Physics Goals of a Phase II Neutrino Program

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There is now an abundance of evidence that neutrinos oscillate among the three known flavors ν_e, ν_μ and ν_τ, thus indicating that they have masses and mix with one another. Indeed, modulo an anomaly in the LSND experiment, all observed neutrino oscillation phenomena are well described by the 3 generation mixing

$$\begin{pmatrix} |\nu_e> \\ |\nu_\mu> \\ |\nu_\tau> \end{pmatrix} = \mathbf{U} \begin{pmatrix} |\nu_1> \\ |\nu_\mathbf{2}> \\ |\nu_\mathbf{3}> \end{pmatrix} \tag{1}$$

$$U = \begin{pmatrix} \mathbf{c_{12}c_{13}} & \mathbf{s_{12}c_{13}} & \mathbf{s_{13}e^{-i\delta}} \\ -\mathbf{s_{12}c_{23}} - \mathbf{c_{12}s_{23}s_{13}e^{i\delta}} & \mathbf{c_{12}c_{23}} - \mathbf{s_{12}s_{23}s_{13}e^{i\delta}} & \mathbf{s_{23}c_{13}} \\ \mathbf{s_{12}s_{23}} - \mathbf{c_{12}c_{23}s_{13}e^{i\delta}} & -\mathbf{c_{12}s_{23}} - \mathbf{s_{12}c_{23}s_{13}e^{i\delta}} & \mathbf{c_{23}c_{13}} \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij} \quad , \quad s_{ij} = \sin\theta_{ij}, \quad i,j = 1,2,3$$

with $|\nu_i>$, $i = 1,2,3$, the neutrino mass eigenstates.

Atmospheric neutrino oscillations are governed by a mass squared difference $\Delta m^2_{32} = m^2_3 - m^2_2 = \pm 2.5 \times 10^{-3}\mathrm{eV}^2$ and mixing angle $\theta_{23} \simeq 45°$; findings that have been confirmed by accelerator generated neutrino beam studies at Super K and MINOS.

As yet, the sign of Δm^2_{32} is undetermined. The so-called normal mass hierarchy, $m_3 > m_2$, suggests a positive sign which is also preferred by theoretical models. However, a negative value (or inverted hierarchy) can certainly be accommodated and if that is the case, the predicted rates for neutrinoless double beta decay will likely be larger and more easily accessible experimentally. Resolving the sign of the mass hierarchy is an exteremly important issue. In addition, the fact that θ_{23} is large and near maximal is also significant for model building. Measuring that parameter with precision is highly warranted.

In the case of solar and reactor neutrino oscillations, one finds $\Delta m^2_{21} = m^2_2 - m^2_1 \simeq 8\times10^{-5}\mathrm{eV}^2$ and $\theta_{12} \simeq 32^\circ$. Again, the mixing angle is relatively large (relative to the analogous Cabbibo angle $\simeq 13^\circ$ of the quark sector). In addition, Δm^2_{21} is large enough, compared, to Δm^2_{32}, to make long baseline neutrino oscillation searches for CP violation feasible and in fact very likely to yield positive results, i.e. the stage is set for a future major discovery (CP violation in the lepton sector).

Currently, we know nothing about the value of the CP violating phase δ $(0 < \delta < 360^\circ)$ and only have an upper bound on the as yet unknown mixing angle θ_{13} $(\theta_{13} < 13^\circ)$

$$\sin^2 2\theta_{13} \leq 0.2$$

The value of θ_{13} is likely to be determined by the coming generation of reactor $\overline{\nu}_e$ disappearance and accelerator based $\nu_\mu \to \nu_e$ appearance experiments if $\sin^2 2\theta_{13} \geq 0.01$. Knowledge of θ_{13} and δ would complete our determination of the 3 generation lepton mixing matrix and provide a measure of leptonic CP violation via the Jarlskog invariant.

$$J_{CP} \equiv \frac{1}{8}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}\sin\delta.$$

which could easily turn out to be much larger than the analogous quark degree of CP violation $J_{CP}^{Quarks} \simeq 3\times10^{-5}$.

Based on our current knowledge and future goals, a phase II neutrino program should include:

- Completing the measurement of the leptonic mixing matrix,
- Study of CP violation,
- Determining the values of all parameters with high precision including J_{CP} as well as the sign of Δm^2_{32}
- Searching for exotic effects perhaps due to sterile neutrino mixing, Extra dimensions, dark energy etc.

Of the above future neutrino physics goals, the search for and study of CP violation is of primary importance and should be our main objective for several reasons which we briefly outline.

CP violation has so far only been observed in the quark sector of the Standard Model. Its discovery in the leptonic sector should shed additional light on the role of CP violation in Nature. Is it merely an arbitrary consequence of inevitable phases in mixing matrices or something deeper? Perhaps, most important, unveiling leptonic CP violation is particularly compelling because of its potential connection with the observed matter–antimatter asymmetry of our Universe, a fundamental problem at the heart of our existence. The leading explanation is currently a leptogenesis scenario in which decays of very heavy right–hand neutrinos created in the early universe give rise to a lepton number asymmetry which later becomes a baryon–antibaryon asymmetry via the B-L conserving 't Hooft mechanism of the Standard Model at weak scale temperatures.

Leptogenesis offers an elegant, natural explanation for the matter–antimatter asymmetry; but it requires some experimental confirmation of its various components before it can be accepted. Those include the existence of very heavy right–handed neutrinos as well as lepton number and CP violation in their decays.

Direct detection of those phenomena is highly unlikely; however, indirect connections may be established by studying lepton number violation in neutrinoless double beta decay and CP violation in ordinary neutrino oscillations. Indeed, such discoveries will go far in establishing leptogenesis as a credible, even likely scenario. For that reason, neutrinoless double beta decay and leptonic CP violation in neutrino oscillations are given very high priorities by the particle and nuclear physics communities.

Designing for CP violation studies in next generation neutrino programs has other important benefits. First , the degree of difficulty needed to establish CP violation and determine $J_{CP}^{leptonic}$ is very demanding but doable. It requires an intense proton beam of about 1–2 MW and a very large detector ($250 \sim 500$ kton Water Cerenkov or its equivalent). Such an ambitious infrastructure will allow very precise measurements of all neutrino oscillation parameters as well as the sign of Δm^2_{32} via $\nu_\mu \to \nu_\mu$ disappearance and $\nu_\mu \to \nu_e$ appearance studies. It will also provide a sensitive probe of “New Physics” deviations from 3 generation oscillations, perhaps due to sterile neutrinos, extra dimensions, dark energy or other exotic effects.

In addition to its accelerator based neutrino program, a well instrumented very large detector offers other physics discovery opportunities. Assuming that it is located underground and shielded from cosmic rays, it can push the limits on proton decay into modes such as $p \to e^+\pi^0$ to 10^{35}yr sensitivity or beyond, a level suggested by gauge boson mediated proton decay in supersymmetric GUTS. Indeed, there is such a natural marriage between the requirements to discover leptonic CP violation and / or see proton decay (i.e. an approximately 500 k ton water cerenkov detector) that it could be hard to imagine undertaking either effort without being able to do the other. Of course, such a large detector would also have additional physics capabilities. It could study atmospheric neutrino oscillations with very high statistics and look for the predicted relic supernova neutrinos left over from earlier ephochs in the history of the Universe, a potential source of cosmological information. Also, if a supernova should occur in our galaxy (expected about every 30 years), such a detector would see about 100,000 neutrino events. In addition, it could be used to look for signals of $n - \bar{n}$ oscillations in nuclei and highly penetrating GUT magnetic monopoles which would leave behind a trail of monopole catalyzed proton decays.

The physics potential of a very large underground detector is exteremly rich. The fact that it can also be used to determine (or bound) leptonic CP violation and measure all facts of neutrino oscillations gives such a facility outstanding discovery potential. It would be an exciting, central component of the world's particle physics program for many decades.