European strategy for long-baseline neutrino-oscillation experiments; The UK perspective

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Executive summary

- .....overview of main conclusions .....

1. Introduction

The study of neutrino oscillations is complentary to the high-energy-collider programme by opening a new window on fundamental physics and testing our models of the physics of flavour.

- The neutrino is unique among the fundamental fermions in that it has no conserved quantum numbers except spin and, perhaps, a global lepton number.
- The established phenomenon of neutrino oscillations implies that: lepton-flavour is not conserved; neutrinos are massive; and that the neutrino mass eigenstates mix to produce the observed flavour eigenstates.
- The phenomenon of neutrino oscillations constitutes physics beyond the Standard Model of particle physics. The already established tiny neutrino mass and (relatively) large neutrino-mixing angles may be related to physics at energy scales beyond the reach of present or future colliding-beam facilities.
- Oscillations are readily described through the introduction of three neutrino mass eigenstates and a unitary mixing matrix (U_{PMNS}) that defines the relationship between the mass and flavour eigenstates (the "Standard Neutrino Model", SνM).
- Although great progress has been made, measurements of the parameters of the mixing matrix are not complete and do not yet rival the precision of the analogous mixing matrix in the quark sector (the CKM matrix).
- The existence of (at least) three neutrino states also admits the possibility of violation of the CP symmetry. This can be parameterised through U_{PMNS} by the presence of a CP-violating phase δ_{CP} whose value is currently unknown.
- Next generation long-baseline neutrino-oscillation experiments will allow us to probe the phase space of δ_{CP} in addition to establish for the first time the hierarchy of mass eigenstates. They will also provide us with precision measurements of U_{PMNS}.

By exploiting the strength of the European neutrino-oscillation community and the unique infrastrucure and expertise available at CERN and at other laboratories, Europe has the opportunity to make unique contributions to the experimental programme that will make precision measurements of neutrino oscillations.

- Europe has an established position of leadership in the international neutrino-physics community.
- The European community (comprising at least 600 physicists) is undoubtably able to exploit the unique infrastructure and expertise in the provision of neutrino beams that is available at CERN, and in national laboratories such as RAL, to make decisive contributions to the international neutrino-oscillation programme.
- European, and indeed UK, physicists have played seminal and leading roles in the current generation of experiments (MINOS/MINOS+ in the USA, ICARUS/OPERA in Europe and T2K in Japan), in the design studies required to define the future programme (EUROnu, LAGUNA, LAGUNA-LBNO, the IDS-NF) and in the R&D necessary to prove the feasibility of the proposed facilities (examples include the EMMA experiment at DL, the MERIT experiment at CERN, the MICE experiment at RAL and the target development programmes at RAL and at other European laboratories).

2. Status of neutrino oscillations

- Over the last 15 years there has been a revolution in our understanding of neutrinos. From having a solar- and atmospheric neutrino problem, we have gone to a state where we understand the neutrino detection rates in terms of solid flux predictions and the effect of neutrino flavour transitions, the phenomenology of which is parametrised by U_{PMNS} via three mixing angles and δ_{CP}. The neutrino transition probabilities depend on these parameters as well as on the difference of the square of the masses of the mass-eigenstates.
- Many of these parameters have now been measured by experiments using solar-, atmospheric-, beam- and reactor-neutrinos to the level of a few percent. Current global-fits result in the following values
$$\begin{aligned}\sin^2\theta_{12} &= 0.312^{+0.017}_{-0.015}\\ \Delta m^2_{21} &= (7.59^{+0.20}_{-0.18}) * 10^{-5}\mathrm{eV}^2 \qquad \text{and}\\ \sin^2\theta_{23} &= 0.51 \pm 0.06\\ \Delta m^2_{31} &= (2.45 \pm 0.09) * 10^{-3}\mathrm{eV}^2 \text{ or}\\ \sin^2\theta_{23} &= 0.52 \pm 0.06\\ \Delta m^2_{31} &= -(2.34 \pm 0.09) * 10^{-3}\mathrm{eV}^2\end{aligned}$$
The last remaining mixing angle, θ_{13}, has been measured in 2011/12 by both accelerator and reactor-based experiments:
$$\sin^2 2\theta_{13} = 0.098 \pm 0.013$$
- What remains, to complete our knowledge of the parameters of the SνM is:
  1. The mass hierarchy i.e. whether $\Delta m^2_{31} = m^2_3 - m^2_1$ is positive or negative (the current experiments are only sensitive to the absolute value of this mass difference).
  2. The value δ_{CP}, which is entirely unknown.
- Having all mixing angles being non-zero allows for CP-violation in the neutrino/lepton sector. If a non-zero δ_{CP} could be verified, it would be a crucial step towards an understanding of the early universe. CP-violation together with lepton number violation are the key ingredients to explaining the matter anti-matter asymmetry of the Universe through leptogenesis.

3. Scientific imperatives for the long-baseline neutrino oscillation programme

To complete the description of neutrino oscillations afforded by the Standard Neutrino Model requires that the sign of Δm^2_{31} be determined and that the value of δ be established.

- The demonstration that $\sin^2 2\theta_{13} \sim 0.1$ implies that:
  - Matter effects are large and the mass hierarchy may be determined from the energy dependence of the oscillation probabilities or by comparison of the neutrino and anti-neutrino oscillation probabilities; and
  - The discovery of CP-invariance violation is possible. The long-baseline neutrino-oscillation programme must therefore be optimised to expedite the search for CP-invariance violation.
- To complete the exploration of the Standard Neutrino Model, it is necessary to:
  - Exploit existing and planned experiments (T2K, MINOS, MINOS+, NOvA), seeking, if possible, to determine the mass hierarchy;
  - Prepare to bring forward a proposal for a long-baseline experiment on a conventional broad-band beam that is capable of exploiting the details of the oscillation spectrum to:
    (a) Determine the mass hierarchy with a confidence level of at least 5σ; and to
    (b) Have the potential to provide the first measurements of CP-invariance violation.

The tiny neutrino masses and the large neutrino-mixing angles, so different to those of the quarks, hint at a rich seam of physics beyond that described by the Standard Model. To expose this seam will require a Neutrino Factory. Precision measurements are required to:

- Prove the unitarity of the neutrino-mixing matrix;
- Establish whether θ_{23} is maximal (i.e. $\theta_{23} \simeq 45^\circ$) which would hint at an as-yet-undiscovered symmetry; and to
- Allow relationships between quark- and lepton-mixing parameters, which arise in theories of the physics of flavour, to be tested quantitatively. In the absence of an unambiguous theoretical steer, the experimental imperative is to make measurements of the neutrino parameters with a precision at least as good as the precision with which the quark-mixing parameters are presently known.

4. Strategy for development of European contributions to the long-baseline oscillation programme

We support a strategy which has a high potential for a discovery at each step. This approach will ultimately give the best insurance of success and offers the best value for money:

- The results from each step, plus the advances in knowledge from complementary projects, will feed into determining the details of the next stage.
- The first step should have the potential to discover MH and with a good sensitivity to CPV. Candidate projects for this are: CERN-to-Pyhasälmi currently being studied as part of LAGUNA-LBNO; staged options being considered for LBNE; GLADE; T2K upgrade options based on a upgraded JPARC beamline and HyperK.
- Europe has the unique opportunity to develop the Pyhasälmi site as a possible location for a far detector for a neutrino beam from CERN and should invest in evaluating the feasibility of such a program. The Pyhasälmi site can also provide a first-class location for astro-particle experiments, e.g. LENA.
- The baseline, beam, infrastructure and detectors to be developed for the future LBL program can be the first step toward building a Neutrino Factory.

Central to the success of such a strategy is a well-defined development programme of essential R&D. We therefore fully support the participation of Europe in the following initiatives:

- development of accelerator injection stages that can power super beams ($> 1MW$) and perhaps muon storage rings at a later stage.
- Detector prototyping/testbeam activity, especially R&D focussing on issues related to scaling liquid argon TPC detectors to large volumes. For this, CERN support for a prototype/testbeam, perhaps in the North Area, is particularly encouraged.
- The control of systematics will be key to the precision measurement of neutrino properties long-term and the use of near detectors will be essential. Increased R&D into their optimal configuration and location needs to begin now.
- Continued support for the hadro-production experiment NA61/SHINE will be important to optimally constrain beam flux systematics with the conventional beam.
- A increased focus on neutrino interaction cross section measurements is crucial in order to reach the sensitivities needed to probe CPV. We endorse support for projects such as the NuSTORM project to fill the gaps in current cross-section results in addition to providing definitive sterile neutrino studies and a first muon storage ring implementation.