Neutrino CP Violating Phase from $\mu$ Decay at Rest

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Overview

1. Measuring $\delta_{CP}$
   - LB Experiments
   - $\mu$DAR

2. $\mu$DARTS
   - JUNO and RENO 50
   - ADS
   - Baseline Optimization

3. Conclusions
In neutrino oscillations, the CP-violating angle $\delta_{CP}$ appears only in the appearance probability; e.g.:

$$P_{\mu \rightarrow e} =$$

$$\sin^2(\theta_{23}) \sin^2(\theta_{13}) \sin^2(\Delta_{31}) + \sin(\delta_{CP}) \sin(2\theta_{13}) \sin(2\theta_{23}) \sin(2\theta_{12}) \sin^2(\Delta_{31}) \sin(\Delta_{21})$$

$$+ \cos(\delta_{CP}) \sin(2\theta_{13}) \sin(2\theta_{23}) \sin(2\theta_{12}) \sin(\Delta_{31}) \cos(\Delta_{31}) \sin(\Delta_{21})$$

$$+ \cos^2(\theta_{23}) \sin^2(\theta_{13}) \sin^2(\Delta_{21})$$

$$\Delta_{ij} = 1.27 \Delta m_{ij}^2 L/E; + (-) \text{ for antineutrinos (neutrinos).}$$
Long-Baseline Experiments

Several long-baseline neutrino experiments, like T2K and NO\(\nu\)A, are studying the oscillation probability at the first maximum of 1 \(-\) 3 oscillation ⇒

\[
L = \frac{\pi E}{2.54|\Delta m^2_{31}|} \simeq \frac{\pi E}{2.54|\Delta m^2_{32}|}
\]

Comparing the oscillation probabilities in the neutrino and the antineutrino sector it is possible to measure \(\delta_{CP}\).

**Challenges**

1. High energy accelerators produce \(\nu\) more efficiently than \(\bar{\nu}\) ⇒ larger errors in the \(\bar{\nu}\) mode

2. At the oscillation maximum, \(P_{\mu \rightarrow e}\) depends only on \(\sin(\delta_{CP})\), dependence on \(\cos(\delta_{CP})\) strongly suppressed ⇒ degeneracy between \(\delta_{CP}\) and \(\pi - \delta_{CP}\)
Alternatively, $\delta_{CP}$ can be determined using only antineutrinos produced from $\mu$ Decay At Rest ($\mu$DAR).

- A high-intensity proton beam (energy 400 MeV - 2GeV) hits a fixed target and produces pions.
- The $\pi^-$ are absorbed inside the target, while the $\pi^+$ decay at rest
  \[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
- The $\mu^+$ are also stopped inside the target and decay at rest:
  \[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]
- The $\bar{\nu}_\mu$ oscillate into $\bar{\nu}_e$, that are detected via IBD in a liquid scintillator.
- Studying the oscillation probability at different baselines, it is possible to determine $\delta_{CP}$
Neutrinos from $\mu$DAR

Advantages

- Expected spectrum is known very well: Michel spectrum
- Low background. The energy range is 30-50 MeV: too high for reactor, spallation and geo- neutrinos, but low enough so the atmospheric neutrino background is small.
- No degeneracy between $\delta_{CP}$ and $\pi - \delta_{CP}$

We discuss the possibility to determine $\delta_{CP}$ using $\mu$DAR in several location in Asia, where some of the experimental components (detectors, accelerators) are already present, planned or under construction.

These ideas are inspired by DAE$\delta$ALUS, but in our opinion presents some advantages that will be described below.
The first proposal along these lines was the DAEδALUS project.  

**J. Alsonso et al., arXiv:1006.0260 [physics.ins-det]**

They plan to create $\bar{\nu}_\mu$ via $\mu$DAR at 3 high-intensity cyclotrons at different baselines; this will help also to break the degeneracy with the mixing angles.

### Why DAEδALUS is difficult?

- At these energies, the direction of the $e^+$ is virtually independent of the direction of the incoming $\bar{\nu} \Rightarrow$ it is not possible to know from which accelerator the $\bar{\nu}$ came from.  
  As results, the 3 complex cannot run at the same time (20% duty factor, including measurement of the background)

- Peak current required is very high: 30-50 mA  
  (to increase the current they have suggested to accelerate $H_2^+$)
Our Proposal: $\mu$DARTS

Our Proposal

- Our idea is to use a single cyclotron complex to produce neutrinos and TWO detectors at different baselines.
- With one small detector (Daya Bay detectors?) near the accelerator it is possible to fix the flux normalization (and test LSND anomaly).
- In our simulations, we considered 20 ktons liquid scintillators, and a neutrino flux equivalent to the one generated by a 10 mA, 800 MeV proton beam.
- This is equivalent to 650 IBD events expected a 10 km with $\delta_{CP} = 0$

NOTE: We will show that it is also possible to obtain a reasonable precision even with just one detector

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If JUNO or RENO 50 opt for a second detector, using a cyclotron as $\mu^+$ source it would be possible to determine $\delta_{CP}$ simultaneously with the hierarchy experiment (different energy range)

EC, J. Evslin, X.M. Zhang, JHEP 1412 (2014) 051

An Accelerator Driven Subcritical Reactor (ADS) is under development in China, and it would be a powerful source of neutrinos via $\mu$DAR

Work in progress

There is also a similar proposal using SuperK/HyperK (water Cherenkov detectors) and a $\mu^+$ source in Toyama (TNT2K)

J. Evslin, S.F. Ge, K. Hagiwara; arXiv:1506.05023

Advantages

- The accelerator can run with practically 100% duty factor $\Rightarrow$ the peak intensity required is 5 times lower
- In the locations proposed, low background
Atmospheric Neutrinos

In our energy range (30-55 MeV) we can neglect the spallation, reactor or geoneutrinos background ⇒ main source of background: atmospheric neutrinos.
A strong horizontal geomagnetic field defects low energy cosmic rays, reducing the low energy atmospheric flux.

China (0.38 G), RENO 50/Kamioka mines (0.31 G)

vs

DUNE (0.17 G), LENA in the Pyhasalmi mine (0.13 G)

Low background: ≃ 50 events in 10 years (compared to 650 events at 10 km with $\delta_{CP} = 0$)

J. Evslin, S.F. Ge, K. Hagiwara; arXiv:1506.05023

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The best location for a second detector for JUNO is ZiLuoShan. The distance between two detectors is compatible with optimal baselines for $\mu$DARTS.
Expected spectra at near and far detectors for $\delta_{CP} = 0^\circ, 90^\circ, 180^\circ, 270^\circ$; normal hierarchy, 10 years lifetime.

With $\delta_{CP} = 0$, 650 expected events between 30 and 55 MeV
The main purposes of an Accelerator Driven Subcritical system (ADS), of the kind being developed in China (C-ADS), are

- recycle the used nuclear fuel
- produce electricity

The byproducts of nuclear fission are still radioactive but cannot sustain a chain reaction. In the C-ADS nuclear reactor the additional neutrons will be provided by a 10 mA, 1.5 GeV proton beam which strikes on a fixed target.


$\mu^+\text{DAR}$ in the target will create a large amount of $\bar{\nu}_\mu$. C-ADS will take a long time to develop, so in what follows we only use phase II, which uses a 8 MW beam.

Also Europe is working on the development of an ADS system: MYRRHA
Baseline Optimization

Sensitivity to $\delta_{CP}$ (averaged over the values of $\delta_{CP}$) as a function of the baseline of the far detector.

Lifetime: 10 years. The three curves correspond to a near detector at 2.5 km, 5 km, 7.5 km. In the simulations the synergy with NO$\nu$A is taken into account.
Sensitivity to $\delta_{CP}$ for $\delta_{CP} = 0^\circ, 90^\circ, 180^\circ, 270^\circ$.

Solid curves: synergy with NO$\nu$A is taken into account.
No Degeneracy $\delta_{CP} \leftrightarrow \pi - \delta_{CP}$

$\chi^2$ as a function of fitted $\delta$, assuming $\delta_{true}^{CP} = 0$. Red (black) curves: NO$\nu$A is (not) taken into account.

- Solid curves: 2 detectors at 2.5 km and 25 km
- Dashed curves: single detector at 25 km

With two detectors $\delta_{CP} = 0^\circ$ and $\delta_{CP} = 180^\circ$ can be cleanly distinguished.
Conclusions

- Neutrinos from $\mu$DAR $\Rightarrow$ low background
- $\mu$DARTS: with two 20 ktons liquid scintillator detectors, it is possible to measure $\delta_{CP}$ with a precision of 16° in 10 years
- C-ADS can provide the required flux of $\bar{\nu}_\mu$
- It is also possible to determine $\delta_{CP}$ in JUNO or RENO 50, while they are measuring the hierarchy
- Even with only one detector, the synergy with LB experiments like NO$\nu$A and T2K will allow to measure $\delta_{CP}$ with good precision