PROCEEDINGS OF SCIENCE

Neutrino CP violating phase from μ decay at rest

Emilio Ciuffoli*
Institute of Modern Physics, CAS, NanChangLu 509, Lanzhou 730000, China
E-mail: emilio@impcas.ac.cn

The determination of the value of θ_{13}, which turned out to be considerably larger than the expected, opened the way to the measurement of the CP violating phase δ_{CP} in the leptonic sector. We consider the following experimental setup: a 800 MeV proton beam hits a target at a single site, creating $\bar{\nu}_\mu$ via μ decay at rest; the electron antineutrinos produced by oscillations interact via IBD in two large liquid scintillators or water Cherenkov detectors. Studying the oscillation probability at different baselines it is possible to measure δ_{CP} with good precision (5-15 degrees in 12 years). We present several possible locations for this experiment in east Asia, each using accelerators or detectors already planned or under construction. No degeneracy is present between δ_{CP} and $\pi - \delta_{CP}$.

The European Physical Society Conference on High Energy Physics
22–29 July 2015
Vienna, Austria

*Speaker.

PoS(EPS-HEP2015)060

1. Introduction

In neutrino oscillation, the CP-violating phase δ_{CP} affects only the appearance channel, not the disappearance. Let's consider the oscillation probability $P_{\mu\to e}$

$$\begin{aligned} P_{\mu\to e} = \; & \sin^2(\theta_{23})\sin^2(\theta_{13})\sin^2(\Delta_{31})+\cos^2(\theta_{23})\sin^2(\theta_{13})\sin^2(\Delta_{21}) \\ & \pm\sin(\delta_{CP})\sin(2\theta_{13})\sin(2\theta_{23})\sin(2\theta_{12})\sin^2(\Delta_{31})\sin(\Delta_{21}) \\ & +\cos(\delta_{CP})\sin(2\theta_{13})\sin(2\theta_{23})\sin(2\theta_{12})\sin(\Delta_{31})\cos(\Delta_{31})\sin(\Delta_{21}) \end{aligned} \tag{1.1}$$

where $\Delta_{ij}=1.27\Delta m^2_{ij}L/E$; the + (-) sign is for neutrinos (antineutrinos). The standard way to determine δ_{CP} is to compare the oscillation probabilities in the neutrino and antineutrino sector: several long baseline neutrino experiments, like T2K [1] and NOνA [2], will perform this measurement in the next decade. However the baseline of these experiments is chosen in order to be at the peak of the $1-3$ oscillations and, due to their narrow energy spectrum, the term proportional to $\cos(\delta_{CP})$ will be strongly suppressed, leading to a degeneracy between δ_{CP} and $\pi-\delta_{CP}$.

It is also possible to determine δ_{CP} using only antineutrinos by studying the oscillation probability at different baselines, in the transition region between the $1-2$ and $1-3$ oscillations. In the experimental setup we considered [3, 4] $\bar{\nu}_\mu$ are produced in an accelerator via μ decay at rest (μDAR). They propagate, oscillating into $\bar{\nu}_e$, which are detected via Inverse Beta Decay (IBD) in two large liquid scintillators. In this way it will be possible to measure δ_{CP} with a precision of 16° in 10 years.

This idea is inspired by the DAEDδLUS proposal [5, 6], however in our opinion it presents some advantages that will be discussed later.

I will present some possible locations for this experiments in East Asia, where part of the experimental apparatus is already present or under construction; I will also discuss the optimization of the baselines and the sensitivity that will be possible to achieve.

2. μDARTS

We considered a proton beam, accelerated to 800 MeV, hitting a fixed target and creating π^+ and π^-. The π^- will be absorbed inside the target, while the π^+ will be stopped, decaying at rest

$$\pi^+\to\mu^++\nu_\mu$$

The μ^+ will also be stopped inside the target and they will decay at rest creating $\bar{\nu}_\mu$

$$\mu^+\to e^++\bar{\nu}_\mu+\nu_e$$

It is important to underline that it is possible to observe only $\bar{\nu}_e$ via IBD on free protons. While ν_e and $\bar{\nu}_e$ interact with C and O in the detectors via charged current quasielastic scattering, the Q value is so high that these events are easily removed with a low energy veto. Elastic scattering of neutrinos also tends to yield lower energies, allowing a veto, and also it does not produce a neutron and so in the case of a scintillator detector or a Gd loaded water Cherenkov detector, as Super-K will be in a few years time, it can be rejected with a double coincidence requirement.

One of the advantages of μDAR is that in this energy range (30-55 MeV) the background is very small. Indeed, it would be possible to neglect the background due to geoneutrinos, reactor neutrinos and, in particular, spallation isotopes, since these are well below the energies considered: this means that the overburden can be significantly smaller than what required in other experiments with similar detector, like JUNO. Another advantage is that the neutrino spectrum and the cross section are known with excellent precision in this energy range and, unlike what happens in the case of the mass hierarchy, the measurement of δ_{CP} does not impose such strong constraints on the detector energy resolution or the unknown non-linear energy response. The main source of background comes from atmospheric $\bar{\nu}_e$ and ν_e interacting via IBD and charged current quasielastic interactions. However, the stronger is the horizontal component of the geomagnetic field, the smaller is the atmospheric neutrino flux; as pointed out in [7], in the locations proposed here this field is particularly strong (0.31-0.38 G) with respect to the locations where other experiments are planned, like DUNE (0.17 G) or LENA, in the Pyhasalmi mine (0.13 G).

The first proposal along these lines was the DAEδALUS project [5]. They want to use one liquid scintillator and three cyclotrons at different baselines to produce $\bar{\nu}_\mu$. However, since in this energy range it is not possible to determine the direction of the incoming neutrinos, the three complex cannot work at the same time, and so will each run with a duty factor of 20%. Moreover, in order to achieve sufficient statistics, the peak current must be very high; a possible solution is to accelerate H_2^+ molecules in order to increase the number of the protons in the beam [6], but this relies on unproven technology, for example to control the H_2^+ excitations.

Our proposal (μDARTS: μ Decay At Rest with Two liquid Scintillators) is to use a single cyclotron complex and two 20-ktons liquid scintillators, plus one small detector to fix the total flux normalization. In this way proton beam can run with a duty factor of essentially 100%, decreasing the requirements on the beam intensity: in the simulations presented here, we assumed a 10 mA, 800 MeV proton beam, which correspond to 625 expected IBD events at 10 km for $\delta_{CP} = 0$, assuming a 20 ktons detector and 12 years lifetime. As pointed out before, the requirements on the energy resolution, the unknown non-linear energy response and the overburden of the detector are decidedly smaller with respect to the ones that must be satisfied in similar experiments, like JUNO: this will reduce significantly the cost of the detectors.

Roughly adapting the results of the simulations from [7], we estimated 50 background events due to atmospheric neutrinos in 12 years. An additional background could be provided by a contamination of $\bar{\nu}_e$ in the $\bar{\nu}_\mu$ beam due to $\mu^- DAR$; the ratio $\mu^- DAR/\ \mu^+ DAR$ depends on the details of the experimental apparatus, however it will be quite small (it could be roughly estimated to be around 5×10^{-4}) and in first approximation can be neglected, so in the simulations here reported it was not considered.

Since the long baseline neutrino experiments (like NOνA and T2K) are more efficient in the production of ν than $\bar{\nu}$, combining their results with the data on $\bar{\nu}$ oscillations obtained from μDAR it is possible to increase the sensitivity to δ_{CP}.

For example, using the synergy with NOνA, even with only one 20 ktons detector it is possible to obtain a reasonable sensitivity to δ_{CP}, as can be seen in Fig. 1.

In Fig. 2 is reported the sensitivity to δ_{CP} with two 20-ktons detector, for different values of the baselines: the optimal baseline is around 2.5 km for the near and 25 km for the far detector; the precision that can be achieved in 12 years lifetime is $16^\circ - 17^\circ$. Needless to say, a single detector

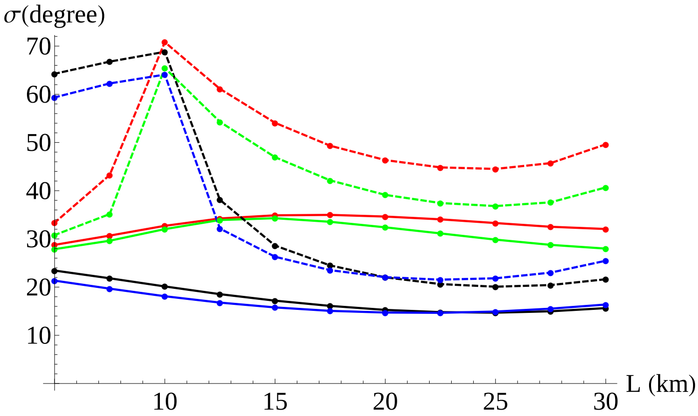

Figure 1: Sensitivity to δ_{CP} using only one detector. Black: $\delta_{CP} = 0°$, red: 90°, blue: 180° , green: 270°. Solid curves: synergy with NOνA is taken into account.

can be built first, and a second one can be added later if and when the required funds will be available.

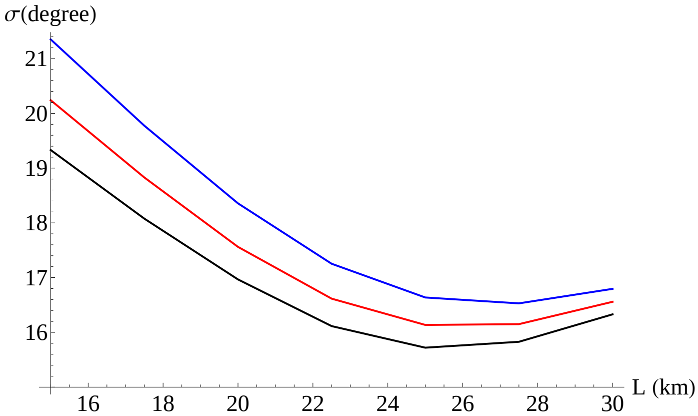

Figure 2: Sensitivity to δ_{CP} (averaged over 4 values of δ_{CP}) as a function of the baseline of the far detector. Lifetime: 10 years. The three curves correspond to a near detector at 2.5 km (black), 5 km (red), 7.5 km (blue). In the simulations the synergy with NOνA is taken into account.

Finally, in Fig. 3 it is shown the value of χ^2 as a function of the fitted value of δ, assuming $\delta_{CP}^{true} = 0$: we can notice that, with two detectors, it is possible to discriminate clearly between δ_{CP} and $\pi - \delta_{CP}$.

3. Possible Locations

It would be extremely expensive to build a dedicated experiment only to measure δ_{CP}; however there are several collaborations where part of the experimental apparatus needed for μDARTS is already present, planned or under construction, and it would be possible to perform the measurement without interfering with the original purpose of the experiment.

Among the possible candidates there are the experiments that in the next years will try to determine the neutrino mass hierarchy, like JUNO [8] and RENO 50 [9]. In these experiments, the

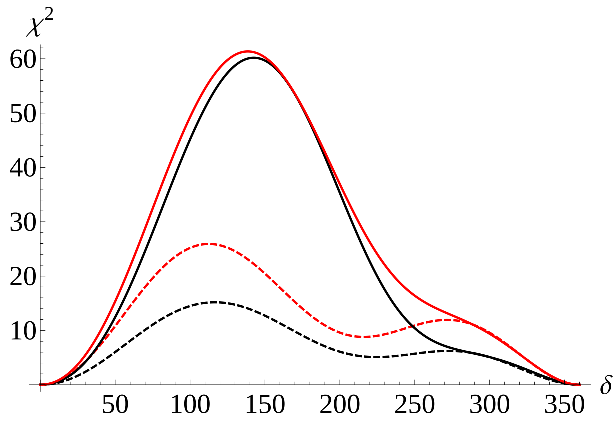

Figure 3: χ^2 as a function of fitted δ_{CP}, assuming $\delta_{CP}^{true} = 0$. Red (black) curves: NOνA is (not) taken into account. Solid curves: 2 detectors at 2.5 and 25 km. Dashed lines: single detector at 25 km.

construction of a second detector would increase the precision and strongly reduce the systematic errors due to the unknown non-linear energy response [10]. Moreover, if the second detector will be built, the difference between the baselines would be within the optimal range for μDARTS [3]. Since the energy range will be quite different from the one of reactor neutrinos (30-55 MeV with respect to 2-10 MeV) it will be possible to run the two experiments at the same time, without interfering with the mass hierarchy determination.

Another possibility is to use the neutrinos produced in the accelerator driven system (ADS), like the one which is currently studied and developed by the Chinese ADS (C-ADS) collaboration [11]. The main idea of ADS subcritical reactors is to sustain a nuclear power plant with spent nuclear fuel, using an accelerator to provide the additional neutrons needed for the reaction: in this way it is possible to accomplish two goals, to produce electricity and to dispose of the nuclear waste, changing it into isotopes with a much shorter lifetime. During the development of the ADS accelerator, the energy of the beam will be gradually increased up to 1.5 GeV; however the measurement of δ_{CP} can start even before the final phase: as mentioned before in our simulations we assumed a beam energy of 800 MeV, that should be reached in the phase II of C-ADS [4].

Finally, the possibility of running μDARTS using the SuperK and HyperK detectors, in Japan, was investigated by J. Evslin, S. Ge and K. Hagiwara in [7]. Due to the larger detector masses, in this scenario it is possible to increase the precision up to 5°.

Acknowledgments

I would like to thank J. Evslin for the useful discussions and comments. This work was supported by NSFC grant 11375201 and the Chinese Academy of Sciences President's International Fellowship Initiative grant 2015PM063.

References

[1] K. Abe *et al.* [T2K Collaboration], ''Neutrino oscillation physics potential of the T2K experiment'' PTEP 2015 (2015) 4, 043C01 and arXiv:1409.7469 [hep-ex]

[2] R. B. Patterson [NOvA Collaboration], "The NOvA Experiment: Status and Outlook" Nucl. Phys. Proc. Suppl. **235-236**, 151 (2013) and arXiv:1209.0716 [hep-ex].

[3] E. Ciuffoli, J. Evslin, X. Zhang, ''The Leptonic CP Phase from Muon Decay at Rest with Two Detectors" JHEP 1412 (2014) 051 and arXiv:1401.3977[hep-ph]

[4] E. Ciuffoli, J. Evslin, F. Zhao, ''Neutrino Physics with Accelerator Driven Subcritical Reactors", arXiv:1509.03494 [hep-ph]

[5] J. Alsonso *et al.*, ''Expression of Interest for a Novel Search for CP Violation in the Neutrino Sector: DAEδALUS" arXiv:1006.0260 [physics.ins-det].

[6] C. Aberle *et al.*, ''Whitepaper on the DAEdALUS Program"; arXiv:1307.2949 [physics.acc-ph]

[7] J. Evslin, S. F. Ge and K. Hagiwara, ''The Leptonic CP Phase from T2(H)K and Muon Decay at Rest", arXiv:1506.05023 [hep-ph].

[8] Y. -F. Li, J. Cao, Y. Wang and L. Zhan, Phys. Rev.D **88** (2013) 013008 .

[9] S. B. Jim, ''Proposal for RENO-50; detector design & goals" talk given at the International Workshop on RENO-50: Towards the Neutrino Mass Hierarchy at Seoul National University.

[10] E. Ciuffoli, J. Evslin, Z. Wang, C. Yang, X. Zhang and W. Zhong, "Advantages of Multiple Detectors for the Neutrino Mass Hierarchy Determination at Reactor Experiments" Phys. Rev. D **89** (2014) 7, 073006 and arXiv:1308.0591 [hep-ph].

[11] Z. Li *et al.*, "Physics design of an accelerator for an accelerator-driven subcritical syste," Phys. Rev. ST Accel. Beams **16** (2013) 8, 080101.

PoS(EPS-HEP2015)060