Measuring the Leptonic Dirac CP Phase with Muon Decay at Rest

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SFG [arXiv:1704.08518]
Why neutrino mass & oscillation?

- Higgs boson $\Rightarrow$ electroweak symmetry breaking & mass.
- Chiral symmetry breaking $\Rightarrow$ majority of mass.
- **The world seems not affected by the tiny neutrino mass?**
  - Neutrino mass $\Rightarrow$ Mixing
  - 3 Neutrino $\Rightarrow$ possible **CP violation**
  - CP violation $\Rightarrow$ Leptogenesis
  - Leptogenesis $\Rightarrow$ **Matter-Antimatter Asymmetry**
  - There is something left in the Universe.
  - Baryogenesis from quark mixing is not enough.

- Majorana $\nu \leftrightarrow$ **Lepton Neumber Violation**

- **Residual $\mathbb{Z}_2$ Symmetries:**
\[
\cos \delta_D = \frac{(s_s^2 - c_s^2 s_r^2)(c_a^2 - s_a^2)}{4 c_a s_a c_s s_s s_r}
\]
CP Measurement @ Accelerator Exps

- T2K

- NO\(\nu\)A

- DUNE/T2KII/T2HK/T2HKK/T2KO; MOMENT/ADS-CI/DAE\(\delta\)ALUS; Super-PINGU
The Dirac CP Phase $\delta_D$ @ Accelerator Exp

- To leading order in $\alpha = \frac{\delta M^2_{21}}{|\delta M^2_{31}|} \sim 3\%$, the oscillation probability relevant to measuring $\delta_D$ @ T2(H)K,

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

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

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

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

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

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

$$P_{\nu_\mu \rightarrow \bar{\nu}_e} - P_{\nu_\mu \rightarrow \nu_e} = \alpha \pi \sin(2\theta_s) \sin(2\theta_r) \sin(2\theta_a) \cos \theta_r \sin \delta_D .$$
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** $\frac{\partial P_{\mu^e}}{\partial \delta_D} \propto \cos \delta_D \Rightarrow \Delta(\delta_D) \propto \frac{1}{\cos \delta_D}$.

- **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] & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ @ $\mu$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])

![Decomposition coefficients for cos$\delta$ and sin$\delta$](image1)

![Decomposition coefficients for cos$\delta$ and sin$\delta$](image2)
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: $\sim 9mA$ [$\sim 4 \times$ lower than DAE$\delta$ALUS]
- Not far beyond the current state-of-art technology of cyclotron [2.2mA @ Paul Scherrer Institute]
- MUCH **cheaper** & technically **easier**.
  - Only one cyclotron.
  - Lower intensity.

Disadvantage?
- A second detector!
  - $\mu$DAR with Two Scintillators ($\mu$DARTS) [Ciuffoli, Evslin & Zhang, 1401.3977]
  - Tokai 'N Toyama to(2) Kamioka (TNT2K) [Evslin, Ge & Hagiwara, 1506.05023]
**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
Lowest Atmospheric Neutrino Background
Backgrounds to IBD ($\bar{\nu}_e + p \rightarrow e^+ + n$)

- Reactor $\bar{\nu}_e$: $E_\nu < 10$ MeV
- Accelerator $\nu_e$: $E_\nu > 100$ MeV
- Spallation: $E_\nu \lesssim 20$ MeV
- Supernova Relic Neutrino: $E_\nu \lesssim 20$ MeV
  
  **Cut with $30$ MeV $< E_\nu < 55$ MeV**

- Accelerator $\nu_\mu \rightarrow \text{Invisible muon}$
- Atmospheric Neutrino Background
  - **Invisible muon** (below Cherenkov limit)
    - $E_\mu \lesssim 1.5 \times m_\mu$, $\mu^\pm \rightarrow e^\pm$
    - $E_\pi \lesssim 1.5 \times m_\pi$, $\pi^+ \rightarrow \mu^+ \rightarrow e^+$
    - 1 neutron
    - No prompt photon
  - Irreducible $\bar{\nu}_e$: $30$ MeV $\lesssim E_\nu \lesssim 55$ MeV
  - Reducible $\nu_e$: $60$ MeV $\lesssim E_\nu \lesssim 100$ MeV
    - 1 neutron
    - No prompt photon
  - **Lowest** at $\mu$DARTS & TNT2K sites
Expected $\mu$DAR IBD signal from 6 yrs of running @ SK (15km) & HK (23km) with NH.

Simulated by NuPro, http://nupro.hepforge.org/
δ_D Precision @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]

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

TNT2K: Measuring the Leptonic Dirac CP Phase with μDAR
\( \delta_D \) Precision @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]

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

Ge, Pasquini, Tortola & Valle [1605.01670]

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

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

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

Unitary  
Non-Unitary  
Non-Unitary + Prior

The effect of including non-unitarity at T2HK [\( \delta_{CP}^{true} = -90^\circ \), NH]

Unitary  
Non-Unitary  
Non-Unitary + Prior
\[ P_{\mu e}^{NP}(L \rightarrow 0) = \alpha_{11}^2 |\alpha_{21}|^2 P_{ee} \approx \alpha_{11}^2 |\alpha_{21}|^2 \approx |\alpha_{21}|^2 \]

Event Spectrum at \( \mu \text{Near} \) [20ton, \( L = 20m \)]

- Signal
- Background

\[ |\alpha_{12}|^{\text{true}} = 0.02 \]

\[ \mu^-\text{DAR}/\mu^+\text{DAR} = 5 \times 10^{-4} \]
$\mu$Near at $\mu$DAR

$1\sigma$ Upper Limit on $|\alpha_{21}|$ at $\mu$Near

Detector Size [ton] vs. Background-Signal Flux Ratio [$\times 10^{-4}$]
$P^{NP}_{\mu e}(L \rightarrow 0) = |\alpha_{21}|^2$
Non-Standard Interaction

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

- **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 \( U(1) \)
  - \( M_{Z'} \sim \mathcal{O}(10) \text{MeV} \)
  - \( g_{Z'} \sim 10^{-5} \)
Corrections to $\delta_D$ [Degree] at T2K

$\varepsilon_{ee} - \varepsilon_{\mu\mu}$

$\varepsilon_{e\tau} - \varepsilon_{\mu\mu}$

Corrections to $|\varepsilon_{e\mu}|$

Corrections to $|\varepsilon_{\mu\tau}|$

Corrections to $|\varepsilon_{e\tau}|$
The effect of NSI on the CP sensitivity at T2K [ $\delta_{D}^{\text{true}} = -90^\circ$ ]

The effect of NSI on the CP sensitivity at $\mu$SK [ $\delta_{D}^{\text{true}} = -90^\circ$ ]

The effect of NSI on the CP sensitivity at T2K+$\mu$SK [ $\delta_{D}^{\text{true}} = -90^\circ$ ]

The effect of NSI on the CP sensitivity at $\nu$T2K+$\mu$SK [ $\delta_{D}^{\text{true}} = -90^\circ$ ]

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TNT2K: Measuring the Leptonic Dirac CP Phase with $\mu$DAR
**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$\delta$ALUS**
  - Only one cyclotron
  - 100% duty factor
  - Much lower flux intensity
  - Much easier
  - Much cheaper
  - Single near detector
Thank You!
The effect of NSI on the CP sensitivity at T2KII [ $\delta_D^{\text{true}} = -90^\circ$ ]

The effect of NSI on the CP sensitivity at $\mu$SK [ $\delta_D^{\text{true}} = -90^\circ$ ]

The effect of NSI on the CP sensitivity at T2KII+$\mu$SK [ $\delta_D^{\text{true}} = -90^\circ$ ]

The effect of NSI on the CP sensitivity at $\nu$T2KII+$\mu$SK [ $\delta_D^{\text{true}} = -90^\circ$ ]
The effect of NSI @ T2K

SFG & Alexei Smirnov [arXiv:1607.08513]
The effect of NSI @ $\mu$SK

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TNT2K: Measuring the Leptonic Dirac CP Phase with $\mu$DAR