Measuring the Leptonic Dirac CP Phase with TNT2K

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I describe how the TNT2K (Tokai and Toyama to Kamioka) configuration with a muon decay at rest (µDAR) add-on to T2(H)K can achieve better measurement of the leptonic Dirac CP phase $\delta_D$. It has five-fold advantages of high efficiency, smaller CP uncertainty, absence of degeneracy, as well as guaranteeing CP sensitivity against non-unitary mixing (NUM) and non-standard interaction (NSI). In comparison to the flux upgrade with T2K-II, the detector upgrade with T2HK, and the baseline upgrade with T2HKK, TNT2K is a totally different concept with spectrum upgrade to solve the intrinsic problems in current and next generations of CP measurement experiments. With a single µDAR source, TNT2K is much cheaper and technically much easier than the DAEδALUS proposal. The latter needs three sources that cannot run simultaneously and consequently requires much higher fluxes. The single µDAR source at TNT2K also allows a single near detector ($\mu$Near) to fully utilize the neutrino flux for the purpose of constraining NUM, but this is impossible at DAEδALUS with three spatially separated sources.

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1 The Intrinsic Problems in CP Measurement

Both T2K and NOνA measure $\delta_D$ by observing the $\nu_\mu \rightarrow \nu_e$ oscillation. To maximize event rate, the neutrino energy and baseline are matched to put oscillation at the first peak, reducing the oscillation probability to have only $\sin\delta_D$ dependence,

$$P_{\nu_\mu \rightarrow \nu_e} \approx 4s_\alpha c_\alpha^2 s_\tau^2 \mp 8c_\alpha s_\alpha c_\tau s_\tau c_\delta s_\delta \sin\phi_21 \sin\delta_D,$$

where $(\theta_a, \theta_r, \theta_s) \equiv (\theta_{23}, \theta_{13}, \theta_{12})$, $(c_x, s_x) \equiv (\cos\theta_x, \sin\theta_x)$, and $\phi_{ij} \equiv \delta m^2_{ij} L/4E_\nu$.

The feature of only $\sin\delta_D$ dependence causes several intrinsic problems. First, the CP term has opposite sign in the neutrino and anti-neutrino modes. With relative suppression by $c_s^2 s_a \approx 1/5$, the CP term can be easily smeared by the uncertainty of $s_a^2$ in the first term of (1). Fortunately, we can extract $\sin\delta_D$ from the difference $P_{\nu_\mu \rightarrow \nu_e} - P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}$ by measuring both neutrino and anti-neutrino modes. To gather comparable event rates, the anti-neutrino mode needs much more time than the neutrino mode due to smaller cross section, $\sigma_{\bar{\nu}} < \sigma_{\nu}$. Roughly speaking, the anti-neutrino mode requires at least $2/3$ of run time. This significantly reduces the event rates, leading to efficiency problem. Secondly, extracting $\sin\delta_D$ cannot uniquely determine $\delta_D$, with degeneracy between $\delta_D$ and $\pi - \delta_D$. Thirdly, the CP uncertainty is proportional to $|1/\cos\delta_D|$ with only $\sin\delta_D$ dependence. The recent global fits with preference for maximal CP $\delta_D \approx -\pi/2$ is not good news for precision measurement.

These three problems are intrinsic problems for accelerator-based experiments, including T2K, NOνA, and the future DUNE. In addition, T2K-II and T2HK have exactly the same configuration and hence the same problems. The baseline upgrade T2HK seems to have better chance. However, it needs to sit at the second oscillation peak to maximize event rate, still leading to the same problems.

2 CP Measurement at TNT2K

TNT2K is designed for better CP measurement by supplementing T2K (T2HK) with a $\mu$DAR source [1] close to SK (HK). This requires a cyclotron to produce the $\mu$DAR neutrino flux by accelerating proton to hit target, producing charged pions which decay through the chain $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow (e^+ + \nu_e + \bar{\nu}_\mu) + \nu_\mu$. The $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channel can be measured via inverse beta decay, $\bar{\nu}_e + p \rightarrow e^+ + n$, with double coincidence. Then T2(H)K can devote all time to the neutrino mode while $\mu$Kam, $\mu$SK ($\equiv \mu$DAR+SK) or $\mu$HK ($\equiv \mu$DAR+HK), measures the anti-neutrino mode. With much larger flux and shorter baseline, $\mu$Kam can collect much more anti-neutrino events than T2(H)K. This combination can significantly improve the efficiency by a factor of 3 (4) in the neutrino (anti-neutrino) mode [2].

| $\delta_D^{true} = -90^\circ$ | T2K | $\mu$SK | T2K+$\mu$SK | $\nu$T2K+$\mu$SK |
|---------------------------|-----|--------|------------|-----------------|
| Event Numbers            | $114\nu + 56\bar{\nu}$ | $212\bar{\nu}$ | $57\nu + 268\bar{\nu}$ | $342\nu + 212\bar{\nu}$ |
The $\nu_\mu$ flux is produced from $\mu^+$ decay at rest with a wide and flat spectrum across the interested energy range, $30 \text{ MeV} \lesssim E_\nu \lesssim 55 \text{ MeV}$. Using the decomposition formalism [3] in the propagation basis in Fig. 1, we can clearly see vanishing $\cos \delta_D$ term at the J-PARC spectrum peak, $E_\nu \approx 600 \text{ MeV}$, in contrast to comparable $\cos \delta_D$ and $\sin \delta_D$ terms across the $\mu$DAR energy range, allowing TNT2K to avoid degeneracy and large uncertainty problems with the help of $\cos \delta_D$ dependence. Fig. 2 shows how CP uncertainty depends on baseline with optimal distance around 23 km [1].

Figure 1: The decomposed coefficients of $P_{\mu e}$ and $\bar{P}_{\mu e}$ at T2(H)K and $\mu S(H)K$.

Figure 2: The baseline dependence of CP sensitivity at TNT2K without or with HK.

3 Non-Unitary Mixing

If heavy neutrino exists and mix with light neutrinos, the usual $3 \times 3$ light neutrino mixing matrix becomes non-unitary,

$$N = N^{NP}U = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U.$$

(2)
For $\mu \rightarrow e$ transition, the phase in $\alpha_{21} \equiv |\alpha_{21}|e^{-i\phi}$ can fake CP effect,

$$
P^{NP}_{\mu e} = \alpha_{12}^2 \left\{ \alpha_{22}^2 \left[ c_{\alpha}^2 |S'_{12}|^2 + s_{\alpha}^2 |S'_{13}|^2 \right] + 2c_{\alpha}s_{\alpha}(\cos \delta_D \Re - \sin \delta_D \Im)(S'_{12}S'_{13}^{*}) \right\} + |\alpha_{21}|^2 P_{ee}
+ 2\alpha_{22}|\alpha_{21}| \left\{ c_{\alpha} \left( c_{\phi} \Re - s_{\phi} \Im \right)(S'_{11}S'_{12}) + s_{\alpha} \left( c_{\phi+\delta_D} \Re - s_{\phi+\delta_D} \Im \right)(S'_{11}S'_{13}) \right\}.
$$

(3)

In addition to $(\cos \delta_D, \sin \delta_D)$, four extra CP terms $(c_{\phi}, s_{\phi})$ and $(c_{\phi+\delta_D}, s_{\phi+\delta_D})$ appear. The CP sensitivity at T2(H)K can be significantly reduced. The TNT2K configuration can partially improve the situation due to the presence of $\cos \delta_D$ dependence. Further adding a near detector close to the $\mu$DAR source can fully restore the CP sensitivity by measuring the zero-distance effect, $P^{NP}_{\mu e} \big|_{L \rightarrow 0} \rightarrow |\alpha_{21}|^2$, to constrain the size $|\alpha_{21}|$ of the extra CP term [4].

4 Non-Standard Interaction

The CP effect can also be faked by NSI. Since NSI enters oscillation as matter potential, its effect is proportional to the neutrino energy which is unfortunately not small at T2K and NO$\nu$A. As show in the first subplot of Fig. 4, the CP sensitivity at T2K $\Delta \chi^2 \approx 15$ can be significantly reduced by a factor of 5. In contrast, the neutrino energy of the $\mu$DAR flux is smaller than T2K by a factor of 10 and feels negligible effect from NSI, see the second subplot of Fig. 4. While T2K measures both the genuine CP $\delta_D$ and NSI, $\mu$DAR focuses on $\delta_D$. As shown in the last two subplots in Fig. 4, TNT2K can measure $\delta_D$ and NSI simultaneously, hence guaranteeing the CP sensitivity against NSI [2].

5 Comparison with DAE$\delta$ALUS

Requiring only one cyclotron, TNT2K can run with duty factor close to 100%, in contrast to the 25% $\sim$ 30% of DAE$\delta$ALUS. The later needs 3 $\mu$DAR sources but they cannot run simultaneously. Otherwise, it is impossible to tell from which source the neutrinos come from and how long they have traveled. To achieve the same $\mu$DAR
event rate as TNT2K, DAEδALUS demands much higher flux which is inversely proportional to duty factor and hence more advanced technology. In addition, the μNear detector for constraining NUM can use the full μDAR flux at TNT2K but this is impossible at DAEδALUS with distributed sources. Comparing with DAEδALUS, TNT2K is cheaper with only one cyclotron, technically easier with lower flux, and physically has more potential.

References

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