The Dirac CP Phase δ_D @ T2(H)K & μDAR

Shao-Feng Ge

(gesf02@gmail.com)

KEK Theory Center

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In collaboration with **Jarah Evslin & Kaoru Hagiwara**

Status

- March 8, 2012, discovery from **Daya Bay** [later from **Reno**]

$$\sin^2 2\theta_r \sim 0.1$$

  by $\mathbf{5.2\sigma}$ & reaching $\mathbf{7.7\sigma}$ by October, 2012.

$$\theta_r \equiv \theta_{13}\,, \qquad \theta_s \equiv \theta_{12}\,, \qquad \theta_a \equiv \theta_{23}\,,$$
$$\delta m_a^2 \equiv \delta m_{31}^2\,, \qquad \delta m_s^2 \equiv \delta m_{21}^2\,.$$

- **Unknowns**
  - **Hierarchy**:

$$\delta m_a^2 \gtrless 0?$$

  - **Octant**:

$$\theta_a \gtrless 45^\circ?$$

  - **CP**:

$$\delta_D = ?$$

Inspired by the discovery of relatively large θ_r, we studied the physics potential of two types of future neutrino experiments:

- Reactor anti-neutrino: **MH** [1210.8141]
  - medium baseline $50\text{km} < L < 60\text{km}$: **DayaBayII** + **Reno50**
  - lower energy $1\text{MeV} < E_\nu < 8\text{MeV}$
- Accelerator neutrino: $\boldsymbol{\delta_D}$, **MH**, $\boldsymbol{\theta_a}$ [split scheme 1308.6522]
  - long baselines: **T2K(T2HK)** (295km) + **Tokai-to-Oki** (653km) + **NOνA** (812km) + **LBNE** (1300km) + **LBNO** (2300km)
  - medium energy $0.5\text{GeV} < E_\nu < 5\text{GeV}$
- Atmospheric neutrino: **MH**, $\boldsymbol{\theta_a}$ [1309.3176, 1312.0457]
  - long baseline $0\text{km} < L < 13000\text{km}$: **SK(HK)** + **INO** + **PINGU** (*)
  - high energy $1\text{GeV} < E_\nu < 20\text{GeV}$
- **μDAR**: $\boldsymbol{\delta_D}$ [1405.xxxx]

The Dirac CP Phase δ_D @ T2(H)K

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

$$P_{\substack{\nu_\mu \to \nu_e \\ \overline{\nu}_\mu \to \overline{\nu}_e}} \approx 4 s^2_a c^2_r s^2_r \sin^2 \phi_{31} - 8 c_a s_a c^2_r s_r c_s s_s \sin \phi_{21} \sin \phi_{31} \left[\cos \delta_D \cos \phi_{31} \pm \sin \delta_D \sin \phi_{31} \right]$$

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

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

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

$$P_{\overline{\nu}_\mu \to \overline{\nu}_e} + P_{\nu_\mu \to \nu_e} = 2 s^2_a c^2_r s^2_r ,$$

$$P_{\overline{\nu}_\mu \to \overline{\nu}_e} - P_{\nu_\mu \to \nu_e} = \alpha \pi \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \cos \theta_{13} \sin \delta_D .$$

The Dirac CP Phase δ_D @ T2(H)K

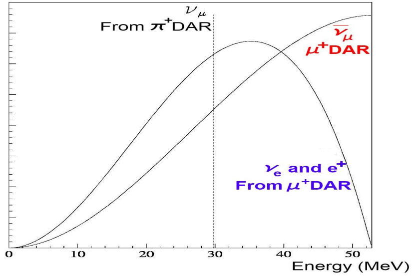
Accelerator experiment, such as T2(H)K, uses off-axis beam to compare ν_e & $\overline{\nu}_e$ appearance @ the oscillation maximum.

- **Disadvantages**:
  - Efficiency:
    - Proton accelerators produce ν more efficiently than $\overline{\nu}$.
    - The $\overline{\nu}$ mode needs more beam time $[T_{\overline{\nu}} : T_\nu = 2 : 1]$.
    - Difficult to reduce the uncertainty.
  - Degeneracy:
    - Only $\sin \delta_D$ appears in $P_{\nu_\mu \to \nu_e}$ & $P_{\overline{\nu}_\mu \to \overline{\nu}_e}$.
    - Cannot distinguish δ_D from $\pi - \delta_D$.
- **Solution**:

  Measure $\overline{\nu}$ mode with μ^+ decay @ rest (μDAR)

μDAR Neutrino Oscillation Experiments

- A cyclotron produces 800 MeV proton beam @ fixed target.
- Produce $\pi^\pm$ which stop &
  - π^- are absorbed,
  - π^+ decay @ rest: $\pi^+ \to \mu^+ + \nu_\mu$.
- μ^+ stops & decays @ rest: $\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$.

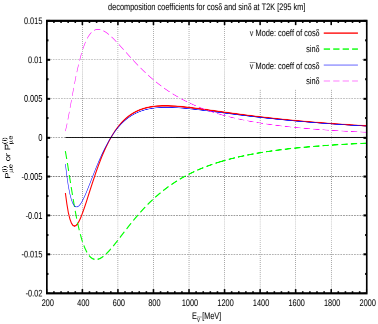


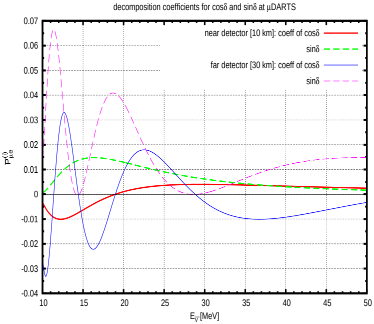
- $\overline{\nu}_\mu$ travel in all directions, oscillating as they go.
- A detector measures the $\overline{\nu}_e$ from $\overline{\nu}_\mu \to \overline{\nu}_e$.

Accelerator + μDAR Experiments

Combining $\nu_\mu \to \nu_e$ **@ accelerator** [narrow peak @ 500 MeV] & $\overline{\nu}_\mu \to \overline{\nu}_e$ **@ μDAR** [wide peak $\sim$ 35 MeV] solves the 2 problems:

- **Efficiency**:
  - $\overline{\nu}$ @ high intensity μDAR is plentiful enough.
  - Accelerator Exps can devote all run time to the ν mode. With same run time, the statistical uncertainty drops by $\sqrt{3}$.
- **Degeneracy**: (decomposition in propagation basis [1309.3176])





DAEδALUS Project

- It's the **FIRST** proposal along this line:
  - **3** μDAR 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 $\overline{\nu}_e$ from different sources
  - Cyclotrons **cannot** run simultaneously (20% duty factor).
  - **Large** statistical uncertainty.
  - **Higher intensity** is necessary.
  - **Expensive** & Technically **challenging**.

New Proposals

1 μDAR source + **2** detectors

Advantages:

- Full (**100%**) duty factor!
- **Lower** intensity: $\sim$ **9mA** [$\sim$ **4**$\times$ lower than DAEδALUS]
- 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!
  - **μDAR** with **T**wo **S**cintillators (**μDARTS**) [1401.3977]
  - **T**okai '**N** **T**oyama to(**2**) **K**amioka (**TNT2K**) [1405.xxxx]

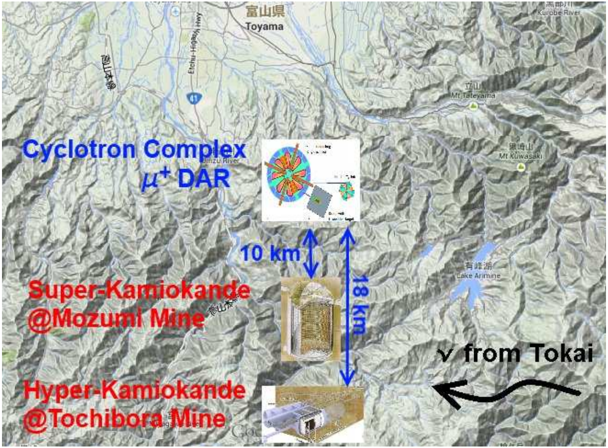
μDARTS (1)

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

- China Atomic Energy Center has a proposal for cyclotron

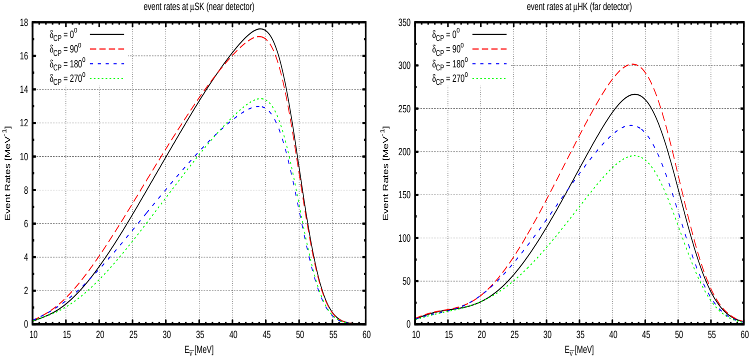
TNT2K (1)

- TNT2K = T2(H)K + μSK + μHK



- μDAR is also useful for material, medicine sciences

Event Shape @ TNT2K



Expected μDAR IBD signal from 6 yrs of running @ SK (10km) & HK (18km) with NH.

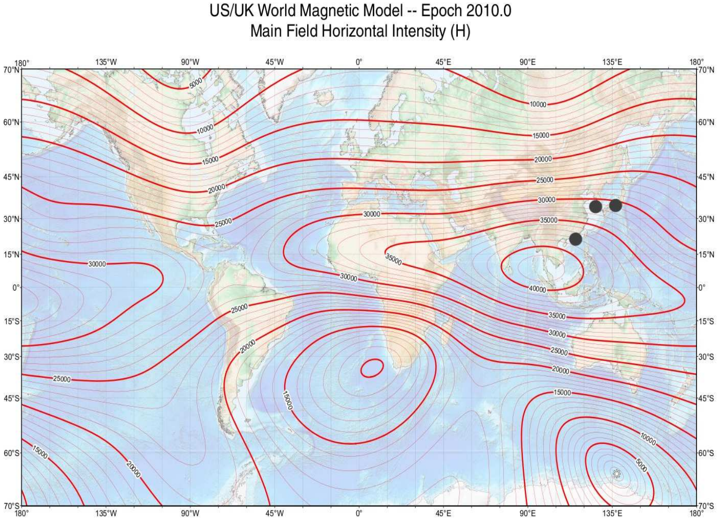
Backgrounds to IBD ($\overline{\nu}_e + p \to e^+ + n$)

- Reactor $\overline{\nu}_e$: $E_\nu < 10$ MeV
- Accelerator ν_e: $E_\nu > 200$ MeV
- Spallation: $E_\nu \lesssim 20$ MeV
- Supernova Relic Neutrino: $E_\nu \lesssim 20$ MeV

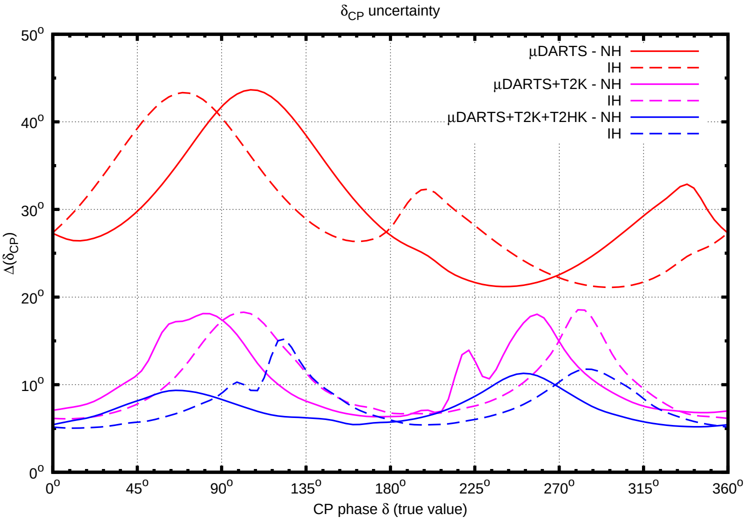
  Cut with 30 MeV $< E_\nu <$ 55 MeV

- Accelerator $\nu_\mu \to$ Invisible muon
- Atmospheric Neutrino Background
  - Invisible muon (below Cherenkov limit)
    - $E_\mu \lesssim 1.5 \times m_\mu$, $\mu^\pm \to e^\pm$
    - $E_\pi \lesssim 1.5 \times m_\pi$, $\pi^+ \to \mu^+ \to e^+$
    - 1 neutron
    - No prompt photon
  - Irreducible $\overline{\nu}_e$: 30 MeV $\lesssim E_\nu \lesssim$ 55 MeV
  - Reducible ν_e: 60 MeV $\lesssim E_\nu \lesssim$ 100 MeV
    - 1 neutron
    - No prompt photon
  - **Lowest** at μDARTS & TNT2K sites

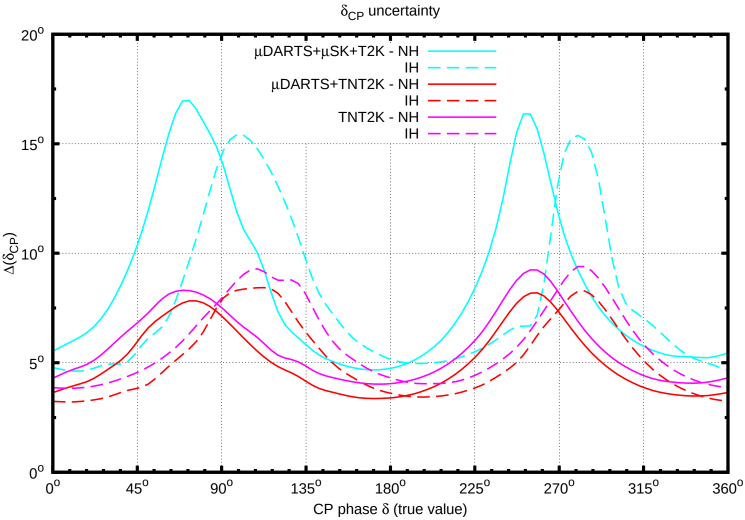
Lowest Atmospheric Neutrino Background



δ_D Precision



δ_D Precision



Summary

- μDAR can run together with accelerator experiments
  - Efficiency
  - Degeneracy
  - Better sensitivity
- 1 μDAR + 2 detector is much better than DAEδALUS
  - Only one μDAR source
  - Lower intensity
  - Technically easier
  - Much cheaper
- Enhance the physics potential of reactor experiments
- JUNO & T2(H)K site has the lowest atmospheric ν background in the world

Thank You!