

Executive Summary: Neutrino Oscillations and Mass, and CP Violations

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Abstract: Our working group reviewed the status and prospects for measurements of neutrino masses and mixings, mainly concentrating on terrestrial neutrino beam sources, and considered how this science couples to an underground laboratory.

Why are neutrino oscillation measurements important? Neutrino masses and mixings give a window on physics at high mass scales: unification, flavor, and extra dimensions. Oscillation studies are essential to answer fundamental questions: Why are neutrino masses so small? Why are their mixings so large? Are there additional “sterile” neutrinos? Is there a connection between the lepton and quark sectors? Is there CP violation, T violation, or CPT violations in the lepton sector? Can the baryon asymmetry of the Universe, which is hard to generate from CP violation in the quark sector where the mixings are small, be a consequence of CP or CPT violation in the lepton sector?

Grand Unified Theories explain the smallness of neutrino masses by the see-saw mechanism in which a large Majorana mass ($m_M \approx 10^{14}$ GeV) and an electroweak scale Dirac mass result in a neutrino mass of m_D^2/m_M . Unification models may also contain extra sterile neutrinos that could be light. Other possibilities for neutrino mass generation include extra dimensions, in which right-handed neutrinos live outside of 3+1 space, and radiative neutrino mass generation with new particles and interactions. These ideas make very different testable predictions for the structure of the neutrino mass matrix.

Neutrino oscillations of three neutrinos depend on two mass-squared differences, three mixing angles, and a CP-violating phase. Atmospheric neutrino data determine $\delta m_{31}^2 \approx 3 \times 10^{-3}$ eV² and $\theta_{23} \approx 45^\circ$. Solar neutrino data determine $\delta m_{21}^2 \approx 6 \times 10^{-5}$ eV² and $\theta_{12} \approx 30^\circ$. Future measurements of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations are crucial to determine θ_{13} (known to be $< 10^\circ$ from reactor experiments), the sign of δm_{31}^2 , and the CP phase δ . θ_{13} is now the key parameter for oscillation phenomenology; it determines whether there are matter effects and whether CP violation is accessible. Neutrino masses and mixings are also important in astrophysics in understanding supernovae, galactic structure formation, etc. Since neutrino oscillations only depend on mass-squared differences, measurements of tritium beta decay (the KATRIN experiment) or double beta decay are also needed to fix the absolute neutrino mass scale and thereby establish whether neutrino masses are hierarchical or degenerate.

A world-wide experimental program is underway to measure the neutrino oscillation parameters. The current oscillation experiments are K2K, that measures ν_μ disappearance over a 250 km baseline from KEK to the SuperKamiokande detector, and MiniBoone, that will search for the $\nu_\mu \rightarrow \nu_e$ appearance signal in the mass-squared region 0.2 to 1 eV² for which a signal was found by the LSND experiment. Upcoming long-baseline (730 km) experiments are NuMI/Minos at Fermilab and CNGS at CERN that will study ν_μ oscillations in the atmospheric δm^2 region. Near-term experiments will use off-axis beams, JHF to SuperK (22.5 kton) and NuMI/Minos (20 kton detector proposed). The next stage will be neutrino superbeam experiments, that may be combined with large proton decay detectors. Four such projects under consideration are: (i) BNL, with an AGS upgrade, to NUSL, (ii) Fermilab, with a proton driver upgrade, to NUSL, (iii) JHF (phase II) to a HyperK detector at the Kamiokande laboratory, and (iv) CERN Superconducting Proton Linac to Frejus. Future neutrino factories, using a muon storage ring, will provide the ultimate in sensitivity and

precision in oscillation measurements.

We outline a roadmap for neutrino oscillation experiments. In Stage 0, the current near term program, NuMI and K2K check atmospheric oscillations and measure δm_{31}^2 to a precision of 10%. Also, MiniBoone makes a definitive check of the LSND effect and measures the associated δm^2 if the effect is confirmed. In Stage 1, the θ_{13} angle is measured or more tightly constrained. The NuMI/MINOS on-axis experiment probes $\sin^2 2\theta_{13} > 0.06$ at 90% CL. The NuMI and JHF off-axis beams can go down to $\sin^2 2\theta_{13} > 0.01$ at 90% CL. A long-baseline experiment from FNAL or BNL to NUSL with a 100 kton detector could have still better sensitivity. In Stage 2, CP violation and the sign of δm_{31}^2 would be measured using superbeams and very large detectors (500 to 1000 ktons). This is feasible if $\sin^2 2\theta_{13} > 0.01$. Measurements of $P(\nu_\mu \rightarrow \nu_e)$ and then $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ are needed. The increased rates needed, especially for the $\bar{\nu}_\mu$ beam, make high intensity proton sources necessary. Finally, at Stage 3, measurements with a Neutrino Factory would probe $\nu_\mu \rightarrow \nu_e$ transitions and map out CP violation with precision down to $\sin^2 2\theta_{13} > 0.0001$.

For Stage 2, one would like to have baselines greater than 1200 km in order to more fully exploit information associated with matter effects. There are some tradeoffs between neutrino interaction rate and physics reach but there is good sensitivity to the oscillation phenomenology over a broad range of baselines. For NUSL, experiments using beams from Fermilab or Brookhaven can be used with complementary capabilities. Using higher energy beams with baselines greater than 1200 km can allow one to probe effects for more than just the first oscillation maximum and provide information simultaneously on CP violation and the sign of δm_{31}^2 . It is also fairly clear that to unravel the ambiguities and correlations associated with matter effects and CP violation, the program will need measurements for two significantly different baselines. Since the detector cost will likely dominate the project, multiple baselines could be realized in the U.S. using beams from both Fermilab and Brookhaven.

There are some general requirements of neutrino oscillation experiments. First, a high intensity beam is needed with the energy initially tuned at the appearance oscillation maximum for the baseline. The neutrino sources would originate from the present laboratories (BNL or Fermilab). There are many detector sites possible, with longer baselines advantageous in resolving degeneracies of oscillation parameters that describe the same event rates. Second, many detector technologies do not need to be located underground. Due to the beam duty cycle, only small overburdens are needed to reduce the cosmic ray background. Third, Superbeam experiments to measure CP violation require very large and consequently costly detectors. It is natural to couple such detectors to proton-decay and supernova detectors. Then the detector needs to be in an underground laboratory. For the detector to be compatible with proton decay requirements some compromises may be necessary. Two types of detectors under consideration are water Cerenkov and liquid argon.

If MiniBoone confirms LSND, there will be three distinct δm^2 values which is beyond the the standard three neutrino scenario. More long and short baseline experiments will be needed to understand the phenomena. A possible solution is oscillations to sterile neutrinos, which can also be tested with better measurements of sterile components in the solar and atmospheric oscillations. Another extreme possibility is CPT violation, with LSND measuring anti-neutrino oscillations and solar experiments measuring neutrino oscillations. This scenario can be tested by measurements with both antineutrino (the KamLAND reactor

experiment) and neutrino sources.

In summary, the neutrino program through 2010 will pursue the measurements of presently unknown oscillation parameters using long-baseline experiments. We need to measure θ_{13} and the sign of δm_{31}^2 and to probe for CP violation. Some information will come from the present on-axis experiments from Fermilab to Soudan and from CERN to Gran Sasso. For example, NuMI/Minos reaches a sensitivity of $\sin^2 2\theta_{13} > 0.06$ at 90% CL. Then off-axis experiments will probe $\sin^2 2\theta_{13} > 0.01$ at 90% CL. The JHF and NuMI off-axis beams have narrow energy distributions that are tunable. We may also find the first evidence of CP violation in these experiments. The combination of data from these two baselines may be important in removing ambiguities in the oscillation parameter determinations. When all the neutrino mixing and mass parameters become known, we anticipate that a theoretical synthesis will be achieved.