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The International Design Study for the Neutrino Factory

K. Long *†
High Energy Physics Group, Department of Physics, Imperial College London, Exhibition Road, London SW7 2BZ.
E-mail: `K.Long@Imperial.Ac.UK`

The properties of the neutrino provide a unique window on physics beyond that described by the Standard Model. The study of sub-leading effects in neutrino oscillations has begun with the race to measure θ_{13}. A consensus is emerging within the international community that a novel neutrino source is required to allow sensitive searches for leptonic CP violation to be carried out and the neutrino mass-hierarchy to be determined. The Neutrino Factory, in which intense neutrino beams are produced from the decay of muons, has been shown to out-perform the other proposed facilities. The physics case for the Neutrino Factory will be reviewed and the baseline design of the facility being developed by the International Design Study for the Neutrino Factory (the IDS-NF) collaboration will be described.

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[*] Speaker.

[†] On behalf of the IDS-NF collaboration.

1. Introduction

Neutrino oscillations is now an established phenomenon (for a review see [1]). The bulk of the data to date has been collected using the dominant, 'disappearance' channels $\nu_e \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$. The next generation of long-baseline experiments seek to discover the existence of sub-leading $\nu_\mu \rightarrow \nu_e$ oscillations while the next generation of reactor experiments seek to find evidence for the sub-leading transitions through the disappearance of $\bar{\nu}_e$. Such a discovery would be exciting indeed since it would herald the next phase in the study of neutrino oscillations: the search for CP violation. Unless the value of θ_{13} is found close to the present upper bound, a novel technique to produce high energy ν_e beams of extremely high flux is required. The Neutrino Factory [2] is able to provide the requisite beams.

2. The Neutrino Factory

At source, with muons circulating in the storage ring, the Neutrino Factory beam will contain equal fluxes of ν_e and $\bar{\nu}_\mu$; a beam with equal fluxes of $\bar{\nu}_e$ and ν_μ will be produced with μ^- in the storage ring. Charged-current interactions induced by 'golden channel', $\nu_e \rightarrow \nu_\mu$ ($\bar{\nu}_e \rightarrow \bar{\nu}_\mu$), oscillations produce muons of charge opposite to that of the stored muons. A magnetised detector is therefore required to distinguish the golden-channel signal from the background produced by un-oscillated muon-neutrinos.

The performance of the baseline Neutrino Factory being developed by the International Design Study for the Neutrino Factory (IDS-NF) collaboration [3] is compared to the various beta-beam and super-beam alternatives in figure 1 [4]. The baseline Neutrino Factory significantly out-performs all other options in terms of the discovery reach for the mass hierarchy and θ_{13}. The Neutrino Factory also out-performs the alternatives in the discovery reach for CP violation. The discovery reach of the beta-beam only approaches that of the Neutrino Factory if ion beams of very high energy are used or data from each of four ion species are combined. The sensitivities of the various facilities are comparable if θ_{13} is 'large' ($\sin^2 2\theta_{13} \gtrsim 10^{-2}$). In this case, consideration needs to be given to the precision with which the parameters that govern neutrino oscillations can be extracted. The excellent precision with which θ_{13}, δ, θ_{23}, and Δm^2_{31} can be measured at the Neutrino Factory is reported in [4] and references therein.

3. The International Design Study for the Neutrino Factory

The Neutrino Factory baseline set-up was derived by optimising the stored-muon energy and the distance from the source to two distant detectors (see [2] and references therein). A detector capable of detecting the golden channel with high efficiency, placed at the 'magic baseline', 7 000–8 000 km from the source has excellent sensitivity to the mass hierarchy and $\sin^2\theta_{13}$. The best sensitivity to CP violation is obtained at a source-detector distance in the range 3 000–5 000 km and requires a stored-muon energy in excess of 20 GeV; a value somewhat larger than that required when optimising the sensitivity to $\sin^2\theta_{13}$ and the mass hierarchy. The sensitivity to non-standard interactions at the Neutrino Factory also improves as the stored-muon energy is increased, reaching a plateau at around ~ 25 GeV [5]. A baseline stored muon energy of 25 GeV has therefore been adopted.

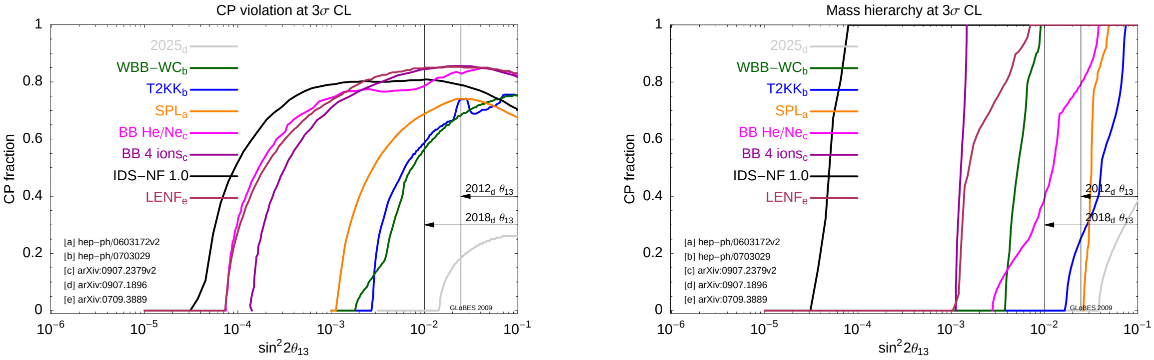

Figure 1: Comparison of the performance of the IDS-NF baseline Neutrino Factory with the proposed super-beam and beta beam facilities. The plots show , as a function of the true value of the discovery reach in δ (left panel) and the mass hierarchy (right panel) at the 3σ c.l. Figures taken from [4].

The baseline accelerator facility, a development of that described in [2], provides a total of 10^{21} muon decays per year split between two distant neutrino detectors. The process of creating the muon beam begins with the bombardment of a pion-production target with a 4 MW, pulsed proton beam. The target must be sufficiently heavy to produce pions copiously, yet not so large as to cause a significant rate of interaction of the secondary pions within the target material. In addition, the target must withstand the substantial beam-induced shock. The IDS-NF baseline calls for a free-flowing, liquid-mercury jet operating in a solenoid-focusing, pion-capture channel. A solenoid transport channel, in which the pions decay to muons, follows the capture section. The muon beam that emerges from the decay channel must be manipulated. First, bunching and phase rotation are performed. The muon beam occupies a large volume of phase space which must be reduced, 'cooled', before it can be injected into the acceleration sections. The short muon lifetime makes traditional cooling techniques inappropriate. The required phase-space reduction is achieved by means of ionisation cooling in which the muon beam is passed through a material (lithium hydride) in which it loses energy through ionisation. The energy lost is replaced in accelerating cavities. Muon acceleration must be rapid, especially at low muon energy. In the IDS-NF baseline, muons are accelerated to 0.9 GeV in a superconducting linac and then to 12.6 GeV in a sequence of two re-circulating linear accelerators (RLAs). The final stage of acceleration, from 12.6 GeV to the baseline stored-muon energy of 25 GeV, is provided by a fixed field alternating gradient (FFAG) accelerator.

The baseline neutrino detector is the Magnetised Iron Neutrino Detector, (MIND). MIND is an iron-scintillator sandwich calorimeter similar in concept to MINOS, but with a sampling fraction optimised for the Neutrino Factory beam [6]. A detector of fiducial mass of 100 kT will be placed at the intermediate baseline. At the magic baseline, a fiducial mass of 50 kT is sufficient. The performance of MIND is sufficient to resolve the principal features of the oscillation pattern [7].

The IDS-NF continues to consider detector options such as the liquid-argon time projection chamber and the totally active scintillator detector. These technologies offer the possibility of reconstructing τ mesons and of identifying the scattered electron (positron) produced in charged-current $\nu_e N$ interactions. A substantial benefit might accrue if it were possible, in addition, to measure the charge of the scattered electron (positron).

A suite of near detectors is essential. For the oscillation physics programme, the near detectors must: measure the flux of the neutrino beam; determine the beam-energy distribution and composition; measure the charm-production cross section; and measure the deep inelastic, quasi-elastic, and resonant scattering cross-sections. The near-detector neutrino-physics programme includes the precise determination of the Weinberg angle, the measurement of polarised and unpolarised parton distributions, the study of QCD and nuclear effects in νN scattering. The near detector must also be capable of searching for new physics, for example by the detection of anomalous rates of τ production. Two options for the near detector are being considered; one based on a high resolution scintillating fibre tracker, the second based on a transition radiation straw tube tracker.

4. Opportunities and conclusions

A consensus is emerging in the international community that a novel, high intensity, accelerator-based facility is required to make definitive measurements of the parameters that govern neutrino oscillations. The Neutrino Factory is the facility of choice for this programme as it has the best discovery reach and has the flexibility to respond to changes in our understanding of neutrino oscillations and the discovery of entirely new phenomena.

The Neutrino Factory, which has a first-rate physics case of its own, is part of a larger muon-physics programme. Intense muon beams are required to serve searches for charged-lepton flavour violation and the Neutrino Factory is an important step on the way to multi-TeV lepton-antilepton collisions at the Muon Collider. The scientific imperative, therefore remains: to make the Neutrino Factory an option for the field.

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