Executive Summary

In the Fall of 1999, the Fermilab Directorate chartered a study group to investigate the physics motivation for a *neutrino factory* based on a muon storage ring that would operate in the era beyond the current set of neutrino-oscillation experiments. We were charged to evaluate the prospective physics program as a function of the stored muon energy (up to 50 GeV), the number of useful muon decays per year (in the range from 10^{19} to 10^{21} decays per year), and distance from neutrino source to detector; and to assess the value of muon polarization within the storage ring. A companion study evaluated the technical feasibility of a neutrino factory and identified an R&D program that would lead to a detailed design.

The principal motivation for a neutrino factory is to provide the intense, controlled, high-energy beams that will make possible incisive experiments to pursue the mounting evidence for neutrino oscillations. The composition and spectra of intense neutrino beams from a muon storage ring will be determined by the charge, momentum, and polarization of the stored muons, through the decays $\mu^- \to e^-\nu_\mu\bar{\nu}_e$ or $\mu^+ \to e^+\bar{\nu}_\mu\nu_e$. There is no comparable source of electron neutrinos and antineutrinos. The neutrino beam also offers unprecedented opportunities for precise measurements of nucleon structure and of electroweak parameters. The intense muon source needed for the neutrino factory would make possible exquisitely sensitive searches for muon-electron conversion and other rare processes.

Experiments carried out at a neutrino factory within the next decade can add compelling new information to our understanding of neutrino oscillations, provided that the number of useful muon decays exceeds 10^{19} per year and the muon energy is at least 20 GeV. By studying the oscillations of ν_μ, ν_e, $\bar{\nu}_\mu$, and $\bar{\nu}_e$, it will be possible to measure, or put stringent limits on, all of the appearance modes $\nu_e \to \nu_\tau$, $\nu_e \to \nu_\mu$, and $\nu_\mu \to \nu_\tau$; to determine precisely (or place stringent limits on) all of the leading oscillation parameters; to infer the pattern of neutrino masses; and, under the right circumstances, to observe CP violation in the lepton sector. Baselines greater than about 2000 km will enable a quantitative study of matter effects and a determination of the mass hierarchy. If the MiniBooNE experiment confirms the $\nu_\mu \leftrightarrow \nu_e$ effect reported by the LSND experiment, experiments with rather short baselines (a few tens of km) could be extremely rewarding.

The physics program at detectors located close to the neutrino factory is also very interesting. The neutrino fluxes are four orders of magnitude higher than those from existing beams. Such intense beams make experiments with high precision detectors and low mass targets feasible for the first time. The spin and flavor structure of the weak interactions allow unique studies of nucleon structure and of the electro-weak couplings themselves.

Recommendations

The physics program we have explored for a neutrino factory is highly promising. We recommend a sustained effort to study both the physics opportunities and the machine realities.

(i) We encourage support for the R&D needed to learn whether a neutrino factory can be a real option in the next decade.

(ii) We propose continued studies of oscillation physics to better understand how to build very massive detectors for long–baseline neutrino oscillation physics at a neutrino factory. These studies should identify the detector R&D that is required to realize detectors with masses of a few times 10 kt or more that are able to detect and measure wrong–sign muons, and detectors of a few kt or more able to observe tau–lepton appearance with high efficiency. It is also desirable to identify and measure the charge of electrons. Because of the size of such detectors both the detector technologies themselves and the civil engineering issues of building such massive detectors need to be addressed.

(iii) We have not completed the optimization of physics performance in terms of baseline. More work is also needed to understand the benefits of polarization. These are appropriate topics for a continuing study.

(iv) This study concentrated on the muon storage ring as a neutrino source and did not cover the additional physics programs which would use the proton driver and the high intensity muon beams. A further study directed at these other facets of physics at a muon storage ring facility would be very useful.