Muon Decay at Rest for CP Measurements

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Based on work done in collaboration with:
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Motivation

There are programs around the world to build Accelerator Driven System (ADS) subcritical nuclear reactors

These nuclear reactors cannot melt down, as they are not critical and can run on or convert spent/nonfissle fuel

They get their neutrons from high intensity proton beams

As part of its C-ADS program, China will build a number of high intensity (about 10 mA) proton accelerators

1) **Built:** 25 MeV (2 accelerators)
2) **2023:** 500 MeV, $>$5 mA (CI-ADS - Research Reactor)
3) **202?:** 200 MeV, 10 mA deuterons (Ningde User Facility)
4) **202?:** 800 MeV (C-ADS phase II - 100 MW reactor)
5) **203?:** 1.5 GeV (C-ADS phase III - 1 GW Commercial Reactor)

What can these do for us?

These new reactors produce reactor neutrinos

As always, these reactor neutrinos are free to use for anyone who can build a detector

These are much better than ordinary reactor neutrinos (which are $\overline{\nu}_e$) because they will be the world's most intense source of $\overline{\nu}_\mu$

By measuring the $\overline{\nu}_e$ appearance (conversion from $\overline{\nu}_\mu$), one can measure leptonic CP-violation

Such CP-violation may or may not arise from terascale physics. Nonetheless, it is an important ingredient in any BSM model

Neutrino Mass Eigenstates

Neutrino flavors are measured via charged current interactions.

The observed final state contains a charged lepton in a mass eigenstate: e, μ or τ

The neutrino which creates this charged lepton, via the absorption or emission of single W boson, is called ν_e, ν_μ or ν_τ respectively.

These are not mass eigenstates.

If there are only 3 neutrino flavors, these may be expanded in terms of three mass eigenstates ν_1, ν_2 and ν_3 via the mixing matrix U

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The Parameters

The mixing matrix can be parametrized by four angles:
$\theta_{12},\ \theta_{13},\ \theta_{23}$ and δ as

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_{23}) & \sin(\theta_{23}) \\ 0 & -\sin(\theta_{23}) & \cos(\theta_{23}) \end{pmatrix} \begin{pmatrix} \cos(\theta_{13}) & 0 & \sin(\theta_{13})e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin(\theta_{13})e^{i\delta} & 0 & \cos(\theta_{13}) \end{pmatrix}$$

$$\times \begin{pmatrix} \cos(\theta_{12}) & \sin(\theta_{12}) & 0 \\ \text{-}\sin(\theta_{12}) & \cos(\theta_{12}) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{12},\ \theta_{13},\ \theta_{23} \in [0^\circ, 90^\circ]$ and $\delta \in [0^\circ, 360^\circ]$

Let the mass of ν_i be M_i and $\Delta M_{ij}^2 = M_i^2 - M_j^2$

In 2012 Daya Bay and RENO measured θ_{13}.
The only unknown parameter is now δ.

Solar neutrino oscillations

Solar neutrino experiments together with the long baseline reactor neutrino experiment KamLAND determine the solar mass splitting and mixing angle:

$\Delta M^2_{21} = 7.5 \times 10^{-5}\ \mathrm{eV}^2, \quad \sin^2(2\theta_{12}) = 0.857$

The sign of ΔM^2_{21} is determined from matter effects in ν oscillations inside of the sun.

Due to the very small solar mass splitting, the corresponding oscillations only occur over long baselines

$\Rightarrow$ they will not play a central role in this talk.

First Oscillation Maximum

As ΔM^2_{31} and ΔM^2_{32} are much larger than ΔM^2_{21}, at short baselines oscillations are dominated by the corresponding oscillations

In this talk we will be interested in the conversion of ν_μ to ν_e.

The shortest baseline at which the maximal conversion occurs, for energy E neutrinos is

$$L = \frac{2\pi E}{|\Delta M^2_{31}|} \sim \frac{2\pi E}{|\Delta M^2_{32}|}$$

The off-axis beams used at T2K and NOνA (and in the past MINOS and future MOMENT (Daya Bay III) and T2HK) have energies peaked at this first maximum.

Relevant Mixing Angles

To leading order in $\alpha = \frac{\Delta M^2_{21}}{|\Delta M^2_{31}|} \sim 0.032$ the probability of conversion in a vacuum, at the first oscillation maximum, is

$$\begin{aligned} P_{\nu_\mu \to \nu_e} &= \sin^2(2\theta_{13})\sin^2(\theta_{23}) \\ &\quad -\frac{\pi}{2}\alpha \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23})\cos(\theta_{13}) \sin(\delta) \end{aligned}$$

Therefore, to extract δ from $\nu_\mu \to \nu_e$ oscillations, it is essential to measure the constant term :

$$\sin^2(2\theta_{13})\sin^2(\theta_{23})$$

Even then, at the oscillation maximum one only learns $\sin(\delta)$ and so cannot distinguish δ from $\pi - \delta$.

Mixing parameter values

So what is $\sin^2(2\theta_{13})\sin^2(\theta_{23})$?

The angle $\sin^2(2\theta_{13})$ has been measured using km baseline reactor neutrino experiments and also long-baseline accelerator experiments, both around the first oscillation maximum.

Daya Bay has found $\sin^2(2\theta_{13}) = 0.0856 \pm 0.0029$.

ν_μ disappearance experiments measure (approximating $\theta_{13} = 0$) $\sin(2\theta_{23}) \sim 1$ but to separate δ from the constant term in $P_{\nu_\mu \to \nu_e}$ we need $\sin(\theta_{23})$. Unfortunately:

$$\frac{\partial \sin(2\theta_{23})}{\partial \sin(\theta_{23})} = 2\frac{\partial\left(\sin(\theta_{23})\sqrt{1-\sin^2(\theta_{23})}\right)}{\partial \sin(\theta_{23})} = \frac{2-4\sin^2(\theta_{23})}{\cos(\theta_{23})} \sim 0$$

So the measured $\sin(2\theta_{23})$ (ν_μ disappearance) is not very sensitive to $\sin(\theta_{23})$ (ν_e appearance).

Neutrino Oscillation Probability

As a result, T2K finds (2018)

$\sin^2(\theta_{23}) = 0.53 \pm 0.03$

Putting everything together, at the first oscillation maximum

$P_{\nu_\mu \to \nu_e} \sim (0.045 \pm 0.003) - (0.014)\sin(\delta)$

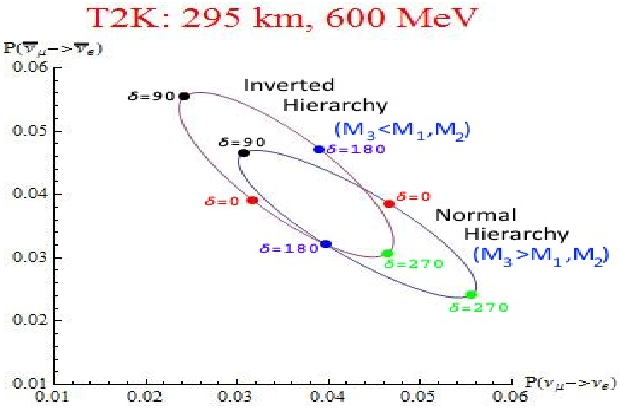
The 1σ uncertainty on the constant term is more than 1/5 as large as the δ-dependent signal, so δ cannot be determined precisely (At 2σ the lower octant is allowed so the allowed range more than doubles).

The solution of course is to also run the accelerator in $\overline{\nu}$ mode, as

$P_{\overline{\nu}_\mu \to \overline{\nu}_e} \sim (0.045 \pm 0.003) + (0.014)\sin(\delta)$

Therefore the difference between ν and $\overline{\nu}$ appearance yields $\sin(\delta)$ and the sum yields $\sin^2(2\theta_{13})\sin^2(\theta_{23})$.

Minakata-Nunokawa Diagram: T2K



Above are the corresponding appearance probabilities for T2K

$\delta = 0^\circ, 90^\circ, 180^\circ, 270^\circ$

Coherent scattering in the Earth separate the upper and lower ellipses, corresponding to the inverted and normal hierarchies

Limitations of a Long-Baseline Accelerator Approach

This off-axis, accelerator approach, comparing ν_e and $\overline{\nu}_e$ appearance at the oscillation maximum, has two disadvantages:

1) High energy proton accelerators produce ν more efficiently than $\overline{\nu}$.

This is because they use ν_μ from $\pi^+ \rightarrow \mu^+ + \nu_\mu$

As a result the $\overline{\nu}$ mode occupies most of the beam time and still dominates the uncertainty

2) Even with a perfect measurement, only $\sin(\delta)$ is determined and so δ cannot be distinguished from $\pi - \delta$.

Note: You could get antineutrinos from $\pi^+ \rightarrow \mu^+ + \nu_\mu$ followed by $\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$ in a decay tunnel

This is the strategy of IHEP's MOMENT experiment

μ^+ Decay at Rest

Solution: Measure $\overline{\nu}$ oscillations using μ^+ decay at rest (DAR)

How does it work?

1) A high intensity 400 MeV-2 GeV proton beam hits a fixed target

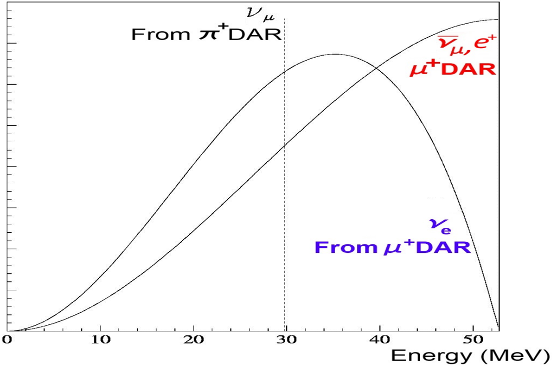
2) The target produces pions which stop.
   The π^- are absorbed in the target while the π^+ decay at rest
   $\pi^+ \rightarrow \mu^+ + \nu_\mu$.

3) The μ^+ then stop and also decay at rest
   $\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$.

4) The $\overline{\nu}_\mu$ travel isotropically in all directions, oscillating as they go

5) A detector measures the $\overline{\nu}_e$ arising from the oscillations $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$.

π and μ DAR spectra



Energy spectra of π^+ and μ^+ DAR products.

The DAR signal is the $\overline{\nu}_\mu$ spectrum.

Muon Decay at Rest Neutrinos

The spectrum of μDAR neutrinos leads to many advantages

1) The spectrum is known extremely well, it is the Michel spectrum

2) 30-50 MeV $\overline{\nu}_e$ interact via inverse β decay, whose cross section is known very precisely

3) The resulting $\overline{\nu}$ energies are 30-50 MeV, higher energies than reactor, spallation or geoneutrino backgrounds but low enough so that atmospheric neutrino backgrounds are small

4) As these are $\overline{\nu}_e$ and not ν_e, their capture by IBD yields a neutron. The subsequent neutron capture provides a double coincidence which strongly reduces the backgrounds if detected

5) The spectrum is broad enough so that its shape breaks the $\delta \rightarrow \pi - \delta$ degeneracy

What proton energies are acceptable?

A proton beam energy $\gtrsim$ 400 MeV is necessary to have sufficient $\overline{\nu}$. At least 600 MeV would be optimal.

$\overline{\nu}$ yield at fixed beam power for various proton beam energies:

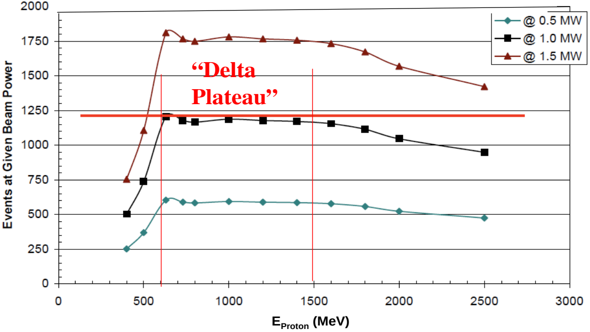


Figure: Simulated by DAEδALUS

Problem Solved?

Combining $\nu_\mu \to \nu_e$ oscillations from a long-baseline experiment with $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations from μ^+ DAR solves the two problems described above:

1) The high energy accelerator, for example, triples its time in ν mode, so the statistical uncertainty on $\nu_\mu \to \nu_e$ oscillations drops by $\sqrt{3}$.

   If the μ^+ source is sufficiently high intensity, the $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations, whose statistical fluctuations dominated the error budget, now are far more plentiful

2) The DAR $\overline{\nu}_e$ are not only at the oscillation maximum, so the shape of the observed spectrum breaks the $\delta \to \pi - \delta$ degeneracy.

   These $\overline{\nu}_e$ are detected via inverse β decay (IBD) and so the observed e^+ energy is easily related to the $\overline{\nu}_e$ energy, allowing a reliable determination of the shape

The DAEδALUS Project

The first proposal along these lines was the DAEδALUS project.

They plan to create μ^+ at 3 high intensity cyclotron complexes, located 1.5, 8 and 20 km from a detector.

The multiple baselines are useful to break various degeneracies between the height and shape of the observed spectrum and the mixing angles, although the relative intensities of the accelerators is a source of uncertainty

But DAEδALUS is expensive and technologically challenging for one reason:

Why DAEδALUS is Hard

At the low energies of IBD, the direction of the measured e^+ is virtually independent of that of the incoming $\overline{\nu}_e$

So DAEδALUS can't tell which $\overline{\nu}_e$ came from which accelerator

As a result, no two accelerator complexes can run at the same time

To also measure the background, DAEδALUS has chosen to run each accelerator with a 20% duty factor

Therefore the instantaneous intensity of each beam needs to be 5 times higher: 30-50 mA!

This can be compared with the current state of the art 2.2 mA accelerator at the Paul Scherrer Institute

To increase the current they have suggested accelerating H_2^+, but then they will need invent a way to extract the excited molecules

Two detectors

Our idea: A single μ^+ source for the DAR and *two* large detectors, at sufficiently different baselines to maximize their synergy.

By having two baselines instead of three, potentially we will have larger systematic errors than DAEδALUS.

So we suggest that Daya Bay or RENO detectors at 50-100 meters be used to determine the flux normalization

Summary:
DAEδALUS has 3 μ^+ sources and 1 large detector.
We have 1 μ^+ source and 2 large detectors.

Note: We will see below that even with *one* detector we obtain a reasonably precise determination of δ

Advantages of Having 2 Detectors and 1 μ^+ Source

Advantages:

1) The accelerator can run with essentially a 100% duty factor.

   Some dead time can be useful to measure backgrounds, but we find that the backgrounds are quite subdominant and so this can be much less than the 40% at DAEδALUS.

2) As the duty factor is five times higher, the necessary instantaneous intensity to achieve the same signal is five times lower.

   In JHEP 1412 (2014) 051, we find that a 7 MW beam yields a good determination of δ (see more below)

3) This will be MUCH cheaper: Only one accelerator complex is needed instead of three and it will have a five times lower intensity

Proposal

Our proposal:
μ^+ Decay At Rest with Two Scintillators (μDARTS)

1) A high intensity proton beam (400 MeV$< E <$2 GeV) strikes a target, creating pions
2) The pions stop. π^- are absorbed. π^+ decay to $\mu^+ + \nu_\mu$.
3) The μ^+ stop and decay at rest to $\overline{\nu}_\mu + e^+ + \nu_e$
4) The $\overline{\nu}_\mu$ oscillate to $\overline{\nu}_e$
5) $\overline{\nu}_e$ inverse β decay in 2 large detectors at 5-30 km
6) ν flux normalization determined by elastic $\nu - e$ scattering in Daya Bay/RENO detectors at 20-100 m

   (may refill with water or oil based scintillator to get more Cherenkov light)

μDARTS vs MOMENT

	μDARTS	MOMENT
Goal	Measure δ	Measure δ
Accelerator	C-ADS	"similar proton linac"
Beam Energy	$\gtrsim$500 MeV	1.5-2.5 GeV
μ^+ Decay	Decay at Rest	Decay in Motion
$\overline{\nu}_\mu$ Energy	30-50 MeV	200-300 MeV
$\overline{\nu}_\mu$ Spectrum	Michel spectrum	Must be measured
Detector	Liquid Scintillator	Water Cherenkov
Detection	Inverse β decay	Quasielastic
Cross-section	Well-known	50% uncertainty
Baseline	5-30 km	100-150 km
δ vs $\pi-\delta$?	can distinguish	depends on ν spectrum

Synergy:

MOMENT measures sin(δ) but δ itself likely requires μDARTs.

Definition of μDARTS

In our simulations we have considered the accelerator intensity and the detector efficiency such that:
For a 6 year run and $\delta = 0$, there will be 350 $\overline{\nu}_e$ IBD events arising from μ^+ DAR at a 20 kton liquid scintillator detector 10 km from the accelerator source.

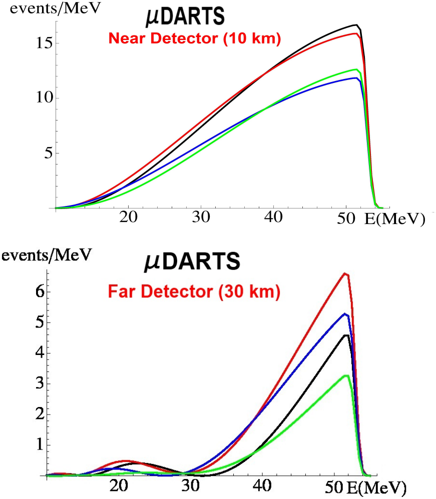
Scaling the results of LSND, this corresponds to:

1) A target which is 12% free protons per weight

2) A 9 mA, 800 MeV proton beam running with a duty factor of 100%
This roughly corresponds to phase II of ADS.

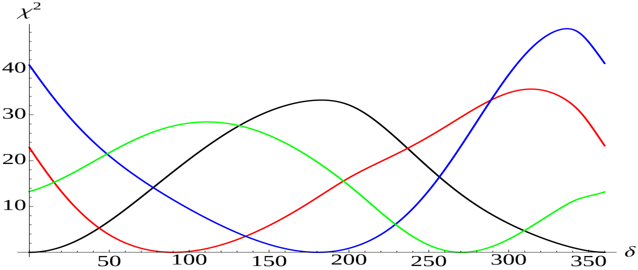
Summary: 1.1×10^{25} POT in 6 years, 60 times more than LSND.

μDARTS Signal



The DAR expected signal in 6 years at μDARTS for $\delta = 0^\circ$, 90°, 180° and 270°, normal hierarchy

No Degeneracies at μDARTS

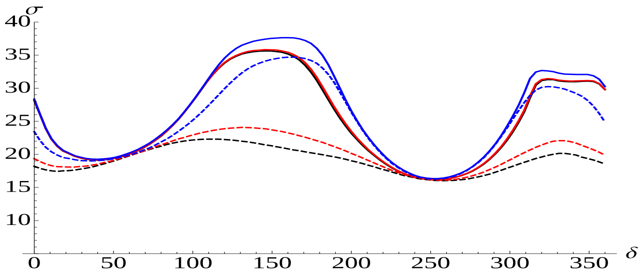


χ^2 fit of 4 true values of δ to other values with 5% normalization uncertainty, perfectly known mass splittings and mixing angle uncertainties expected after Daya Bay, JUNO, T2K and NOνA:

$$\frac{\delta \sin^2(2\theta_{12})}{\sin^2(2\theta_{12})} = 1\%, \qquad \frac{\delta \sin^2(2\theta_{13})}{\sin^2(2\theta_{13})} = 4\%$$

$$\delta \sin(\theta_{23}) = 0.02.$$

Sensitivity of μDARTS to δ

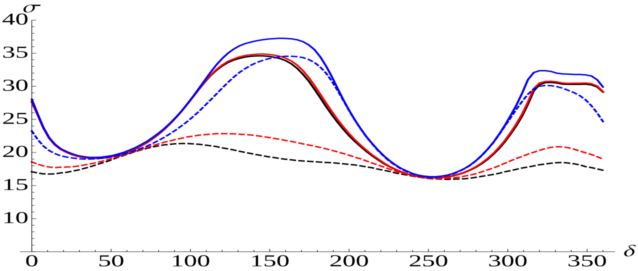


1σ precision with which δ can be determined by μDARTS with a normalization uncertainty of 1%, 5%, 20% .

The solid curves use pre-2014 mixing angle uncertainties while the dashed curves include T2K, NOνA, Daya Bay and JUNO.

If the flux uncertainty is 5%: The determination of θ_{23} at T2K and NOνA breaks a degeneracy between δ and the flux, improving the uncertainty in δ by 10° for about half of all possible values

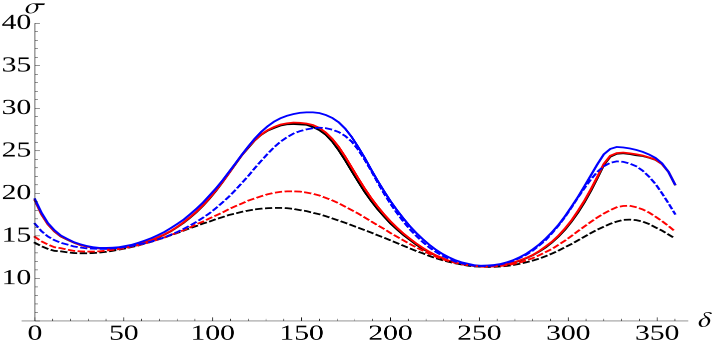
μDARTS and θ_{23}



As above, but now all angles are fixed except for θ_{23} which assumes its pre-2014 value in the solid curves, but includes improvements from T2K and NOνA in the dashed curves.

Notice that all of the improvement from future measurements on the previous slide is also here: The synergy between μ^+ DAR and off-axis accelerator experiments is useful.

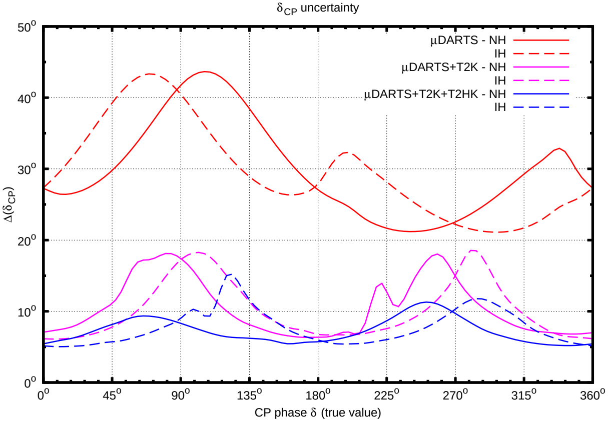
Sensitivity of μDARTS to δ in 12 years



1σ precision with which δ can be determined by μDARTS in 12 years with a normalization uncertainty of 1%, 5%, 20% .

A determination of δ with an uncertainty of 15° seems possible.

μDARTS including T2K and T2HK



Preliminary 1σ precision with which δ can be determined by μDARTS in 6 years with a normalization uncertainty of 5% including various combinations of experiments in Japan.

Atmospheric Neutrino Background

Atmospheric $\overline{\nu}_e$, with energies beneath 60 MeV, IBD with free protons in the detector, producing an irreducible background

In our signal range, 30 to 53 MeV, the unoscillated atmospheric $\overline{\nu}$ rate will be about 90 $\overline{\nu}_e$ and 210 $\overline{\nu}_\mu$ per m^{2}sr sec in Guangdong with an uncertainty of about 30% (Barr et al.).

Weighting by the average oscillation probability and integrating over solid angles yields 1.3×10^3 $\overline{\nu}_e/\text{m}^2$sec.

Each 20 kton detector contains 2.4 kton, or 1.4×10^{33} protons with an average IBD cross section of $2 \times 10^{-44}\text{m}^2$.

In 6 years $= 2 \times 10^8$ sec the expected IBD background is then 7 events for μDARTS .

This agrees well with a rescaling of similar calculations for GADZOOKS! and DAEδALUS

Super-K's atmospheric $\overline{\nu}_e$ background

In its diffuse supernova background search, Super-K's best fit for ν_e and $\overline{\nu}_e$ backgrounds is 50 events between 34 and 54 MeV which corresponds to 6 times this rate.

According to GADZOOKS! this background can be reduced by vetoing events with γ emission and also requiring a double coincidence with neutron capture on Gd.

In the scintillator detectors of μDARTS there is no Gd, but a double coincidence with neutron capture on hydrogen can be used.

If the γ emission is simultaneous with the IBD, it may be challenging for these detectors to distinguish it from the positron

Non-IBD Backgrounds?

Our GENIE simulations show that the non-IBD electron neutrino events observed at Super-K are CCQE events

However there may be about 10 QE events from $\overline{\nu}_e$ or ν_e with a final state interaction which have a final state neutron and so will give us a total background of 20 events.

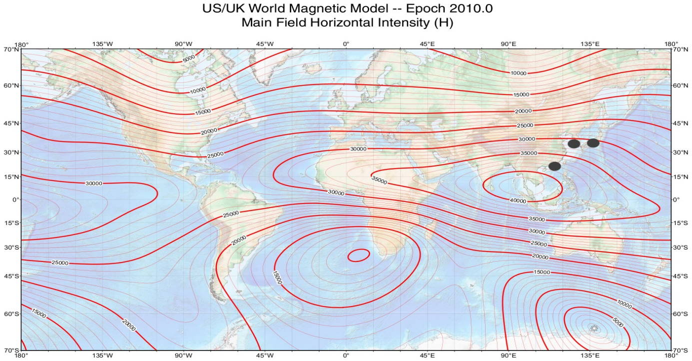
There is also a large background from NC atmospheric neutrino interactions which often create a n

40% of these create ^{11}C whose decay can be used to identify this background

We are looking into using pulse shape discrimination (as will be used by JUNO in a similar context) for the rest

Summary: We expect a signal of 350 (70) events at the near (far) detector and 10-20 CC background events at each.

Horizontal Geomagnetic Field Map



A strong horizontal geomagnetic field deflects low energy cosmic rays, reducing the low energy atmospheric ν flux.

CIADS/JUNO (0.38 G), KNO/Kamioka mines (0.31 G) *vs* LBNE (0.17 G), LENA in the Pyhäsalmi mine (0.13 G)

$\Rightarrow$ Backgrounds will be reduced by about a factor of 2 at our proposed DAR sites as compared with other proposals

Summary

In at most 4 years the Daya Bay experiment will be finished and will no longer need its eight 20 ton liquid scintillator detectors.

An ADS with an energy $\gtrsim$ 400 MeV will allow a first-ever measurement of the CP-violating phase δ, using 1 or 2 large scintillator detectors 5-30 km away

Near detectors borrowed from Daya Bay at 50-100 meters, besides providing real-time monitoring of the reactor, can test the LSND anomaly and be sensitive to sterile neutrinos with masses 3 times smaller than LSND

At a deuteron energy of 200 MeV, Daya Bay detectors at 5-30 meters are sensitive to sterile neutrinos

Backup Slides

Continue reading to enjoy some backup slides

IsoDAR

At energies about 2 MeV/nucleon, a beam strikes a thick target, providing a neutron source

The neutrons move into a converter, where they are absorbed (by ^{7}Li), forming radioactive isotopes (^{8}Li)

These **Iso**topes β-**D**ecay **A**t **R**est (**IsoDAR**)

The decay produces $\overline{\nu}_e$, which fly to the (liquid scintillator) detector, perhaps oscillating on the way

We measure the $\overline{\nu}_e$ spectrum using Inverse β Decay (IBD):
$\overline{\nu}_e + p \rightarrow n + e^+$

In the first part of the talk: We discuss how IsoDAR can be used to test neutrino disappearance anomalies, and to see whether these anomalies are caused by sterile neutrinos

Deuteron Beam

We have simulated a 200 MeV, 15 mA deuteron beam striking a ^{9}Be target emersed in heavy water and surrounded by 99.99% pure ^{7}Li sleeves: 5×10^{23} ^{8}Li decays $\Rightarrow$ 2×10^4 IBD events at 30 meters

We have since demonstrated that our target station is not optimal and we are optimizing it now, this will reduce the necessary run time (from 5 years) but leave the other results unchanged

The deuteron collisions generate neutrons ($0.6n/d$) which are moderated by the heavy water and 6% are absorbed by the ^{7}Li to produce ^{8}Li, whose β decay is our $\overline{\nu}_e$ source

The $\overline{\nu}_e$ energy spectrum extends up to 13 MeV, and in general energies are nearly twice those of reactor $\overline{\nu}_e$

As a result our inverse β decay (IBD) detection cross section is about 3 times higher.

Backgrounds

One main background is the β decay of ^{9}Li, created by interactions of cosmogenic μ with ^{12}C in the scintillator detector

If the detector is at a depth of 100 meters: 3 background events/day

This background is quite well understood and has been studied extensively, for example, at Daya Bay

The rate that we find with our simulations agrees with that observed at Daya Bay

We have found beam-on backgrounds using GEANT4 simulations, but have not yet incorporated them into our analysis

To eliminate these other backgrounds, we impose a low energy veto

We are now studying the fast neutron background, which will be the most important

Reactor Neutrino Backgrounds

The CI-ADS site is 48 km from the reactors at Daya Bay/Ling Ao
$\Rightarrow$ 0.1 reactor $\overline{\nu}_e$ per day

It is a similar distance from the proposed reactor complex at Lufeng

However a reactor complex is also planned in Huizhou, just 2 km southwest of the CI-ADS site

In China it takes 4-5 years to build a reactor and then every year another reactor in the complex is completed, often up to six

So it is unlikely that any of these reactors will be built before CI-ADS turns on in 2023

With all 6 reactors, the background will be 70 $\overline{\nu}_e/day$

We consider a 6 MeV low energy veto in all simulations
$\Rightarrow$ 10 reactor $\overline{\nu}_e$ background/day

With a 7 MeV veto it would be 5/day

Sterile neutrinos - Motivation

Various observed *disappearance* anomalies could be explained by sterile neutrinos:

1) **Reactor Anomaly:** A systematic deficit of about 5% of $\overline{\nu}_e$ from nuclear reactors has been reported by many experiments, with baselines of 30 m and above

   This requires a sterile neutrino mass of at least about 0.3 eV

2) **Gallium anomaly:** Less neutrinos are observed than expected from sources placed inside of detectors (GALLEX and SAGE)

   This requires a sterile neutrino mass of at least about 1 eV

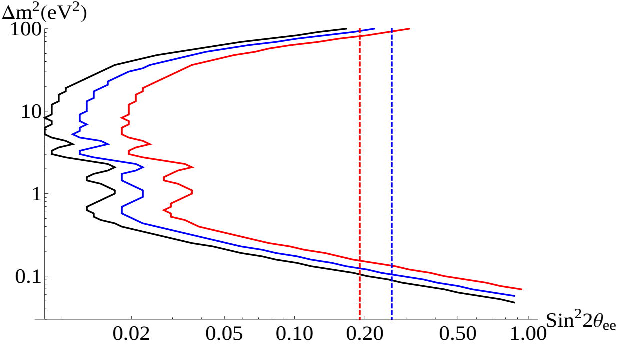
We parametrize the ν_e disappearance with the parameter θ_{ee}

$$P_{ee} = 1 - \sin^2(2\theta_{ee}) \sin^2\left(1.27\frac{\Delta M^2 L}{E}\right)$$

Sterile neutrinos - Results

We assume one Daya Bay detector at 5 m and one at 15 m

In 5 years of running (much less with an optimized configuration) we will find the following 2σ, 3σ and 5σ bounds on θ_{ee}



The area of interest for anomalies will be covered at about 5σ

The dashed lines are long baseline and solar bounds

The Competition

There are many other proposed experiments to search for the same effect, using $\overline{\nu}_e$ from research reactors

Many of these are at an advanced stage (NUCIFER is taking data)

However we have several advantages:

1) The shape of our expected spectrum is known more precisely
2) We have multiple detectors, in principle up to eight, and so we can compare any signal with the known distance dependence for neutrino oscillations
3) Our detectors can be placed underground, since we do not need to be next to a research reactor
4) Due to our higher energy:
   A) We have longer baselines (for the same oscillations)
   $\longrightarrow$ more shielding *and* sensitive to higher ΔM^2
   B) Our accidental coincidence backgrounds are reduced by more than 2 orders of magnitude (with a 6 MeV low energy veto)

Improvements and Optimization

We are now using simulations to optimize this configuration

We are also considering proton beams, and W and Pb targets

These targets have higher neutron yields when beam $E > 50$ MeV

Instead of ^{7}Li sleeves surrounding D_2O, as is planned at JUNO, etc., we also consider a mix of isotopically pure LiOD and D_2O

Target station design is more compact than a research reactor core or the metallic Li target for JUNO and KamLAND IsoDAR
⇒ sensitivity to higher mass sterile neutrinos
⇒ whereever the neutron stops, it can be absorbed by lithium

We can obtain about twice the $\overline{\nu}_e$ with less than half as much ^{7}Li using such converters

We are also considering liquid nitrogen cooling of the ^{7}Li converter in the target station, to reduce the distance that neutrons travel:

Less ^{7}Li → cheaper and compact source → high ΔM^2 sensitivity

The 25 MeV Beam

IMP and IHEP are now each building a 25 MeV, 10 mA proton beam

These are demonstration facilities for the ADS injector

The IMP beam has already achieved 26 MeV but at a low current

After that it has no users, but the ADS team will spend several years trying to maximize the stability

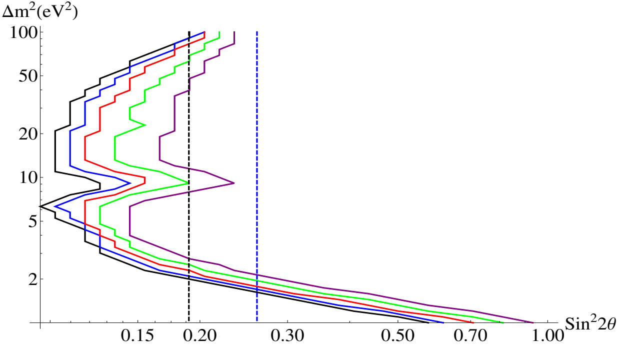
As our new design gets more $\overline{\nu}_e$ per proton, we are now investigating using a 50-200 MeV deuteron beam at the NingDe user facilty for sterile ν physics

At 25 MeV a ^{9}Be target yields the most neutrons, above 50 MeV a heavy metal (W, Pb or Bi) target yields more neutrons

Sterile neutrinos with the 25 MeV beam

Using the 25 MeV beam and a 30 kg ^{7}Li mass target station (costs 1-2 million RMB), with a 400 kg detector at 2-3 meters (2 million RMB):

In 3 years of running we will find the following 2σ bounds on θ_{ee}



Getting all of the neutrons

In our original design, only 6% of neutrons created in the target were captured by ^{7}Li and so generated $\overline{\nu}_e$.

With the new design, neutrons that stop anywhere in the moderator can be captured by ^{7}Li and so we can get up to 30%

What about the other 70%? They are lost in 4 ways:

1) Absorbed by ^{6}Li impurities (0.01% of our Li)

2) Absorbed by H impurities (1% of our D)

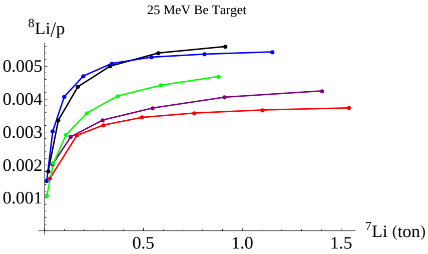
3) Escape the target station

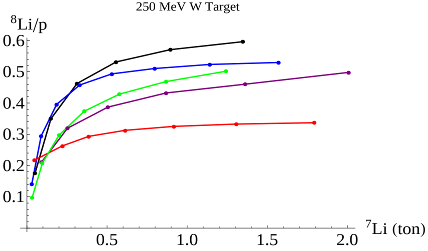
4) Bounce off the moderator back into the target

The first three problems can be reduced with more money.

For the fourth: We will place a gap between the target and the converter so that neutrons bouncing back from the converter can cross the gap and return into the converter

Improved Neutrino Yield





A 25 MeV *p* beam with a Be target and 250 MeV *p* with a W target and a 10 cm gap.

μDAR

Sterile neutrinos are a hot topic, but their existence is considered to be a long shot

Leptonic CP-violation on the other hand occurs generically in models of massive neutrinos and so is more interesting

However it can only be observed in an appearance experiment

Appearance experiments require beam energies of at least 400 MeV

In the rest of this talk, we will consider μ Decay At Rest (μDAR)

The beam creates π^+ in the target, which stop and decay yielding μ^+ which stop and decay yielding $\overline{\nu}_\mu$, which we use for our experiments

These are *reactor* neutrinos:
Conventional reactors create only $\overline{\nu}_e$, but ADS reactors also create $\overline{\nu}_\mu$ and so allow much richer physics programs

What Now for μDARTS?

1) We will determine the neutrino physics reach of μDARTS with a 400 MeV proton beam

2) We are using GENIE for a full, quantitative study of the invisible μ and atmospheric ν_e backgrounds, including the CCQE component.

3) We are determining the optimal baselines, so as to identify candidate sites for the detector

LSND Anomaly

Z-decay at LEP has shown that 3 generations of neutrinos are charged under electroweak symmetry.

Their mass splittings are:

$$\Delta M^2_{21} = 7.5 \times 10^{-5}\ \mathrm{eV}^2, \quad |\Delta M^2_{31}| \sim |\Delta M^2_{32}| = 2.4 \times 10^{-3}\ \mathrm{eV}^2.$$

The corresponding oscillations occur at baselines of

$$L_{12} \sim \frac{2\pi E}{|\Delta M^2_{21}|} \sim 17 \frac{E}{\mathrm{MeV}}\mathrm{km}, \quad L_{13} \sim L_{23} \sim \frac{2\pi E}{|\Delta M^2_{31}|} \sim 0.5 \frac{E}{\mathrm{MeV}}\mathrm{km}$$

Therefore for μ DAR neutrinos, which have energies of 30-50 MeV, one expects oscillations to first peak around 20 km.

LSND Anomaly:

LSND detected, at 4σ, $\overline{\nu}_\mu \to \overline{\nu}_e$ conversion at just 30 meters

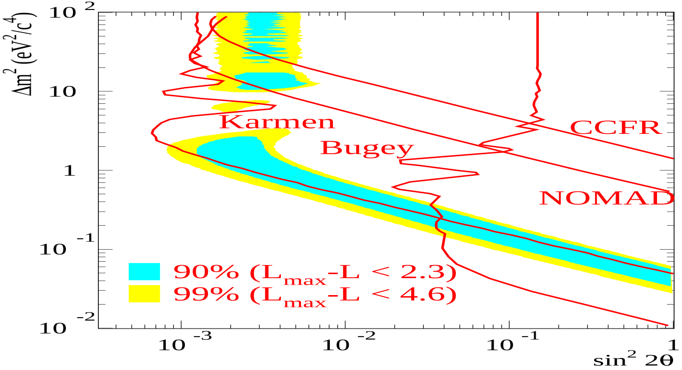
The MiniBooNE experiment also observed anomalous appearance with 1 GeV ν and $\overline{\nu}$ at a similar E/L

LSND Anomaly and Sterile Neutrinos

A fourth, sterile neutrino has been proposed to explain the data

The blue and yellow regions below fit the data, while areas right of the red curves are ruled out by other experiments

$(\Delta m^2, \sin^2(2\theta))$ extends from $(1\ eV^2, 3\times 10^{-3})$ to $(0.2\ eV^2, 3\times 10^{-2})$



Sterile neutrinos with μDARTS

	μDARTS	LSND
proton energy	800 MeV	798 MeV
proton current	10 mA (C-ADS)	1 mA (LANSCE)
runtime	6 years	17 months
protons on target	2×10^6 C	3×10^4 C
detector	liq. scintillator	liq. scintillator
target mass	$N \times 20$ ton	167 ton
baseline	50-100 meters	30 meters

To determine the unoscillated flux, μDARTS can use N old Daya Bay detectors at 50-100 meters, detecting $\overline{\nu}$ via elastic scattering.

If the LSND anomaly is a real effect, *each* Daya Bay detector will observe more ν via IBD than LSND.

Distance dependence → whether the anomaly is due to sterile ν

Longer baseline → sensitivity to 3×lighter sterile ν

Sterile neutrinos with IsoDAR

Like C-ADS, the DAEδALUS project invisages staged progress to a GeV energy, high intensity accelerator.

The first phase is called IsoDAR.

1) A 60 MeV/amu, 600 KW H_2^+ beam strikes a ^{9}Be target, releasing neutrons
2) The neutrons enter a ^{7}Li sleeve and are captured, creating ^{8}Li
3) The ^{8}Li β decays, producing $\overline{\nu}_e$ with an average energy of 6 MeV and max energy of 13 MeV (cosmogenic backgrounds are large)
4) $\overline{\nu}_e$ detected by KamLAND or JUNO, 5 meters away

First measurement of θ_W using ν, so sensitive to some new physics

2.7×10^7 IBD events at JUNO $\rightarrow$ $\overline{\nu}_e$ *disappearance* is sensitive to the LSND anomaly

Sterile neutrinos with CIADS

The θ_W measurement is very sensitive to cosmogenic backgrounds, so requires a depth of at least 700 meters

A depth of 700 meters would also be required to build the accelerator next to JUNO

However I suspect that a test of the LSND anomaly may be done using CIADS at a depth of less than 300 meters (maybe near the surface with a good muon veto), using old Daya Bay detectors

CIADS has the same nucleon current as IsoDAR but the beam energy is 4 times higher

If 4 times more $\nu \rightarrow$ for Daya Bay detectors at 5 meters about $2.8 \times 10^7 \times 4 \times (20/20000) \times (15/5)^2 \sim 10^6$ IBD events/detector

This means sensitivity to $\sin^2(2\theta) \sim 10^{-3}$, sufficient to test the LSND anomaly

Summary

In 7 years the Daya Bay experiment will be finished and will no longer need its 8, 20 ton liquid scintillator detectors.

An ADS with an energy $\gtrsim$ 400 MeV will allow a first-ever measurement of the CP-violating phase δ, using 1 or 2 large scintillator detectors 5-30 km away

Near detectors borrowed from Daya Bay at 50-100 meters, besides providing real-time monitoring of the reactor, can test the LSND anomaly and be sensitive to sterile neutrinos with masses 3 times smaller than LSND

At a proton energy of 250 MeV, Daya Bay detectors at 5 meters may be sensitive to the LSND anomaly, but (due to backgrounds) the experiment may need to be 100-300 meters underground