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# Future accelerator-based neutrino facilities and program

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**Summary.** — Near-future and proposed longer-term accelerator-based neutrino experiments are described and discussed.

## 1. – Introduction

In the last 15 years we have learnt that neutrinos oscillate, and that three-flavor mixing provides a good first description of the associated phenomenology. Most of the associated mixing parameters have now been measured, but there is much more to do. In particular we would like to know:

- Are neutrinos Majorana and/or Dirac particles?
- What is the absolute neutrino mass-scale?
- Is three-flavor mixing the whole story?
- Which of the two possible patterns of neutrino masses (the mass hierarchy) is the correct one?
- Is $\theta_{23}$ different from $\pi/4$, and if yes, which octant does it inhabit?
- What is the value of $\delta_{CP}$ and is there observable CP violation (CPV) in the neutrino sector?

We hope that the answers to some or all of these questions will provoke theoretical progress in understanding the origin of the tiny neutrino mass-scale, the relationship, if any, between quark- and lepton-mixing, and perhaps a deeper understanding of the origin and nature of flavor. However, answering the questions will require an ambitious long-term experimental program using accelerators, reactors, radioactive sources, and "natural" neutrino sources. The following focuses on the accelerator part of the program.

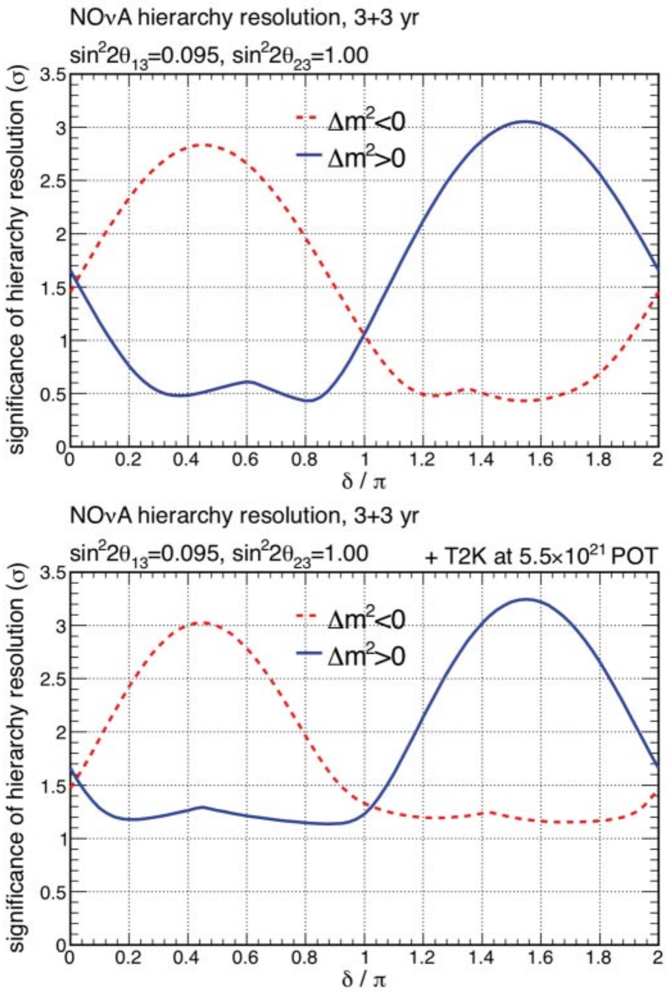

Fig. 1. – Expected significance for resolution of the neutrino mass hierarchy, shown as a function of the CP phase $\delta_{CP}$, for NOvA after 6 years of running (top plot), and the improvement when combined with the anticipated final T2K data sample (bottom plot). The two curves correspond to the two possible hierarchies. Figure kindly provided by the NOvA Collaboration.

## 2. – The near future

Defining the near-future program as the set of experiments that are running or about to run, it consists of one experiment in Japan (T2K), and four experiments in the U.S. (MINOS+, MINERvA, NOvA, and MicroBooNE).

T2K measures a neutrino beam that originates at J-PARC and travels 295 km to the Super-Kamiokande detector. The experiment has received $6.6 \times 10^{20}$ protons-on-target (POT), and has recently confirmed [1] it's initial observation of $\nu_e$ appearance with a measured value for $\theta_{13}$ consistent with measurements from reactor $\overline{\nu}_e$ disappearance experiments. Over the next few years the T2K collaboration anticipates about an order of magnitude more POT. This will enable an improved knowledge of $\theta_{23}$ and will contribute to constraints and/or measurements of $\delta_{CP}$ and the determination of the mass hierarchy. The T2K beam is presently off. Although the schedule for restarting is unclear, we hope the experiment continues in the near future.

At Fermilab, the accelerator complex has recently restarted after a 16 month shutdown during which the accelerator performance was upgraded for a new neutrino experiment, NOvA [2], at the Main Injector neutrino beam (NuMI). In the coming year there will also be a new neutrino experiment using the Booster neutrino beam (BNB), MicroBooNE [3]. At that time the two Fermilab neutrino beams will be serving 4 neutrino experiments and 6 detectors. The two older experiments (MINOS+ [4] and MINERvA [5]) utilize existing detectors but will run with a higher energy NuMI beam than previously, the so-called medium energy beam favored by NOvA. This will extend the energy range covered by the neutrino interaction experiment MINERvA, and will enable MINOS+ to look for deviations from three-flavor-mixing on timescales shorter than those corresponding to the first oscillation maximum.

The new NuMI experiment, NOvA, has both near- and far-detectors which are built from PVC extrusions filled with liquid scintillator and read out using APDs. The far detector is located at Ash River, which is 810 km from Fermilab and 14.6 mrad off-axis with respect to the NuMI beam. This means that the 14 kt detector sees a narrow band beam with a peak energy of about 2 GeV, which at 810 km corresponds to the first oscillation maximum. The primary beam power is expected to ramp up from 300 kW at startup, to 700 kW over the next couple of years. Although the NOvA detector will be completed next summer, commissioning and data taking is already beginning with a partial detector.

T2K and NOvA will give us complementary long-baseline measurements, covering similar values of L/E but at very different baselines and energies, and hence with different sensitivities to matter effects and $\delta_{CP}$. For example, the anticipated sensitivities to the mass-hierarchy for NOvA alone and for NOvA combined with T2K are compared in Fig. 1. The sensitivity depends on the value of $\delta_{CP}$ and on whether the hierarchy is normal or inverted. For significant regions of parameter space, the combined results are expected to give an indication of the mass hierarchy at 2 standard deviations or better. With additional information from atmospheric- and reactor-experiments, it is quite possible that the mass hierarchy will be definitively established within the coming decade.

The new BNB experiment, MicroBooNE, consists of a 170 ton liquid Argon TPC which will measure neutrinos with energies $\sim 0.7$ GeV at a baseline of $\sim 470$ m. They will run for several years to receive a total of $6 \times 10^{20}$ POT starting mid-2014. The experiment is designed to be able to probe the low energy $\nu_e$-like appearance signal reported by MiniBooNE. If it is $\nu_e$ appearance then the signal events will be tagged by an electron appearing in the detector. However, the MiniBooNE detector could not discriminate between electron- and photon-interactions. If MicroBooNE confirms there is a signal, the experiment should be able to discriminate between these two possibilities at the $4\sigma$ to $5\sigma$ level.

## 3. – Next-generation long-baseline experiments

All participating regions (Asia, Europe, Americas) have been considering new ambitious long-baseline experiments to search for CPV in the neutrino sector, and precisely test the 3-flavor mixing framework. Of these two goals. searching for CPV is usually

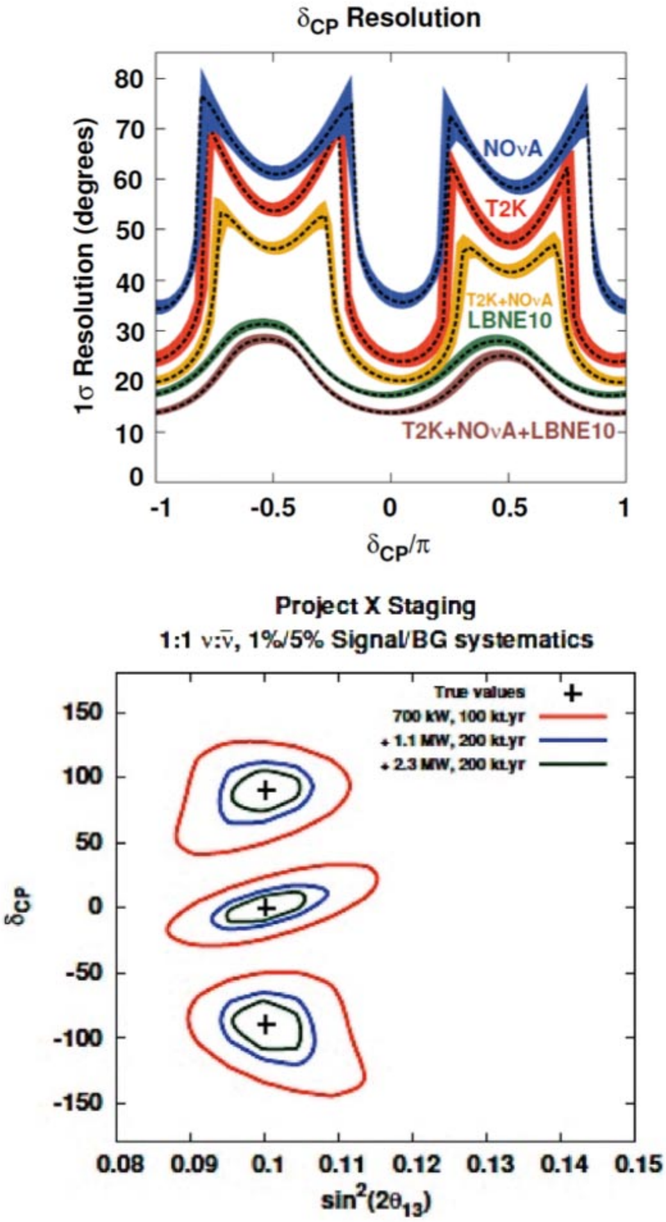

Fig. 2. – Anticipated precision for the determination of the CP phase $\delta_{CP}$ and the mixing parameter $\sin^2 2\theta_{13}$. Top plot shows, as a function of $\delta_{CP}$, how the resolution on $\delta_{CP}$ is expected to improve with time as future experiments run and deliver results. Bottom plot shows how the precision in determining the point in $(\delta_{CP}, \sin^2 2\theta_{13})$-space improves with statistics. See C. Adams et al. [6]. Figure kindly provided by the LBNE Collaboration.

emphasized. Three-flavor mixing, which has not yet been well tested, deserves greater emphasize in planning the future long-baseline program. A discovery that 3-flavor mixing is not the whole story would have a profound impact on our understanding of particle physics.

The candidate next-generation long-baseline experiments explored so far are:

- LBNE [6] in the U.S: Beam from Fermilab with a 35 kton liquid Argon detector at a baseline of 1300 km.
- LBNO [7] in Europe: Beam from CERN with a greater than 20 kton liquid Argon detector at a baseline of 2300 km.
- T2HK [8] in Japan: Beam from JPARC with a 1 Mton water cerenkov detector at a baseline of 295 km.

We hope that at least one of these candidate experiments will received final approval within the next couple of years. As representative of their capabilities, Fig. 2 shows, for the proposed LBNE experiment, the expected precision with which the CP phase could be measured as a function of the underlying value of the parameters and the amount of data accumulated (kW-kt-yrs). It is apparent that there is a need for the largest detector in the most intense beam that is practical.

## 4. – The future of short-baseline experiments

It should not be forgotten that the accelerator-based short-baseline anomalies [9] from LSND and MiniBooNE are as yet unresolved. The level of enthusiasm for pursuing these anomalies in the longer term will depend upon results from MicroBooNE and from experiments probing the reactor- and radioactive-source-anamolies. If any of the anomalies are shown to be due to new physics (due to the existance sterile neutrinos, for example) the neutrino community will want to pursue an ambitious short-baseline accelerator-based program with high priority. If the reactor- and source-anomalies do not survive the next generation of measurements, it is still important that the short-baseline accelerator-based program ends up with conclusive results that confirm or lay-to-rest the LSND and MiniBooNE anomalies. It seems likely that this will require an experiment that will follow MicroBooNE.

## 5. – Towards a Neutrino Factory

Over the last 15 years there has been a steady progress in developing the concepts and technologies for a Neutrino Factory [10] in which an intense neutrino beam is produced from muons circulating and decaying within a storage ring with long straight sections. This would produce a beam with a well know flux and spectra, that consists of 50% $\nu_e$ and 50% $\overline{\nu}_\mu$ from $\mu^+ \to e^+\nu_e\overline{\nu}_\mu$ decays if $\mu^+$ are stored, and 50% $\nu_\mu$ and 50% $\overline{\nu}_e$ from $\mu^- \to e^-\nu_\mu\overline{\nu}_e$ decays if $\mu^-$ are stored. The $\nu_e$ ($\overline{\nu}_e$) in the initial beam would facilitate measurements of $\nu_e \to \nu_\mu$ ($\overline{\nu}_e \to \overline{\nu}_\mu$) oscillations which have an experimental signature (a wrong-sign muon in the far detector) with a very low background . Taking data with both $\mu^+$ and $\mu^-$ stored, and exploiting all the flavors in the initial beams $(\nu_e, \nu_\mu, \overline{\nu}_e, \overline{\nu}_\mu)$ would enable measurements to be made that go beyond the sensitivity thought achievable with conventional neutrino beams, and extend the variety of measurements to provide more stringent tests of the mixing framework. If we want this additional capability we will need to find a fiscally practical way of realizing this new type of facility.

One possibility is to advance towards a Neutrino Factory in stages, with each stage delivering physics. It has been proposed that a first step along this path might be NuSTORM [11] in which charged pions are injected into a storage ring with long straight sections. The daughter muons from pion decay remain captured in the ring, and subsequently decay to produce a neutrino beam. This is a poor-mans neutrino factory. It lacks the intensity needed for a long-baseline experiment, but would be well suited for a short-baseline experiment, including testing the LSND and MiniBooNE anomalies, and measuring $\nu_e$ and $\overline{\nu}_e$ cross-sections. NuSTORM has been proposed to Fermilab and to CERN.

## 6. – Final remarks

Neutrinos are the most common matter particles in the Universe. In number, they exceed the constituents of ordinary matter by a factor of ten billion, and probably account for at least as much energy as all the stars combined. An experimental program to precisely measure the properties of the neutrino would therefore seem well motivated. However, the real motivation for pursuing an ambitious long-term neutrino program is the possibility of discovering new physics beyond the Standard Model. The future accelerator-based neutrino program will not only help us better understand the Universe in which we live, but also has good prospects of making paradigm-changing discoveries.

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## REFERENCES

[1] K. Abe et al. (T2K Collab.) Phys. Rev. D 88, 032002 (2013)
[2] D. Ayres et al. (NOvA Collab.) Fermilab-Proposal-0929, arXiv:hep-ex/0503053v1
[3] A. Szelc, “The MicroBooNE Experiment”, talk at the XXIV Workshop on Weak Interactions and Neutrinos, Natal, Brazil, 16-21 September, 2013.
[4] G. Tzanakos et al. (MINOS+ Collab.), Fermilab-Proposal-1016, DocDB-9923
[5] J. Mousseau, “MINERvA”, talk at the XXIV Workshop on Weak Interactions and Neutrinos, Natal, Brazil, 16-21 September, 2013.
[6] C. Adams et al. (LBNE Collab.), “Scientific Opportunities with the Long-Baseline”, arXiv:1307.7335v2 [hep-ex] 1 Oct 2013.
[7] A. Stahl et al. (LBNO Collab.) CERN-SPSC-2012-021 ; SPSC-EOI-007
[8] T. Ishida, “T2HK”, talk at Nufact2013, IHEP, Beijing, China, 19-24 August, 2013.
[9] S. Brice et al., Short Baseline Focus Group Report, FERMILAB-FN-0947, 7 June, 2012.
[10] S. Geer, Phys. Rev. D57 (1998) 6989-6997, arXiv:hep-ph/9712290
[11] D. Adey et al. (nuSTORM Collab.), arXiv:1308.6822v1.