Measure the Leptonic Dirac CP Phase with Muon Decay at Rest

Shao-Feng Ge
(gesf02@gmail.com)

Max-Planck-Institut für Kernphysik, Heidelberg

2016-11-28

### ν Oscillation Data

(for NH) \( \delta m_s^2 \equiv \delta m_{12}^2 (10^{-5} \text{eV}^2) \)

\[
\begin{array}{cccc}
\delta m_s^2 & -1\sigma & \text{Best Value} & +1\sigma \\
7.42 & 7.60 & 7.79 \\
\end{array}
\]

\( |\delta m_a^2| \equiv |\delta m_{13}^2| (10^{-3} \text{eV}^2) \)

\[
\begin{array}{cccc}
|\delta m_a^2| & -1\sigma & \text{Best Value} & +1\sigma \\
2.41 & 2.48 & 2.53 \\
\end{array}
\]

\[
\sin^2 \theta_s \ (\theta_s \equiv \theta_{12}) \quad 0.307 \ (33.6^\circ) \quad 0.323 \ (34.6^\circ) \quad 0.339 \ (35.6^\circ) \\
\sin^2 \theta_a \ (\theta_a \equiv \theta_{23}) \quad 0.439 \ (41.5^\circ) \quad 0.567 \ (48.9^\circ) \quad 0.599 \ (50.8^\circ) \\
\sin^2 \theta_r \ (\theta_r \equiv \theta_{13}) \quad 0.0214 \ (8.4^\circ) \quad 0.0234 \ (8.8^\circ) \quad 0.0254 \ (9.2^\circ) \\
\end{array}
\]

\[
\delta_D \quad ? \quad ? \quad ? 
\]

Forero, Tortola & Valle, [arXiv:1405.7540]
CP Measurement @ Accelerator Exps

- T2K

- NO$\nu$A

- DUNE, T2KII/T2HK/T2HKK/T2KO, MOMENT/ADS-CI, Super-PINGU

Measure the Leptonic Dirac CP Phase with $\mu$DAR
To leading order in $\alpha = \frac{\delta M_{21}^2}{|\delta M_{31}^2|} \sim 3\%$, the oscillation probability relevant to measuring $\delta_D @ T2(H)K$,

$$P_{\nu_{\mu} \rightarrow \nu_e} \approx 4s_a^2 c_r^2 s_r^2 \sin^2 \phi_{31}$$

$$- 8c_a s_a c_r^2 s_r c_s s_s \sin \phi_{21} \sin \phi_{31} [\cos \delta_D \cos \phi_{31} \pm \sin \delta_D \sin \phi_{31}]$$

for $\nu$ & $\bar{\nu}$, respectively. [$\phi_{ij} \equiv \frac{\delta m_{ij}^2 L}{4E_\nu}$]

- $\nu_\mu \rightarrow \nu_\mu$ Exps measure $\sin^2(2\theta_a)$ precisely, but not $\sin^2 \theta_a$.

- Run both $\nu$ & $\bar{\nu}$ modes @ first peak [$\phi_{31} = \frac{\pi}{2}$, $\phi_{21} = \alpha \frac{\pi}{2}$],

$$P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e} + P_{\nu_\mu \rightarrow \nu_e} = 2s_a^2 c_r^2 s_r^2,$$

$$P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e} - P_{\nu_\mu \rightarrow \nu_e} = \alpha \pi \sin(2\theta_s) \sin(2\theta_r) \sin(2\theta_a) \cos \theta_r \sin \delta_D .$$
The Dirac CP Phase $\delta_D$ @ Accelerator Exp

Accelerator experiment, such as T2K, uses off-axis beam to compare $\nu_e$ & $\bar{\nu}_e$ appearance @ the oscillation maximum.

- **Disadvantages:**
  - **Efficiency:**
    - Proton accelerators produce $\nu$ more efficiently than $\bar{\nu}$ ($\sigma_\nu > \sigma_{\bar{\nu}}$).
    - The $\bar{\nu}$ mode needs more beam time [$T_{\bar{\nu}} : T_{\nu} = 2 : 1$].
    - Undercut statistics $\Rightarrow$ Difficult to reduce the uncertainty.
  - **Degeneracy:**
    - Only $\sin \delta_D$ appears in $P_{\nu_\mu \rightarrow \nu_e}$ & $P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}$.
    - Cannot distinguish $\delta_D$ from $\pi - \delta_D$.

- **CP Uncertainty**
  \[
  \frac{\partial P_{\nu_\mu \rightarrow \nu_e}}{\partial \delta_D} \propto \cos \delta_D \ \Rightarrow \ \Delta(\delta_D) \propto \frac{1}{\cos \delta_D}.
  \]

- **Solution:**
  Measure $\bar{\nu}$ mode with $\mu^+$ decay @ rest ($\mu$DAR)
A cyclotron produces 800 MeV proton beam @ fixed target.

Produce $\pi^\pm$

- $\pi^-$ is absorbed,
- $\pi^+$ decays @ rest: $\pi^+ \rightarrow \mu^+ + \nu_\mu$.

$\mu^+$ stops & decays @ rest: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$.

$\bar{\nu}_\mu$ travel in all directions, oscillating as they go.

A detector measures the $\bar{\nu}_e$ from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation.
Accelerator + $\mu$DAR Experiments

Combining $\nu_\mu \rightarrow \nu_e$ @ accelerator [narrow peak @ 550 MeV] & $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ @ $\mu$DAR [wide peak $\sim 45$ MeV] solves the 2 problems:

- **Efficiency:**
  - $\nu$ @ high intensity, $\mu$DAR is plentiful enough.
  - Accelerator Exps can devote all run time to the $\nu$ mode. With same run time, the statistical uncertainty drops by $\sqrt{3}$.

- **Degeneracy:** (decomposition in propagation basis [1309.3176])

![Graphs showing decomposition coefficients for cos $\delta$ and sin $\delta$ at T2K (285 km) and µDARs near detector (10 km) and far detector (30 km).]
It’s the **FIRST** proposal along this line:
- 3 $\mu$DAR with 3 high-intensity cyclotron complexes.
- 1 detector.
- Different baselines: 1.5, 8 & 20 km to break degeneracies.

**Disadvantages:**
- The scattering lepton from IBD @ low energy is *isotropic*.
- **Cannot** distinguish $\bar{\nu}_e$ from different sources
- Baseline *cannot be measured*.
- Cyclotrons **cannot** run simultaneously (20~25% duty factor).
- **Large** statistical uncertainty.
- **Higher intensity** is necessary.
- **Expensive** & Technically **challenging**.
New Proposals

1 $\mu$DAR source + 2 detectors

Advantages:
- Full (100%) duty factor!
- Lower intensity: $\sim 9$ mA [$\sim 4 \times$ lower than DAE$\delta$ALUS]
- Not far beyond the current state-of-art technology of cyclotron [2.2 mA @ Paul Scherrer Institute]
- MUCH cheaper & technically easier.
  - Only one cyclotron.
  - Lower intensity.

Disadvantage?
- A second detector!
  - $\mu$DAR with Two Scintillators ($\mu$DARTS) [1401.3977]
  - Tokai 'N Toyama to(2) Kamioka (TNT2K) [1506.05023]
**μDARTS – JUNO & RENO50**

- **Two detectors** are suggested to overcome the **unknown energy response**. [Ciuffoli et al., PRD 2014; 1307.7419]

- China Atomic Energy Center is proposing a **cyclotron**.
TNT2K

- $T2(H)K + \mu SK + \mu HK$

$\mu$DAR is also useful for material, medicine industries in Toyama
Expected $\mu$DAR IBD signal from 6 yrs of running @ SK (15km) & HK (23km) with NH.

Simulated by NuPro, http://nupro.hepforge.org/
$\delta_D$ Precision @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]

Simulated by NuPro, http://nupro.hepforge.org/

Measure the Leptonic Dirac CP Phase with $\mu$DAR
Measure the Leptonic Dirac CP Phase with $\mu$DAR

Simulated by NuPro, http://nupro.hepforge.org/
Non-Unitarity Mixing (NUM)

Ge, Pasquini, Tortola & Valle

\[ N = N^{NP} U = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ |\alpha_{21}| e^{i\phi} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U. \]

\[ P^{NP}_{\mu e} = \alpha_{11}^2 \left\{ \alpha_{22}^2 \left[ c_a |S'_{12}|^2 + s_a |S'_{13}|^2 + 2c_a s_a (\cos \delta_{D R} - \sin \delta_{D I}) (S'_{12} S'^*_{13}) \right] + |\alpha_{21}|^2 P_{ee} \right. \]

\[ + 2 \alpha_{22} |\alpha_{21}| \left[ c_a (c_\phi R - s_\phi I) (S'_{11} S'^*_{12}) + s_a (c_\phi + \delta_{D R} R - s_\phi + \delta_{D I} I) (S'_{11} S'^*_{13}) \right] \}

The effect of including non-unitarity at T2K [\( \delta_{CP}^{\text{true}} = -90^\circ, \text{NH} \)]

The effect of including non-unitarity at T2HK [\( \delta_{CP}^{\text{true}} = -90^\circ, \text{NH} \)]
The effect of including non-unitarity at T2K+μ SK [δ_{CP}^{true} = -90°, NH]

The effect of including non-unitarity at T2HK+μ HK [δ_{CP}^{true} = -90°, NH]

The effect of including non-unitarity at T2K+μ SK+μ Near [δ_{CP}^{true} = -90°, NH]

The effect of including non-unitarity at T2HK+μ HK+μ Near [δ_{CP}^{true} = -90°, NH]

\[ P^{NP}_{\mu e} (L \to 0) = |\alpha_{21}|^2 \]
Non-Standard Interaction

\[ \mathcal{H} \equiv \frac{1}{2E_\nu} U \begin{pmatrix} 0 & \Delta m_s^2 \\ \Delta m_a^2 & \end{pmatrix} U^\dagger + V_{cc} \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix} \]

- **Standard Interaction** – \( V_{cc} \) (also \( V_{nc} \))

- **Non-Standard Interaction** – \( \epsilon_{\alpha\beta} \)
  
  - Diagonal \( \epsilon_{\alpha\alpha} \) are real
  - Off-diagonal \( \epsilon_{\alpha \neq \beta} \) are complex
  - Both can fake CP

- \( Z' \) in **LMA-Dark** model with \( L_\mu - L_\tau \) gauged as \( U(1) \)
  
  - \( M_{Z'} \sim \mathcal{O}(10) \text{MeV} \)
  - \( g_{Z'} \sim 10^{-5} \)
The effect of NSI on the CP sensitivity at T2K \( [\delta_D^{\text{true}} = -90^0] \)

The effect of NSI on the CP sensitivity at μSK \( [\delta_D^{\text{true}} = -90^0] \)

The effect of NSI on the CP sensitivity at T2K+μSK \( [\delta_D^{\text{true}} = -90^0] \)

The effect of NSI on the CP sensitivity at νT2K+μSK \( [\delta_D^{\text{true}} = -90^0] \)
Summary

- **Better CP measurement than T2K**
  - Much larger event numbers
  - Much better CP sensitivity around maximal CP
  - Solve degeneracy between $\delta_D$ & $\pi - \delta_D$
  - Guarantee CP sensitivity against NUM
  - Guarantee CP sensitivity against NSI

- **Better configuration than DAE$\delta$LUS**
  - Only one cyclotron
  - 100% duty factor
  - Much lower flux intensity
  - Much easier
  - Much cheaper
  - Single near detector
Thank You!
Measure the Leptonic Dirac CP Phase with $\mu$DAR
The effect of NSI @ T2K

Shao-Feng Ge (MPIK); CosPA, 2016-11-28, Sydney

Measure the Leptonic Dirac CP Phase with $\mu$DAR
The effect of NSI @ $\muSK$

Shao-Feng Ge (MPIK); CosPA, 2016-11-28, Sydney

Measure the Leptonic Dirac CP Phase with $\mu$DAR