals. DAE δ ALUS and IsoDAR are two examples of applications of these machines. However, one can envision uses beyond these within neutrino physics, including cross sections and Beyond Standard Model Searches. These cyclotrons are also valuable commercially, which is why DAE δ ALUS has a strong industry-university collaboration on the R&D program.

This whitepaper reports on the status of the DAE δ ALUS program for the Division of Particles and Fields 2013 Community Study (“Snowmass”). We provide an overview of the physics: the CP Violation search, the $\bar{\nu}_e$ disappearance search, the measurement of cross sections; and the search for new physics. We then provide a discussion of status and plans: an introduction to the context; progress on the design; the studies at a Best Cyclotrons, Inc., teststand and the planned Catania teststand; and the required longer term R&D. We end by discussing the broader impacts of these machines. This whitepaper incorporates the text from the many one- or two-page whitepapers that the DAE δ ALUS collaboration has provided to the Neutrino Working Group (Intensity Frontier), the Working Group on High Intensity Secondary Beams Driven by Protons (Frontier Capabilities) and the Working Group on Accelerator Technology testbeds and test Beams (Frontier Capabilities). As we combine the content of these whitepapers, we maintain the philosophy that each section should be short, but well-justified through the references, which is possible because of extensive documentation concerning the program already on the arXiv and in published journals.

2 Physics of The Program

2.1 DAE δ ALUS: The CP Violation Search

The DAE δ ALUS phased program for CP -violation studies is formed by sets of “modules” consisting of an ion source, an injector cyclotron (DIC), a superconducting ring cyclotron (DSRC), and a target/dump. Modules are arranged at three sites. The experiment uses π/μ decay-at-rest (DAR) to search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with the atmospheric Δm^2 . The $\bar{\nu}_e$ will be detected, via the inverse beta decay interaction, in an underground, ultra-large free-proton-based (water or oil) detector. The CP -violation signal is extracted by measuring the oscillation wave as a function of distance L that the neutrinos have travelled, with positions at $L = 1.5$ km, 8 km, and 20 km. The final phase of the program leads to a unique CP -violation experiment.

The program proceeds in four phases. Phase I, which is well underway, involves development and testing of an ion source and low-energy beam transport system, including design of the inflection system that guides the beam into the cyclotron. Phase II establishes the injector cyclotron, discussed in Sec. 2.2, below. Phase III will result in a running DSRC and associated target/dump; i.e. the first full accelerator module. This module will be located nearest to the detector and runs with a 13% duty factor, producing 0.8 MW average power on the dump/target. The physics case for this module is based on short-baseline searches for Beyond Standard Model physics [4, 5]. Lastly,

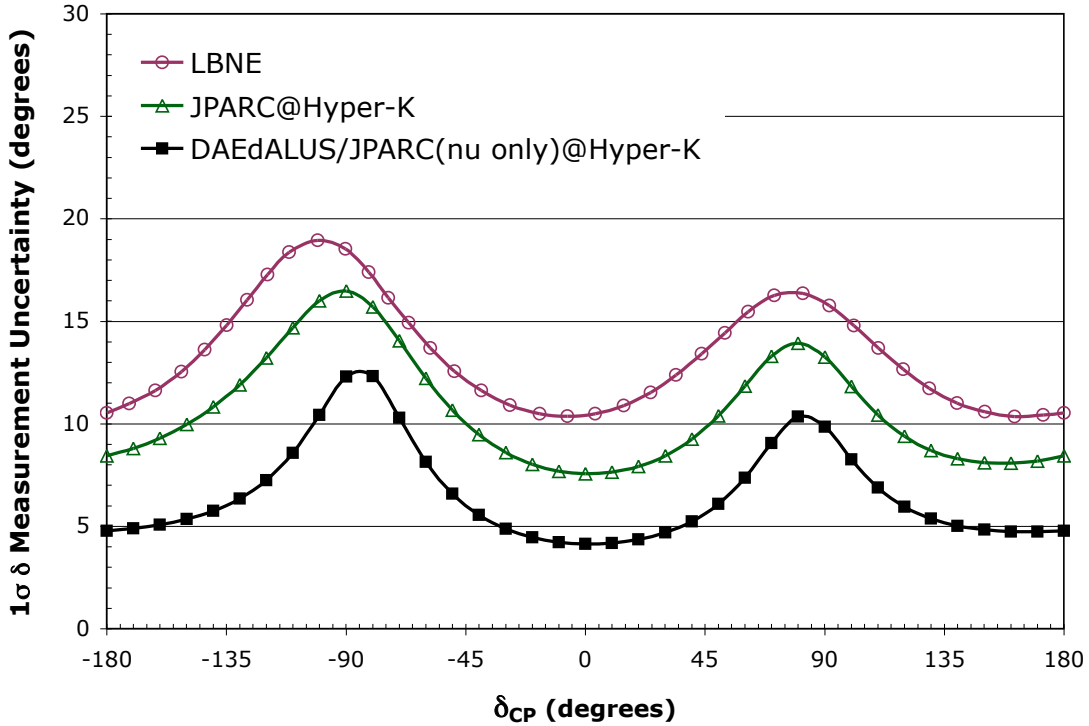
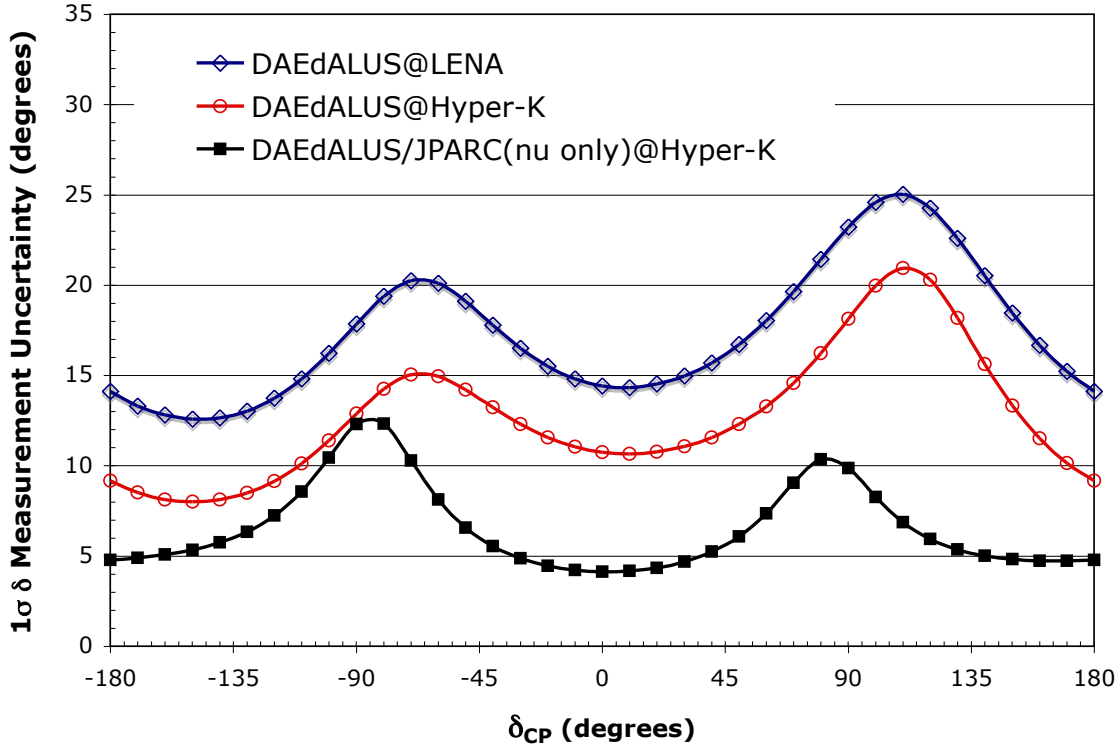


Figure 1: Top: The sensitivity of the CP-violation search in various configurations: Dark Blue – DAE δ ALUS@LENA, Red–DAE δ ALUS@Hyper-K, Black–DAE δ ALUS/JPARC(nu-only)@Hyper-K. Bottom: Light Blue– LBNE; Green–JPARC@Hyper-K [3] Black–DAE δ ALUS/JPARC(nu-only)@Hyper-K (same as above). See Table 1 for description of each configuration.

Configuration Name	Source(s)	Average Long Baseline Beam Power	Detector	Fiducial Volume	Run Length
DAE δ ALUS@LENA	DAE δ ALUS only	N/A	LENA	50 kt	10 years
DAE δ ALUS@Hyper-K	DAE δ ALUS only	N/A	Hyper-K	560 kt	10 years
DAE δ ALUS/JPARC (nu only)@Hyper-K	DAE δ ALUS & JPARC	750 kW	Hyper-K	560 kt	10 years
JPARC@Hyper-K	JPARC	750 kW	Hyper-K	560 kt	3 years ν + 7 years $\bar{\nu}$ [3]
LBNE	FNAL	850 kW	LBNE	35 kt	5 years ν + 5 years $\bar{\nu}$ [6]

Table 1: *Configurations under study for Snowmass.*

Phase IV introduces the modifications for high-power running needed at the mid and far sites for CP -violation studies.

The program requires free proton targets, hence water or scintillator detectors. The original case was developed for a 300 kt Gd doped water detector at Homestake, in coordination with LBNE [7]. Subsequently, DAE δ ALUS was incorporated into LENA [8] (called “DAE δ ALUS@LENA”). As a 50 kt scintillator oil detector, LENA is substantially smaller than the original 300 kt water design, but has the advantage of lower backgrounds. The sensitivity of DAE δ ALUS@LENA is shown in Fig. 1 (Top). For the Snowmass study, we have also considered a phased program in Japan, beginning by pairing with the existing Super-K detector (with Gd-doping) and followed by running with a Gd-doped 560 kt Hyper-K [3] (“DAE δ ALUS@Hyper-K”). This program could be combined with Hyper-K running with the 750 kW JPARC beam (“DAE δ ALUS/JPARC@Hyper-K”). In this scenario, JPARC provides a pure ν_μ flux, which is the strength of a conventional beam, while DAE δ ALUS provides a high statistics $\bar{\nu}_\mu$ flux. This leads to a impressive sensitivity to δ_{CP} , as shown on Fig. 1 (Top). A comparison with the expectation of a 35 kt LBNE detector running at 850 kW [6] and JPARC@Hyper-K [3] is shown in Fig. 1 (Bottom). A summary of the assumptions for the various configurations is provided in Table 1. Further description of this study is in [9]. A short-baseline beam from the ESS [10] may also be appealing, as neither the DAE δ ALUS nor ESS baselines are subject to matter effects.

This idea for a CP violation search has been well received by the wider community. The NRC Committee to Assess the Science Proposed for a Deep Underground Science and Engineering Laboratory wrote: “Proposals for new second generation experiments with water Cherenkov detectors include very imaginative possibilities, such as the DAE δ ALUS proposal to create neutrinos using a series of small nearby cyclotrons” [11].

2.2 IsoDAR: A Search for $\bar{\nu}_e$ Disappearance at Short Baseline

IsoDAR is a novel isotope decay-at-rest source of $\bar{\nu}_e$ for Beyond Standard Model searches. The source [12] consists of an accelerator producing 60 MeV protons [18] that impinge on a ^9Be target, producing neutrons. IsoDAR can use the same cyclotron design as the injector cyclotron for the two-cyclotron DAE δ ALUS system. The protons enter a surrounding 99.99% isotopically pure ^7Li sleeve, where neutron capture results in ^8Li ; this isotope undergoes β decay at rest to produce an isotropic $\bar{\nu}_e$ flux with an average energy of ~ 6.5 MeV and an endpoint of ~ 13 MeV. The $\bar{\nu}_e$ will interact in a scintillator detector via inverse beta decay (IBD), $\bar{\nu}_e + p \rightarrow e^+ + n$, which is easily tagged through prompt-light–neutron-capture coincidence. When paired with KamLAND [19], the experiment can observe 8.2×10^5 reconstructed IBD events in five years. With this data set, IsoDAR will decisively test sterile neutrino oscillation models, allow precision measurement of $\bar{\nu}_e$ - e scattering, and search

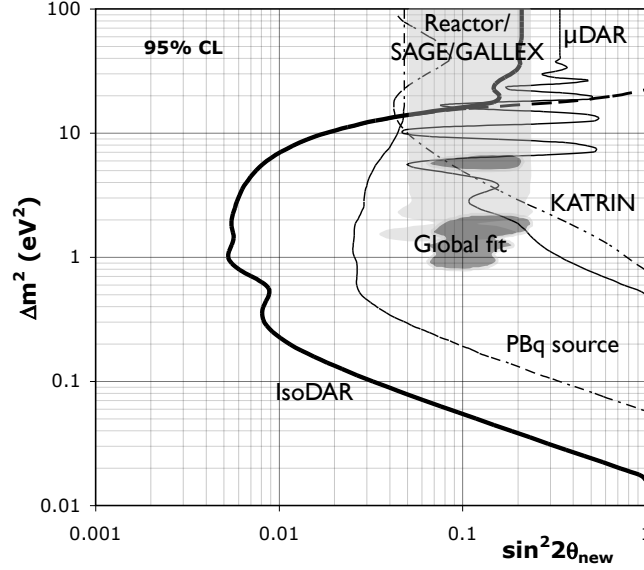


Figure 2: The sensitivity of the IsoDAR experiment to $\bar{\nu}_e$ disappearance in a five-year run, reprinted from Ref. [12]. The sensitivities for both rate+energy shape (solid line) and shape-only (dashed line) are shown. Other curves from Refs. [13, 14, 15, 16].

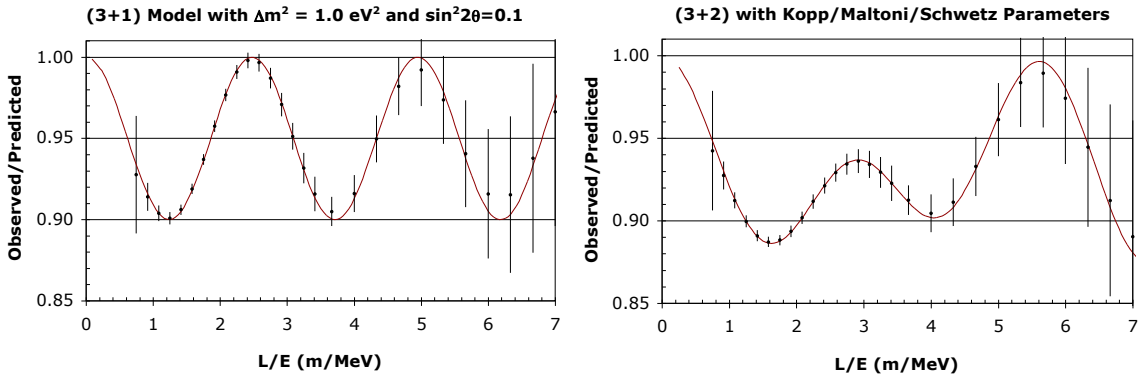


Figure 3: The L/E dependence of two example oscillation signatures after five years of IsoDAR running considered in Ref. [12]. The solid curve is the oscillation probability with no smearing in the reconstructed position and energy. The 3+2 example (right) represents oscillations with the global best fit 3+2 parameters from Ref. [17].

for production and decay of exotic particles.

The sterile neutrino search uses electron flavor disappearance, interpreted within models with three active and one (3+1) or more sterile neutrino flavors [20, 17, 21, 22]. These models result from fits to combined appearance (muon-to-electron flavor [23, 24, 25]) and disappearance (muon flavor [26, 27, 28] and electron flavor [13, 14, 29]) data. Fig. 2 presents the oscillation landscape at 95% confidence level for electron flavor disappearance in a 3+1 model. IsoDAR covers the global fit allowed region for $\bar{\nu}_e$ disappearance [20] (dark grey) at 5σ in four months. The high statistics of the five-year run can distinguish models with one or more sterile neutrinos, as shown in Fig. 3. The impressive capability of IsoDAR led to its choice as a Physical Review Letters highlight [30].

2.3 Precision Fluxes, Cross Sections and Searches for New Physics

The decay-at-rest (DAR) beams produced by the cyclotrons for the DAE δ ALUS and IsoDAR programs are unique sources for precision cross-section studies and high-sensitivity searches. As a result,

interest has been expressed by the cross-section [31, 32, 33, 34] and exotic physics search communities [35, 36, 37, 38, 39]. Therefore, these cyclotrons can be seen as a new tool within the overall neutrino program. Stand-alone sites can be implemented by coalitions of universities within the neutrino community. The relatively modest cost range (from \$25M to \$100M, depending on design) makes several centers potentially feasible.

As neutrino physics enters the precision era, π/μ -DAR and isotope-DAR beams (e.g., ^8Li), in which the energy dependence and the flavor contents are precisely known (see Fig. 4), are valuable. There is already a history of cross-section physics from π/μ sources [40, 41, 42]. The primary issue for precision measurement is that absolute flux rates are only predicted to $\sim 20\%$ [43]. However, one can potentially normalize to inverse beta decay or to neutrino-electron scattering, both of which have cross sections known to $< 1\%$, greatly reducing normalization errors.

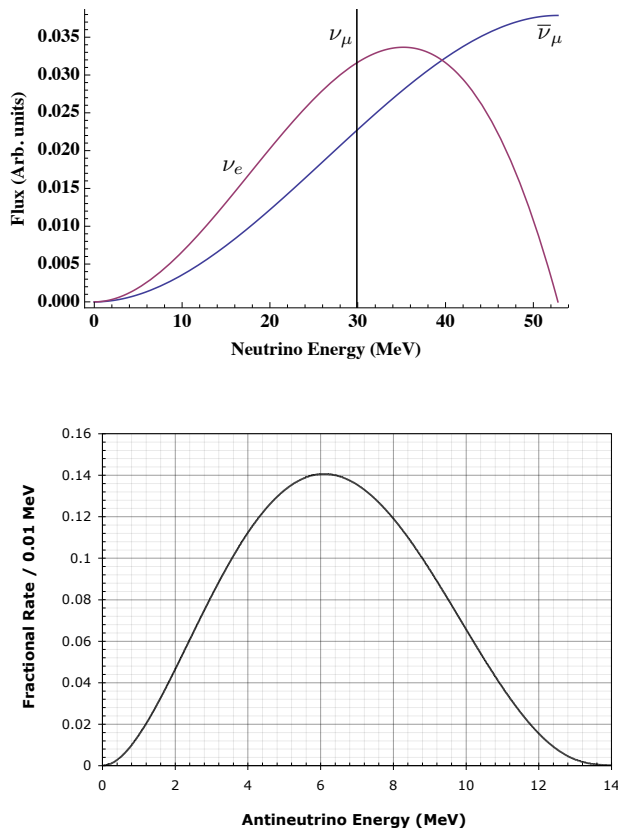


Figure 4: Fluxes from π/μ (top) and ^8Li (bottom) decay at rest, from Ref. [9].

The sources can be designed to deliver ~ 100 kW to 1 MW, depending on the flux required. If space is limited, such as at an underground lab, the optimal energy range for an ^8Li DAR driver is about 60 MeV/amu [44]. On the other hand, the driver energy is ~ 800 MeV/amu for π/μ DAR sources[1]. A variety of detectors can be paired with isotope and pion/muon DAR sources, including dark matter detectors [32] and scintillator detectors [23, 41].

Alternatively, the accelerators can provide charged particle beams either directly (isotopes) or in a secondary line (pions, muons), allowing applications beyond neutrino physics. This has led to worldwide interest. For example, our 60 MeV/amu machine is quite similar to the cyclotron being developed for the SPES (Selective Production of Exotic Species) Project [45], at Laboratori Nazionali di Legnaro in Italy. Also, our 800 MeV/amu cyclotron is quite similar to the existing superconducting ring cyclotron of RIKEN used to drive their Radioactive Ion beam facility [46].

For the Snowmass study, the collaboration is presenting searches for nonstandard interactions (NSIs) through studies of antineutrino-electron scattering as an example of a precision search and coherent neutrino scattering as an example of cross-section studies.

2.3.1 Antineutrino-Electron Scattering

A sample of > 2400 antineutrino-electron scattering (ES) events ($\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$) will be collected by IsoDAR in a 5 year run—a five times larger sample in the low Q^2 range than exists today [47, 48, 49, 50]. This allows for sensitive searches for Beyond Standard Model physics through deviations of the cross section from the *ab initio* prediction, which is highly precise given the recent electroweak results from LHC [51]. In our example, we examine the effect of non-standard interactions on the

measured weak couplings, g_R and g_L , or, equivalently, $\sin^2 \theta_W$. NSIs, introduced into the theory via an effective 4-fermion term in the Lagrangian [52], can induce instantaneous transitions from electron flavor to some other flavor, leading to deviations in the measurement from expectation.

The analysis method follows that of Ref. [53], which proposed a similar measurement for reactors. The IsoDAR-based measurement has the advantage of a higher energy flux than that of a reactor. The ES event rate is normalized by inverse beta decay events and the expected backgrounds for a run at the KamLAND detector are well understood from the solar neutrino studies [54] which are also a single-flash signal.

Our analysis will be described in Ref. [55], which is in draft, and will appear on the arXiv in time for the final Snowmass Meeting. Our study considered rate-only, energy-dependence-only, and rate-plus-energy-dependence. The strength of the result is in the rate, with $\delta \sin^2 \theta_W = 0.0085$ for rate-only and $\delta \sin^2 \theta_W = 0.0084$ for rate-plus-energy-dependence. Although backgrounds are constrained by beam-off running, subtraction adds considerably to the error. If directional reconstruction becomes available through addition of fast PMTs that allow Cerenkov reconstruction [56], then the backgrounds may be reduced by a factor of two. In this case, we achieve $\delta \sin^2 \theta_W = 0.0065$.

IsoDAR’s sensitivity to the NSI parameters ϵ_{ee}^{eL} and ϵ_{ee}^{eR} are shown in Figure 5 (left). The IsoDAR result provides complementary information to the currently allowed global regions for these parameters[57].

2.3.2 Coherent Neutrino and AntiNeutrino Scattering

Coherent neutrino scattering is an as-yet-unobserved Standard Model process; however, its cross section is well-predicted. This process has a large cross section in the energy regime relevant for DAR sources from the DAE δ ALUS program. However, the signature, which is a recoil nucleon with ~ 10 keV, is quite difficult to observe. With this said, modern dark matter detectors have this capability. Thus, the injector cyclotron used in IsoDAR or the full-scale DAE δ ALUS system open up the opportunity for discovering new physics through this precision measurement.

The collaboration has already published results on the sensitivity of the π/μ DAR design to new physics through coherent scattering [32, 38]. Therefore, here we focus on the latest results which explore the expectation for the ${}^8\text{Li}$ flux. For further details, see Ref. [9].

Figure 5(right) shows the expected rates in terms of nuclear recoil energy for an IsoDAR source ($2.58 \times 10^{22} \bar{\nu}_e/\text{year}$) in combination with a 1000 kg argon detector at a 10 m average baseline from the source with a 1 keV nuclear recoil energy threshold and 20% energy resolution. While such a detector is not yet available, this is within the goals of future dark matter experiments. Given these assumptions, about 1200 events per year could be collected for a high statistics sampling of this event class. A first observation of the process is clearly possible with a more modest size detector as well.

3 Accelerator Studies Status and Needs

3.1 Context for further discussion

The key to the program is state-of-the-art cyclotrons. Before presenting specifics, it is worthwhile to briefly review cyclotron design and terminology, since those reading this report may not have experience with cyclotron accelerators.

In a “compact” cyclotron, charged particles from an ion source are injected at the center, often via a “spiral inflector” – a device that directs the beam from a vertical (axial) direction to the horizontal median plane of the cyclotron magnet. Once inflected, the particles are bent by the magnetic field into roughly circular orbits. An RF cavity system accelerates the particles and, as they gain energy,

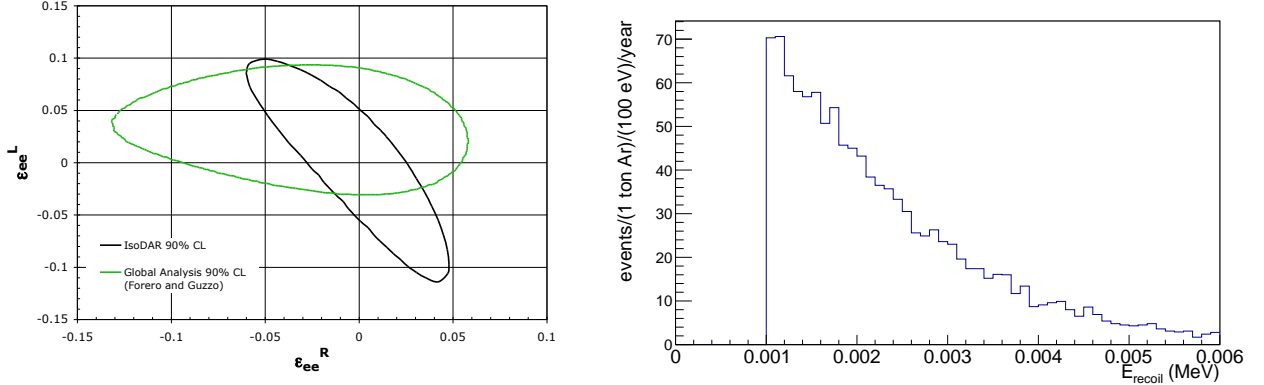


Figure 5: *Left: IsoDAR’s 90% CL sensitivity to ϵ_{ee}^L and ϵ_{ee}^R compared to the present global allowed region from Ref. [57]. Further details will be provided in Ref. [55]. Right: Coherent event rate in terms of nuclear recoil energy with a 1000 kg argon detector at a 10 m average baseline from the IsoDAR source.. Further explanation provided in Ref. [9].*

their trajectories spiral outwards. At the outer radius a “septum” (thin sheet of conducting material such as carbon, copper, tantalum) placed between the N th and $(N+1)$ th turns enables bending the particles into an extraction channel by a strong electric field. The spatial separation between the “turns” grows smaller as the beam approaches the outer edge of the cyclotron, making extraction without losing a lot of beam on the septum more difficult for higher energies.

A compact cyclotron uses a single coil surrounding the (generally very complicated) iron pole structure, and provides the smallest and most economical design for achieving the required beam energy. The iron pole is generally machined with azimuthal “sectors.” The pole face will have “hills” and “valleys” producing regions of high and low magnetic fields, which are needed to provide beam focusing and “isochronicity.” The isochronicity condition ensures the orbital revolution time is independent of beam energy, so that the RF frequency does not need to change as the particles are accelerated.

An alternate design, involving “separated sector” or individual pie-shaped magnets, offers advantages for higher intensity beams at the cost of complexity, size, and increased capital costs. The Paul Scherrer Institute (PSI) Injector II accelerator [58] is of this type. Beam can be injected into such a separated-sector machine at higher energies if one employs a booster accelerator such as an RFQ or high-voltage platform. This can mitigate much of the space-charge-induced reduction in beam quality of the compact, spiral-inflection design.

Presently, the highest current achieved for axially-injected compact proton (or H^-) cyclotrons is $\lesssim 2$ mA. The separated-sector PSI injector runs at 3 mA. To achieve the required neutrino fluxes we need 10 mA of protons on target. Our concept for achieving this much higher current is to work with molecular hydrogen (H_2^+) beams. As each ion carries two protons, only 5 electrical milliamperes (emA) are required to produce 10 mA of protons. Furthermore, because of the doubled mass, the ions carry more momentum, and are thus less affected by the space-charge forces that tend to cause the beam size to increase. These space-charge forces are characterized by a parameter K called “generalized perveance.” In fact, K for a 5 emA H_2^+ at our planned injection energy of 70 keV (35 keV/amu) is similar to that of a 2 mA proton beam. On this basis, we believe that we can achieve the required currents on target using the less-expensive compact design. Should it be necessary, we can always fall back on the more expensive separated sector concept.

To achieve the 800 MeV energies needed for DAE δ ALUS, the second cyclotron (the DSRC) must be of the separated-sector design. While the compact injector can have a normal-conducting (iron-

dominated) magnet, the higher energy machine must have superconducting coils and quite high ($\sim 6\text{T}$) peak fields. Injection is achieved, with the 60 MeV/amu energy with a series of electrostatic and magnetic elements that nudge the beam into the lowest-radius orbit. RF cavities again accelerate the beam to high energies, as quickly as possible to avoid beam losses due to stripping in the residual gas of the cyclotron. Extraction is done by a stripping foil; the H_2^+ ion enters the foil but emerges as two protons. These spiral inwards, but because of the highly irregular magnetic field a stripper-foil location can be found that enables the protons to exit the machine cleanly, about 180 degrees from the foil position. This stripping technique avoids the need for clean turn separation, which as mentioned earlier becomes very difficult at high energies. The only consequence is that ions hitting the foil could come from one of several turns (hence have an energy spread $\sim 1\%$). It is easy to design the extraction channel to have momentum acceptance adequate to accommodate this.

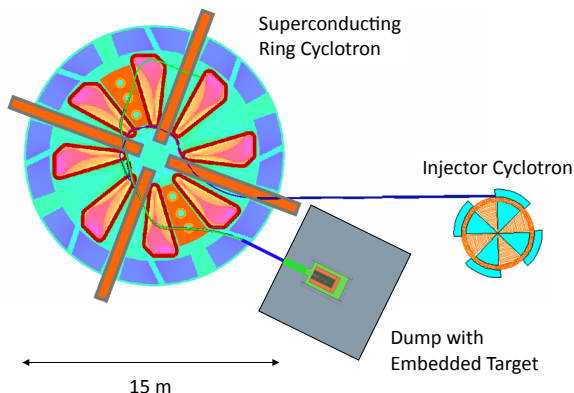


Figure 6: *Layout of the two-cyclotron system. The magnetic field regions are indicated by the pastel colors. The injector cyclotron (small) is a compact design and the superconducting cyclotron (large) is a separated sector design. Figure from Ref. [9].*

Fig. 6 shows the layout of the DAE δ AUS two-cyclotron system. The magnetic fields are indicated by the pastel colors, where blue is negative and red is positive field. The position of the RF in the valleys is indicated in the orange on the DSRC.

The DSRC shares characteristics of several cyclotrons. TRIUMF, in Vancouver, Canada, is a 500 MeV H^- machine, over 18 meters in diameter (of beam orbit) but with a very low peak field to prevent Lorentz stripping of the very loosely-bound H^- ions. The PSI cyclotron is 590 MeV , 12 m in diameter, and is an 8-sector normal-conducting Ring Cyclotron. PSI has the distinction of being the world’s highest power cyclotron, at 1.3 MW currently. The RIKEN Superconducting Ring Cyclotron in Wako, Japan, [59] is designed for low-current heavy ion beams, but its magnet shares almost identical engineering specifications to the requirements for the

DSRC. This machine serves as a valuable engineering and costing model for the DSRC.

In Sec. 2.1, we broke the approach toward achieving the final system into four phases that had accompanying physics goals: 1) ion source, low energy beam transport and inflection; 2) acceleration in the injector cyclotron, and subsequent extraction; 3) acceleration in the superconducting ring cyclotron, and 4) producing the DAR fluxes (targeting and shielding). We will refer to these phases in the more detailed information we provide in the following sections.

3.2 The Cyclotron Design Parameters

In this section we discuss the current design parameters of the two cyclotrons: the DAE δ ALUS injector cyclotron (DIC) and the DAE δ ALUS Superconducting Ring Cyclotron (DSRC). Progress on the design on both machines has been published [18, 60, 61]. This section records the design parameters of the leading options for these two cyclotrons, at present. We note that the designs are under development and alternatives are under study.

The DIC can be used as a stand-alone accelerator for production of isotope-decay-at rest fluxes, as in the IsoDAR sterile neutrino search (Sec. 2.2), as well as an injector for the DAE δ ALUS CP violation search. The primary design option for the DIC is an H_2^+ accelerator. The design parameters

E_{max}	60 MeV/amu	E_{inj}	35 keV/amu
R_{ext}	1.99 m	R_{inj}	55 mm
$\langle B \rangle @ R_{ext}$	1.16 T	$\langle B \rangle @ R_{inj}$	0.97 T
Sectors	4	Hill width	28 - 40 deg
Valley gap	1800 mm	Pole gap	100 mm
Outer Diameter	6.2 m	Full height	2.7 m
Cavities	4	Cavity type	$\lambda/2$, double-gap
Harmonic	6th	RF-frequency	49.2 MHz
Acc. Voltage	70 - 250 kV	Power/cavity	< 110 kW
ΔE /turn	1.3 MeV	Turns	107
ΔR /turn @ R_{ext}	20 mm	ΔR /turn @ R_{inj}	> 56 mm
Coil size	200x250 mm ²	Current density	3.1 A/mm ²
Iron weight	450 tons	Vacuum	< 10^{-7} mbar

Table 2: *DIC design parameters, as of Snowmass 2013.*

E_{max}	800 MeV/amu	E_{inj}	60 MeV/amu
R_{ext}	4.9 m	R_{inj}	1.8 cm
$\langle B \rangle @ R_{ext}$	1.88 T	$\langle B \rangle @ R_{inj}$	1.06 T
Sectors	8	Hill width	23 deg
B_{max}	6.05 T	Pole gap	60 mm
Outer Diameter	14 m	Full height	5.6 m
Cavities	6	Cavity type	Single gap (4) Double gap (2)
Harmonic	6th	RF-frequency	49.2 MHz
Acc. Voltage	550-1000 kV	Power/cavity	300 kW
ΔE /turn	3.6 MeV	Turns	420
ΔR /turn @ R_{ext}	5 mm	ΔR /turn @ R_{inj}	> 10 mm

Table 3: *DSRC design parameters, as of Snowmass 2013.*

are shown in Table 2.

For IsoDAR, an important question under study is whether to use H_2^+ , as it is planned for DAE δ ALUS or instead run deuterons which, like H_2^+ , has charge-to-mass (q/m) ratio of 0.5. This represents a change in philosophy at the target of IsoDAR, where the H_2^+ design requires neutron production from the beryllium target, while a deuteron design delivers neutrons directly to the target. In this latter configuration, lower beam energies can produce the required rate of ^8Li . Thus the DIC central region would be maintained, but we would employ a smaller accelerating magnet radius for the lower energy beam. This reduces costs and makes underground construction easier although more beamline shielding will be required. During the period of the Snowmass study, we made great progress on this alternative design. We will compare this to the H_2^+ -based DIC design for IsoDAR at a review at the Eloisatron Workshop on High power cyclotrons and targets for Neutrino Physics, Nov. 12-17, 2013.

The DSRC is used to accelerate the 60 MeV/amu H_2^+ to 800 MeV/amu [18] for production of pion/muon decay at rest fluxes [2]. The parameters of the DSRC are given in Table 3. Aspects of the 8-sector design are very similar to the RIKEN cyclotron [59]. In Table 4, we provide a comparison of parameters. The primary difference is that RIKEN is a 6-sector machine. Based on the success of the RIKEN accelerator and the engineering complexities of an 8-sector design, the

Basic Parameters	DSRC	RIKEN-SRC	Unit
Maximum field on the hill	6.05	3.8	T
Maximum field on the coil	6.18	4.2	T
Stored Energy	280	235	MJ
Coil size	30× 24 or 15× 48	21× 28	cm ²
Coil Circumference	9.8	10.86	m
Magnetomotive force	4.9	4	MA _{tot} /sector
Current density	34	34	A/mm ²
Height	5.6	6.0	m
Length	6.9	7.2	m
Weight	≤450	800	ton
Additional magnetic shield	0	3000	ton/total
Magnetic Forces			
Expansion	1.87 or 1.8	2.6	MN/m
Vertical	3.7	3.3	MN
Radial shifting	2.7	0.36	MN
Azimuthal shifting	0.2	0	MN
Main Coil			
Operational current	5000	5000	A
Layer × turn	31×16	22×18	
Cooling	Bath cooling	Bath cooling	
Maddock Stabilized Current	6345	6665	A
Other Components			
SC trim	no	4	sets
NC trim × turn	no	22	pairs
Stray field in the SRC valley region	0.7	0.04	T
Gap for thermal insulation	40	90@min.	mm
Extraction method	Stripper foil	Electrostatic channel	

Table 4: Comparison of the DSRC design at the time of Snowmass 2013 (an 8-sector design) with RIKEN (a 6-sector design).

DSRC is now proceeding through a second iteration where we are examining the viability of a six-sector configuration. We have completed an engineering study of the new six-sector layout, which is published in Ref. [61]. This report develops a viable engineering design satisfying requirements for the superconductor, as well as structural and cryogenic requirements. The work includes solid modeling and analyses for the conductor and winding pack design, high temperature superconductor and copper current leads for the magnet, structural design of the magnet cold mass, cryostat and warm-to-cold supports, cryogenic design of the magnet cooling system, and magnet power supply sizing. A beam simulation study for the six-sector design is now under way.

3.3 Status of Present and Near Future Accelerator R&D

We have begun an extensive experimental testing program of the designs. Our first tests are being performed in the spring/summer of 2013 at the Vancouver site of Best Cyclotron Systems, Inc. The VIS, or Versatile Ion Source, a off-resonant microwave discharge ion source [62] built at the Laboratori Nazionali del Sud (LNS) in Catania, Italy, has been shipped to Vancouver for these tests. This source is designed to provide ~50 mA of protons or deuterons and is expected to reach >20 mA

of H_2^+ when optimized. Best Cyclotrons has built a small test cyclotron suitable for 1 MeV (to ensure no neutron production), which allows captured beam to be accelerated to eight turns. The central region, consisting of a spiral inflector, dee configuration, and post-collimator, is being assembled as the final Snowmass meeting begins.

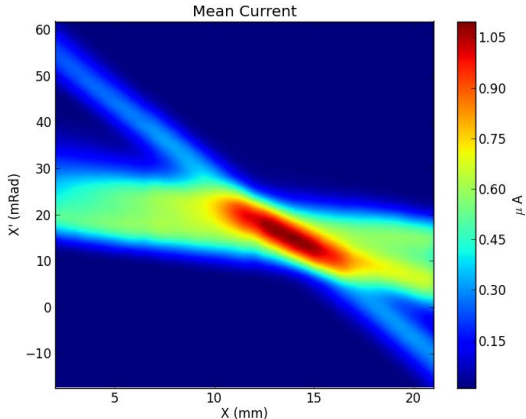


Figure 7: *Emittance measurement result performed at the Best teststand. Three ellipses related to protons, H_2^+ and H_3^+ produced from the ion source can be seen.*

Source characterization measurements and optimization for H_2^+ ions have been started; the emittance plot shown in Fig. 7 is an example. Emittance is a measure of beam quality, plotted on (x, x') or (y, y') axes. A good beam will be represented by an ellipse. The area of the beam ellipse is the emittance, which does not change for conservative systems. In the plot shown in Fig. 7, one can discern three ellipses associated with the three beam species: protons (most tilted and weakest), H_2^+ , and slightly closer to the axis a small admixture of H_3^+ . The different tilt of each ellipse reflects different focusing strengths for the three beams. Total beam current for this run was ~ 10 mA. The ratio of the three species can be varied by changing the microwave power fed to the source. This figure represents an optimum for H_2^+ , with this ion

comprising roughly 40% of the beam.

The measurements obtained for the run at Best Cyclotrons will provide constraints for the DAE δ ALUS OPAL simulations. The OPAL code [63], developed at the PSI, is widely used for simulations of highly space-charge-dominated beams in cyclotrons and beam-lines. Benchmarking code predictions with experimental results is a key element of the overall R&D program.

While we are making substantial progress towards our ultimate goal with the tests in Vancouver, development of the complex central region often requires iterations, and we envision the need to improve the design based on these measurements. As a result, we are already planning the follow-up experiment: a new test-stand to be built at INFN-LNS in Catania, Italy. This will use an improved ion source, a redesigned transport line, and a 7 MeV/amu cyclotron. The central region of this new cyclotron will be designed based on the experience gained from the tests in Vancouver. The magnetic field study for the Catania teststand cyclotron has been completed, and Best Theratronics [64] will provide the engineering study in 2013. The order for all cyclotron components (magnet, RF cavities, vacuum system, diagnostic system, and electrostatic deflector) will be completed during winter 2013-14. The timescale to construct the components is one year. Thus assembly would begin in late 2014, contingent on funding.

3.4 Areas of R&D – A Summary for Each Phase

During the Snowmass Study, we were requested by the Frontier Capabilities Working Groups, as well as the Facilities Panel for DOE High Energy Physics, to discuss the R&D needs for each phase. This section briefly reviews the information we provided.

Phase I is well underway. As discussed above, the INFN-Catania ion source is now running in the teststand at Best Cyclotron Systems, Inc. Simulating the inflector is quite difficult, and so development of this piece, and the overall central region, requires experimental iterations. Our second iteration on the test stand, also described above, will be performed at Catania.

Beyond this, an interesting technical challenge for the *CP* program, which runs H_2^+ at 800 MeV/amu, is the removal of ions in the high vibrational states. At 800 MeV, the high vibrational states of this molecule will Lorentz-strip in the 6 T outer field of the DSRC. As much as 10% of the beam could be lost through this process if the ions are not removed from the beam. Calculations show that the lowest four states will be stable [65]. We are investigating ways to remove the high vibrational states. Work in collaboration with Oak Ridge National Laboratory retested the methods of Sen, *et al.* [66], which involve introducing a noble gas into the ion source. Results were difficult to interpret in the first round of tests; however, dissociation of these vibrational states by this mechanism in the ion source is believed to require long (millisecond) residency times of the ions prior to extraction. If this is true, then we must consider a redesign of the source [66] or a method of removing the vibrational states after the H_2^+ exits the source.

Phase II is also underway. The overall goal is output of 5 mA of H_2^+ (or 10 mA of protons) at 60 MeV/amu. The generalized perveance, which characterizes the space charge of the cyclotron, is, at injection, equivalent to existing machines. An important paper relevant to the space-charge issues of this cyclotron is Ref. [60]. Note that this is a full OPAL simulation, which is the well-established and experimentally benchmarked code for these type of studies (it is the GEANT-equivalent for cyclotrons). Our first iteration of this cyclotron passed an internal review held at Erice in November 2012, and a second iteration of the design parameters has already been established. We plan another review of the Phase I and Phase II combined results for next October, to be held at PSI.

The primary issue for the Phase III development is the DRSC. After a careful review, we have moved from the eight-sector design of Ref. [18] to a 6-sector design which is very close to the existing RIKEN cyclotron. Simulations of the new machine are underway. As discussed above, we have had a detailed engineering study performed of this six-sector design [61]. This has allowed a detailed US-style costing for the magnet, which is the most expensive novel element within DAE δ ALUS. Other costs can be determined directly from the RIKEN and PSI experience with the correction for the differences in accounting.

The 1 MW target is part of the Phase III development. Because the beam is extracted via stripping foils, we can extract to several targets to limit instantaneous power. Also, the beam will be painted over a 30 cm target face, greatly reducing power issues.

Phase IV, which is at the least advanced stage, takes the Phase III system to high power. The collaboration has several competing conceptual designs on how to achieve this. The ideas presently under consideration will be carefully reviewed in the future, as this final phase develops.

To briefly summarize the top experimental issues on which the collaboration is working at present:

1. Increasing current of the source to >50 mA H_2^+ .
2. Demonstrating the removal of high vibrational states of H_2^+ .
3. Demonstrating 5 mA beam capture and emittance control in the central region of the injector cyclotron.
4. Detailed simulation of high-efficiency beam extraction from the injector.
5. Full end-to-end simulation of beam dynamics using the proven OPAL code.

A long-term experimental goal is likely to involve a full-scale prototype of one sector of the DSRC. We are in the process of planning for this.

The collaboration working on this R&D includes universities, international laboratories, and industry. Along with members of Best Cyclotrons, Inc., we have also collaborated with scientists from other cyclotron companies (IBA [67], and AIMA [68]) on aspects of our design.

In summary, we are proposing a step-wise approach for the development of the components of the DAE δ ALUS cyclotrons. No single component must be pushed orders of magnitude beyond existing technology. But when these smaller steps are combined, the system represents a substantial leap forward.

4 Broader Impacts of These Machines

Accelerators for America's Future has stated: “The United States, which has traditionally led the development and application of accelerator technology, now lags behind other nations in many cases, and the gap is growing. To achieve the potential of particle accelerators to address national challenges will require sustained focus on developing transformative technological opportunities...” [69]. Cyclotrons are a clear example. Despite being originally developed in the US, most cyclotron research and companies are located outside of the US. The major laboratories involved in this initiative (INFN-Catania, PSI, and RIKEN) are outside the US. On the other hand, the universities involved in this program are largely US-based. This allows for technology transfer and ensures the next generation of cyclotron physicists in the U.S. Through this, the program serves a valuable national interest.

This evolving R&D program provides examples of synergy between the goals of fundamental physics research and the needs of society. This has motivated close collaboration between laboratories, universities, and industry on this project. In a time when R&D funding for physics is decreasing, this program illustrates a cost-effective approach for development of tools for basic science.

As a very immediate example, the Catania test-stand is drawing substantial support from the private sector. Best Medical Italy is actively contributing to the collaboration. Underlining the value of the test-stand, Krishnan Suthanthiran, president of TeamBest (parent company of the Best family of companies) wrote in a letter of support, “[The] original motivation for the device is for it to become the injector for a very high intensity neutrino source for pure science research (DAE δ ALUS). The same concepts you have described have an immediate medical radioisotope application.” Our project represents an excellent example of the societal value of basic accelerator research. The value to medical isotope production arises from two aspects of the test-stand. The first is development of high-current proton beams which ultimately enhance the production rate of isotopes. The second is that the system being developed can accelerate any ion with the same charge-to-mass ratio as H $_2^+$, including He $^{++}$ and deuterons. In particular, ^{211}At is optimally produced by 28 MeV alpha (He $^{++}$) beams (note that 28 MeV alphas have 7 MeV/amu, as per our machine design). This isotope, being a pure alpha-emitter, is a very powerful therapeutic agent. Its widespread clinical use is limited today only by the availability of production capacity [70]. The test cyclotron developed in this project, coupled with an existing commercial ion source for doubly stripped helium ions [71], can immediately be applied to the production of this isotope. Alpha beams can also be applied to the production of carrier-free ^{99}Mo , and numerous other isotopes of commercial interest.

The injector cyclotron can be a powerful tool for isotope production. As a source of 60 MeV protons at 600 kW, it represents substantially higher beam power than available at existing isotope machines. This could enable significantly greater yield. It should be noted that along with the improved cyclotron, a new system of targeting must be developed to handle the higher power. Time was devoted during this Snowmass study to developing a concept to address this, and more details are provided in Ref. [9], now in draft. Also, most existing machines are in the 30 to 40 MeV range. Thus the energy opens new opportunities also. A list of isotopes that are uniquely produced in the 60 to 70 MeV range is provided in Table 5. The isotope which is especially valuable is ^{82}Sr , the parent to ^{81}Rb . Finally, making use of the fact that ions of the same charge-to-mass ratios can also

Table 5: *Medical isotopes relevant to IsoDAR energies, from Ref. [72].*

Isotope	half-life	Use
^{52}Fe	8.3 h	The parent of the PET isotope ^{52}Mn and iron tracer for red-blood-cell formation and brain uptake studies.
^{122}Xe	20.1 h	The parent of PET isotope ^{122}I used to study brain blood-flow.
^{28}Mg	21 h	A tracer that can be used for bone studies, analogous to calcium
^{128}Ba	2.43 d	The parent of positron emitter ^{128}Cs . As a potassium analog, this is used for heart and blood-flow imaging.
^{97}Ru	2.79 d	A γ -emitter used for spinal fluid and liver studies.
^{117m}Sn	13.6 d	A γ -emitter potentially useful for bone studies.
^{82}Sr	25.4 d	The parent of positron emitter ^{81}Rb , a potassium analogue This isotope is also directly used as a PET isotope for heart imaging.

be accelerated, α beams can be produced. These have currents limited only by the availability of He^{++} ion sources. There is tremendous potential associated with these beams. A document related to IsoDAR medical applications has been posted on the arxiv [73].

The DAE δ ALUS SRC takes the next step beyond PSI, increasing the extracted energy from 590 to 800 MeV, with a factor of 5 in current. This makes this machine a member of the GeV-scale, 10-MW-class of accelerators. These are sought-after machines for “ADS” (Accelerator-Driven Systems)—used for nuclear waste transmutation, driving of sub-critical reactors (e.g. thorium), and tritium production. Many proposals exist, but cost has been a major impediment to their realization. To date, only one such project has progressed to the advanced R&D and construction phase: this is MYRRHA [74] in Mol, Belgium.

The DAE δ ALUS cyclotron design began as a concept for ADS [75]. Our cyclotrons are attractive because they will have substantially reduced cost over the linacs, which until now have been viewed as the only viable technology to reach these levels of beam power at the GeV energy range. This could facilitate deployment of more than one machine, maintaining production when any particular accelerator is serviced. With successful development of these relatively inexpensive cyclotrons, a substantial growth in the ADS field can be anticipated. The application of DAE δ ALUS machines to ADS technology is under study by scientists at Brookhaven National Laboratory [76]. Their design uses two full power accelerator modules (DIC+DSRC) and one half-power.

5 Conclusions

This whitepaper has summarized the status and plans of the DAE δ ALUS program. The cyclotrons open up a rich physics program, where only a subset is presented here. Progress toward realizing these machines has been excellent and a clear R&D program has been laid out.

It is apparent that there are substantial studies required to prove the DAE δ ALUS design. We note that while the R&D aspects of each piece of the system are challenging, they are not orders of magnitude beyond what has been accomplished. The remarkable step forward occurs when the smaller steps are combined. Thus, as the final Snowmass meeting begins, the DAE δ ALUS program is well placed to advance neutrino physics as well to bring cyclotron innovation back to its birthplace.

References

- [1] J. Alonso, *et al.*, [DAE δ ALUS Collaboration], arXiv:1006.0260 [physics.ins-det] (2010).
- [2] J.M. Conrad and M.H. Shaevitz, Phys. Rev. Lett. **104**, 141802 (2010).
- [3] K. Abe, *et al.* [The Hyper-K Collaboration], arXiv:1109.3262 [hep-ex] (2011).
- [4] S. K. Agarwalla and P. Huber, JHEP **1108**, 059 (2011).
- [5] S. K. Agarwalla, J. M. Conrad and M. H. Shaevitz, JHEP **1112**, 085 (2011)
- [6] M. Bishai, *et al.*, arXiv:1307.0807 [hep-ex] (2013).
- [7] J. Alonso, *et al.*, arXiv:1008.4967 [hep-ex] (2010).
- [8] M. Wurm, *et al.* [LENA Collaboration], arXiv:1104.5620 [astro-ph.IM] (2011).
- [9] A Adelman, *et al.*, “Cyclotrons as Drivers for Precision Neutrino Measurements,” Invited paper for Advances in High Energy Physics, Special Volume Celebrating the 100th Birthday of Pontecorvo, in draft.
- [10] E. Baussan, M. Dracos, T. Ekelof, E. F. Martinez, H. Ohman and N. Vassilopoulos, arXiv:1212.5048 [hep-ex] (2012).
- [11] An Assessment of the Deep Underground Science and Engineering Laboratory (DUSEL), by the Ad Hoc Committee to Assess the Science Proposed for a Deep Underground Science and Engineering Laboratory, A. Lankford, chair, available from the National Research Council, http://www.nap.edu/catalog.php?record_id=13204 (2011).
- [12] A. Bungau *et al.*, Phys. Rev. Lett. **109**, 141802 (2012).
- [13] J. M. Conrad and M. H. Shaevitz, Phys. Rev. D **85**, 013017 (2012).
- [14] G. Mention, M. Fechner, T. Lasserre, T. A. Mueller, D. Lhuillier, M. Cribier and A. Letourneau, Phys. Rev. D **83**, 073006 (2011).
- [15] M. Cribier *et al.*, Phys. Rev. Lett. **107**, 201801 (2011).
- [16] J. A. Formaggio and J. Barrett, Phys. Lett. B **706**, 68 (2011).
- [17] J. Kopp, M. Maltoni and T. Schwetz, Phys. Rev. Lett. **107**, 091801 (2011).
- [18] M. Abs *et al.*, arXiv:1207.4895 [physics.acc-ph] (2012).
- [19] S. Abe *et al.* [KamLAND Collaboration], Phys. Rev. Lett. **100**, 221803 (2008).
- [20] C. Giunti and M. Laveder, Phys. Lett. B **706**, 200 (2011).
- [21] M. Sorel, J. M. Conrad and M. Shaevitz, Phys. Rev. D **70**, 073004 (2004).
- [22] J. M. Conrad, C. M. Ignarra, G. Karagiorgi, M. H. Shaevitz and J. Spitz, arXiv:1207.4765 [hep-ex] (2012).
- [23] A. Aguilar *et al.* [LSND Collaboration], Phys. Rev. D **64**, 112007 (2001).

- [24] A. A. Aguilar-Arevalo *et al.* [The MiniBooNE Collaboration], Phys. Rev. Lett. **98**, 231801 (2007).
- [25] A. A. Aguilar-Arevalo *et al.* [The MiniBooNE Collaboration], Phys. Rev. Lett. **105**, 181801 (2010).
- [26] P. Astier, *et al.* Phys. Lett. B **570** 19, 2003.
- [27] F. Dydak *et al.*, Phys. Lett. B **134** 281, 1984.
- [28] I.E. Stockdale *et al.*, Phys. Rev. Lett. **52**, 1384 (1984); Z. Phys. C **27**, 53 (1985).
- [29] C. Giunti and M. Laveder, Phys. Rev. C **83**, 065504 (2011).
- [30] <http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.109.141802>, Oct 4, 2012.
- [31] R. Lazauskas and C. Volpe, J. Phys. G **37**, 125101 (2010).
- [32] A. J. Anderson, J. M. Conrad, E. Figueroa-Feliciano, K. Scholberg and J. Spitz, Phys. Rev. D **84**, 013008 (2011).
- [33] K. Patton, J. Engel, G. C. McLaughlin and N. Schunck, Phys. Rev. C **86**, 024612 (2012).
- [34] G. Pagliaroli, C. Lujan-Peschard, M. Mitra and F. Vissani, arXiv:1210.4225 [hep-ph] (2012).
- [35] J. S. Diaz and V. A. Kostelecky, Phys. Lett. B **700**, 25 (2011).
- [36] J. S. Diaz and A. Kostelecky, Phys. Rev. D **85**, 016013 (2012).
- [37] A. Kostelecky and M. Mewes, Phys. Rev. D **85**, 096005 (2012).
- [38] A. J. Anderson, J. M. Conrad, E. Figueroa-Feliciano, C. Ignarra, G. Karagiorgi, K. Scholberg, M. H. Shaevitz and J. Spitz, Phys. Rev. D **86**, 013004 (2012).
- [39] L. Lello and D. Boyanovsky, arXiv:1212.4167 [hep-ph] (2012).
- [40] L. B. Auerbach *et al.* [LSND Collaboration], Phys. Rev. C **64**, 065501 (2001).
- [41] B. E. Bodmann *et al.* [KARMEN Collaboration.], Phys. Lett. B **332**, 251 (1994); B. Armbruster, *et al.* [KARMEN Collaboration], Phys. Rev. C **57**, 3414 (1998).
- [42] D. A. Krakauer, *et al.*, Phys. Rev. C **45**, 2450 (1992).
- [43] R. L. Burman, Nucl. Instrum. Meth. A **368**, 416 (1996); R. L. Burman, M. E. Potter and E. S. Smith, Nucl. Instrum. Meth. A **291**, 621 (1990).
- [44] A. Adelman, *et al.*, arXiv:1210.4454 [physics.acc-ph] (2012).
- [45] <http://www.lnl.infn.it/~spes/>
- [46] H. Okuno, "Recent Achievements and Upgrade Programs at RIKEN Radioactive Isotope Beam Factory," Proceedings of IPAC2012, MOPPD029, 2012.
- [47] F. Reines, H. S. Gurr and H. W. Sobel, Phys. Rev. Lett. **37**, 315 (1976).
- [48] M. Deniz *et al.* [TEXONO Collaboration], J. Phys. Conf. Ser. **375**, 042044 (2012).

- [49] A. I. Derbin, A. V. Chernyi, L. A. Popeko, V. N. Muratova, G. A. Shishkina and S. I. Bakhlanov, *JETP Lett.* **57**, 768 (1993) [*Pisma Zh. Eksp. Teor. Fiz.* **57**, 755 (1993)].
- [50] Z. Daraktchieva *et al.* [MUNU Collaboration], *Phys. Lett. B* **615**, 153 (2005).
- [51] J. Erler and S. Su, *Prog. Part. Nucl. Phys.* **71**, 119 (2013).
- [52] Z. Berezhiani and A. Rossi, *Phys. Lett. B* **535**, 207 (2002).
- [53] J. M. Conrad, J. M. Link and M. H. Shaevitz, *Phys. Rev. D* **71**, 073013 (2005).
- [54] S. Abe *et al.* [KamLAND Collaboration], *Phys. Rev. C* **84**, 035804 (2011).
- [55] J.M. Conrad, *et al.*, “Precision $\bar{\nu}_e$ –electron Scattering Measurements with IsoDAR to Search for New Physics,” to be submitted to *Phys. Lett B.*, in draft.
- [56] C. Aberle, A. Elagin, and L. Winslow, “Directionality in Kilo-ton Scale Scintillating Neutrino Detectors,” in draft, to be submitted to *Phys. Rev. C.*
- [57] D. V. Forero and M. M. Guzzo, *Phys. Rev. D* **84**, 013002 (2011).
- [58] J. Stetson, S. Adam, M. Humbel, W. Joho and T. Stambach, “The commissioning of PSI injector 2 for high intensity, high quality beams,” *Proceedings of the 13th Int.l Conf. on Cyclotrons and Their App.*, 1992.
- [59] H. Okuno *et al.*, *IEEE Trans. on App. Supercon.*, **17**:2, 1063 (2007).
- [60] J. J. Yang *et al.*, *Nucl. Instrum. Meth. A* **704**, 84 (2013).
- [61] J. Minervini, *et al.*, arXiv:1209.4886 [physics.acc-ph] (2012).
- [62] F. Maimone, L. Celona, F. Chines, G. Ciavola, G. Gallo, N. Gambino, S. Gammino and D. Mascali *et al.*, *Conf. Proc. C* **0806233**, MOPC151 (2008).
- [63] Y. J. Bi, *et al.*, *Phys. Rev. ST Accel. Beams* **14**, 054402 (2011).
- [64] TeamBest is the parent company for the family of “Best” companies, including Best Cyclotrons, Best Theratronics, Best Medical Italy, and several others. See <http://www.teambest.com>.
- [65] . D. Haxton, W. McCurdy, U.C. Davis, Private Communication.
- [66] A Sen, “Production of Low Vibrational State Ions for Recombination Experiments,” Thesis, University of Western Ontario, London, Ontario, Canada, 1985.
- [67] <http://www.iba-cyclotron-solutions.com/>
- [68] <http://www.aima.fr/>
- [69] <http://www.acceleratorsamerica.org/files/Report.pdf>
- [70] M. Zalutsky, M. Pruszyński, *Curr. Radiopharm.* **4(3)**, 177-185 (2011).
- [71] For example, the PantechNIK ISIS-PK source, specified beam current of 2.4 emA of He⁺⁺, <http://www.pantechnik.com/#!sources/vstc2=isis-pk>

- [72] “Cost / Benefit Comparison For 45 MeV and 70 MeV Cyclotrons,” Conducted by Jupiter Technical, Security and Management Solutions for the U.S. Department of Energy, Office of Nuclear Science, Energy and Technology, www.isotopes.gov/outreach/reports/Cyclotron.pdf (2005).
- [73] J. R. Alonso, arXiv:1209.4925 [nucl-ex] (2012).
- [74] <http://myrrha.sckcen.be/>
- [75] L. Calabretta, D. Rifuggiato, V. Shchepounov, “High Intensity Proton Beams from Cyclotrons for H_2^+ ,” Proc. 1999 Particle Accel Conf, NY 1999, pp3288-3290.
- [76] F. Meot, T. Roser, W. Weng and L. Calabretta, “MW-Class 800 MeV/n H_2^+ SC-Cyclotron for ADS Application: Design Study and Goals,” Proceedings of IPAC2012, New Orleans, Louisiana, THPPR064, 2012.