IC/HEP/08-17

The International Design Study for the Neutrino Factory *

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The International Design Study for the Neutrino Factory (the IDS-NF) has been established by the Neutrino Factory community to deliver the Reference Design Report (RDR) for the facility by the 2012 decision point identified by the C.E.R.N. Council Strategy Group. The motivation for measurements of the neutrino-mixing parameters with a precision approaching that with which the quark-mixing parameters are known is briefly reviewed. The baseline design for the facility, developed through the International Scoping Study for a future Neutrino Factory and super-beam facility (the ISS), is described and its performance is presented.

1. Introduction

Neutrino oscillations have been observed using neutrinos produced in the sun, neutrinos produced by cosmic-ray interactions in the atmosphere, anti-neutrinos produced in nuclear reactors, and using neutrino beams produced by high-energy particle accelerators [1]. The phenomenon is readily described by postulating the existence of three neutrino-mass eigenstates, the flavour eigenstates being obtained by taking appropriately weighted combinations of the mass eigenstates. If the three neutrino masses are not equal, neutrino oscillations are a necessary consequence of the quantum-mechanical interference between the mass eigenstates. Alternative explanations for the phenomenon have been proposed, each of which is strongly dis-favoured, or ruled out, by the data.

The challenge to the neutrino community is to measure all the mixing angles of the MNS matrix as precisely as possible, to determine the sign of Δm^2_{23} and to measure precisely Δm^2_{12} and Δm^2_{23}, and, by measuring δ, to discover leptonic-CP violation if it occurs. The fundamental importance of the search for leptonic-CP violation is self-evident. Precision measurements of the parameters that govern neutrino oscillations are essential if a complete understanding of the nature of the neutrino is to be obtained. The ultimate theory must surely unify the quark and lepton sectors; so, for the experimentalist, the goal must be to measure the neutrino-mixing parameters with an uncertainty that matches the precision with which the quark-mixing parameters are known. Such measurements will either establish the minimal model outlined above or, by establishing parameter sets inconsistent with it, point to the existence of entirely new phenomena.

2. Motivation for the International Design Study for the Neutrino Factory

The present status of measurements of the neutrino mixing parameters are described elsewhere in these proceedings. In summary: the solar mixing angle (θ_{12}) is known with a precision of $\sim$ 10%; the atmospheric mixing angle (θ_{23}) with a precision of $\sim$ 20%; and the two mass-squared differences, Δm^2_{23} and Δm^2_{12} with precisions of $\sim$ 10% and $\sim$ 5% respectively. Two first-generation super-beam experiments, T2K in Japan [2,3] and NOνA in the US [4], are be-

*Talk presented at the Neutrino Oscillation Workshop, Conca Specchiulla, Otranto, Lecce, Italy, $6^{\rm th}$ – 13^{th} September 2008.

ing mounted with the objective of demonstrating that $\sin^2 2\theta_{13}$ is greater than zero. Both T2K and NOνA will improve the determination of θ_{23} and Δm^2_{23} to the level of a few percent after five years of data taking. However, neither T2K (Phase I) nor NOνA will have the sensitivity required to discover leptonic-CP violation or to deliver the precision measurements of the parameters that are required for a full understanding of neutrino oscillations.

To take the study of neutrino oscillations further requires a second-generation facility ready to begin operation in the second half of the next decade. Three types of facility have been proposed to provide the required neutrino beams: the Neutrino Factory, in which intense high-energy neutrino beams are produced from the decay of a stored muon beam; second-generation super-conventional-beam experiments; and the beta-beam in which electron neutrinos (or anti-neutrinos) are produced from the decay of stored radioactive-ion beams.

To put in place the facility (or facilities) required to serve the second-generation programme requires that a conceptual design be prepared by the 2012 decision point identified by the C.E.R.N. Council Strategy Group [6]. A step on this road was taken by the International Scoping Study of a future Neutrino Factory and super-beam facility (the ISS).

The ISS studied the performance of a number of representative, second-generation super-beams and a range of beta-beam and Neutrino Factory scenarios. The results of the performance evaluation are shown in figure 1 [7]. Figure 1a shows the fraction of all possible values of the true value of the CP phase δ ('Fraction of δ') for which $\sin^2 2\theta_{13} = 0$ can be excluded at the 3σ confidence level as a function of the true value of $\sin^2 2\theta_{13}$. Figures 1b and 1c show the discovery reach of the various facilities in the sign of Δm^2_{31} and δ respectively; the various bands shown in the figures having the same meaning as those in figure 1a. For large values of θ_{13} ($\sin^2 2\theta_{13} \gtrsim 10^{-2}$), the three classes of facility have comparable sensitivity; the best precision on individual parameters being achieved at the Neutrino Factory. For intermediate values of θ_{13} ($5 \times 10^{-4} \lesssim \sin^2 2\theta_{13} \lesssim 10^{-2}$), the super-beams are out-performed by the beta-beam and the Neutrino Factory. For small values of θ_{13} ($\sin^2 2\theta_{13} \lesssim 5 \times 10^{-4}$), the Neutrino Factory out-performs the other options.

The International Design Study of the Neutrino Factory (the IDS-NF) has been established to deliver the Reference Design Report for the facility, in time for the 2012 decision point. The RDR will include: the physics performance of the Neutrino Factory and the specification of each of the accelerator, diagnostic, and detector systems; the cost and schedule for the implementation of the facility at a level of accuracy appropriate for the RDR to inform a decision to initiate the Neutrino Factory project; and the outstanding technical and financial uncertainties and an appropriate uncertainty-mitigation plan [5].

3. The International Design Study for the Neutrino Factory

In addition to evaluating the performance of the various proposed facilities, the ISS established an internationally agreed baseline for the Neutrino Factory accelerator complex [8] and neutrino detectors [9]. The IDS-NF has adopted the ISS specification with a small number of minor revisions [10]. A schematic diagram of the accelerator facility is shown in figure 2 [10]. The baseline for the stored muon energy is 25 GeV and the facility will deliver a total of 10^{21} useful muon decays per year. The baseline for the storage rings is that both signs of muon are stored at the same time. The fluxes quoted are those used in the performance evaluation presented in figure 1.

The baseline for the long-baseline neutrino detectors is the Magnetised Iron Neutrino Detector (MIND). A detector with a fiducial mass of 50 kTonne is located at an intermediate baseline ($3\,000 - 5\,000$ km) and a second detector of fiducial mass 50 kTonne is located at a long baseline ($7\,000 - 8\,000$ km). The detector is optimised for the search for leptonic-CP violation, the determination of the mass hierarchy, and the measurement of θ_{13} through the detection of $\nu_e \rightarrow \nu_\mu$ transitions, the 'golden channel'. The IDS-NF baseline includes a Magnetised Emulsion Cloud

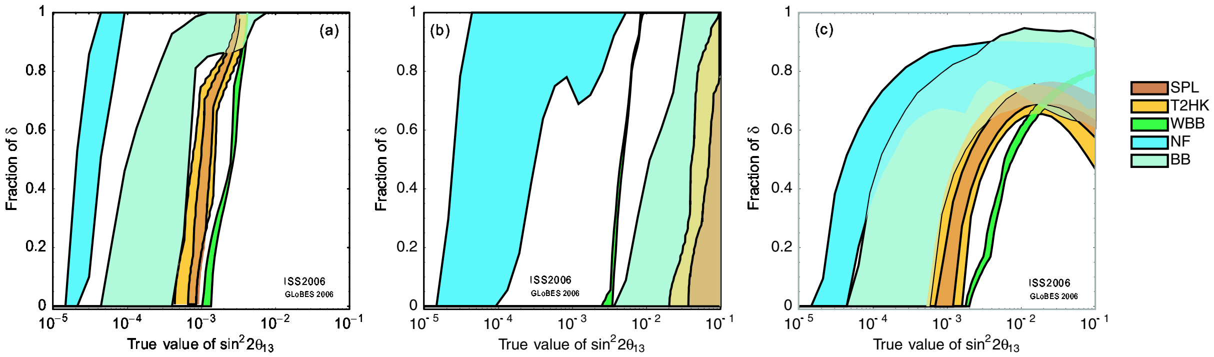

Figure 1. Predicted sensitivities for the determination of (a) $\sin^2\theta_{13}$, (b) the mass hierarchy, and (c) δ. The sensitivities are plotted as a function of $\sin^2\theta_{13}$ for different proposed facilities. The bands correspond to configurations ranging from conservative to challenging for each technique. Precise details can be found in the ISS Physics report [7] from which the figures are reproduced.

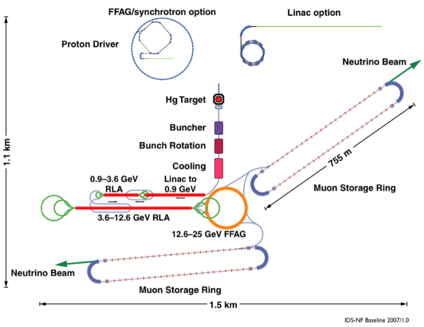

Figure 2. Schematic drawing of the ISS baseline for the Neutrino Factory accelerator complex. The various systems have been drawn to scale. More details can be found in [10] from which the figure is reproduced.

Chamber (MECC, 10 kTonne fiducial mass) for the detection of ν_τ appearance, the 'silver channel'. The silver channel is important in the search for effects beyond the 'Standard Neutrino Model'.

4. Conclusions

The search for leptonic CP violation and the ambition to understand the physics of flavour justify an energetic programme of high-precision measurements of neutrino oscillations. The Neutrino Factory, the facility that offers the best discovery reach and the best precision on the various parameters, is required as part of this programme. The International Design Study for the Neutrino Factory (the IDS-NF) collaboration [11] has been established to deliver a Reference Design Report for the facility by the 2012 decision point, so making the the Neutrino Factory an option for the field.

Acknowledgements

I would like to thank the organisers for giving me the opportunity to present the plans of the International Design Study for the Neutrino Factory. I gratefully acknowledge the help, advice, and support of my many colleagues within the international Neutrino Factory community who have freely discussed their results with me and allowed me to use their material.

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