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LONG BASELINE NEUTRINO BEAMS AND LARGE DETECTORS

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Abstract. - We are entering a new era in the study of neutrino physics. This is due to the great successes of the past many years involving the enumeration of just three neutrinos, their small but finite masses, and their ability to mix. The important issues to be addressed are the mass hierarchy, the values of the mixing parameters, i.e. the mass differences and especially theta 13 and CP violation. One promising strategy involves utilizing long neutrino flight paths, distances greater than 1000 kilometers, detectors of mass in units of 100 ktons water equivalent, beam intensities of 1 MW, and neutrino beam energies of 1-10 GeV. Details on the realization of this exciting possibility using a high energy, high intensity neutrino beam from Fermilab to the new underground laboratory at DUSEL with large water Cerenkov and/or liquid argon detectors will be explored, An added bonus to this approach is the simultaneous study of proton decay and supernovas. This certainly makes for a program well worth pursuing.

It is amazing to acknowledge that in roughly 70 years from when the existence of the neutrino was postulated, we are now contemplating investigating the mysteries of this particle (or particles) requiring and utilizing detectors of 300 ktons , distances of 1,000 - 2,000 kilometers, beam intensities of megawatts and underground depth of 5,000 feet.

This evolution has evolved slowly, from the experimental discovery of the neutrino in 1956, to the demonstration that there were two neutrinos in 1962 and three and only three by 1991. The great excitement occurred in the 2000's coming from the study of solar and atmospheric neutrinos in which neutrinos were observed to oscillate and therefore have mass. Although the absolute mass of any of the neutrinos has yet to be determined (the upper limit is less than 1 electron volt) the difference in this square of these masses has been measured, yielding a value of $(2.3\pm.2)10^{-3}$ eV^2 for atmospheric neutrinos and $(7.6 \pm .2)10^{-5}$ eV^2 for solar neutrinos. In addition their mixing angles were found to be 45° for atmospheric neutrinos and 34° for solar neutrinos. This present state of knowledge on neutrinos is pictorially displayed in Fig. 1.

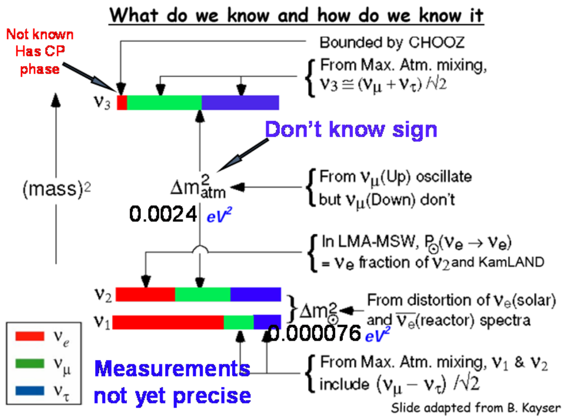

Figure 1:

Of course, mixing between flavors had already been observed in the quark sector as exemplified by the Cabbibo-Kobayashi-Meskawa Matrix. It was therefore natural to extend this formalism to the lepton sector involving unitary 3×3 matrices and one CP violating phase. This is shown in Fig. 2 for the two sectors, quark and leptons including the Jarlskog invariant (J).

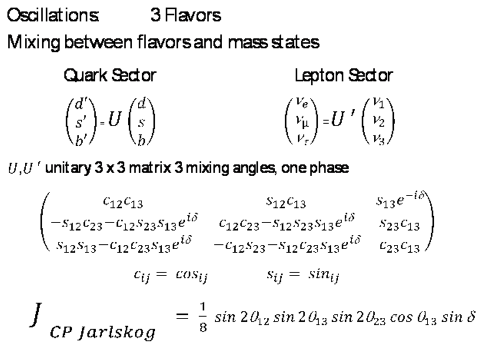

Figure 2:

It has become evident that values for those two matrices U and U' are very different, the quark sector being diagonal with a mixing angle of $\approx 57°$ and a $J = 3.1 \times 10^{-5}$, while the lepton sector is far from diagonal with a small unknown missing angle θ_{13} , an unknown phase and $J = .11 \sin^2\theta_{13} \sin\delta$. The task is to determine these unknowns as well as the neutrino masses. It should be noted that if we equate the Jarlskog quark and lepton invariant, this would require very small θ_{13} and δ, of the order of $1°$.

The formalism in the study of neutrino oscillations has to also include matter effects, namely take into account that electron neutrinos have a charged current as well as neutral current interaction. This complete expression is shown in fig. 3 where the probability for a muon neutrino oscillating into an electron neutrino is expressed in terms of all the pertinent parameters.

There are four terms, the first three are relevant in the neutrino energy range greater than 3 GeV, the fourth term involves solar parameters and also energies less than 1 GeV, with terms 2,3 sensitive to CP violation and mainly energies between 1-3 GeV. Other important observations are that the second CP violating term scales as L/E, vanishes at a distance of 7500 km, is linearly dependent on alpha = 1/30, and grows as θ_{13} becomes smaller. With the rate decreasing with θ_{13} the value of δ is independent of θ_{13}; the third term is CP conserving and finally for anti-neutrinos, δ goes into minus δ whereby the second term changes signs. All the above pertains to appearance experiments. For disappearance experiments the probability is one (1) minus the above expression in Fig. 3. We are now set to explore the consequences of all the present state of knowledge in this neutrino sector.

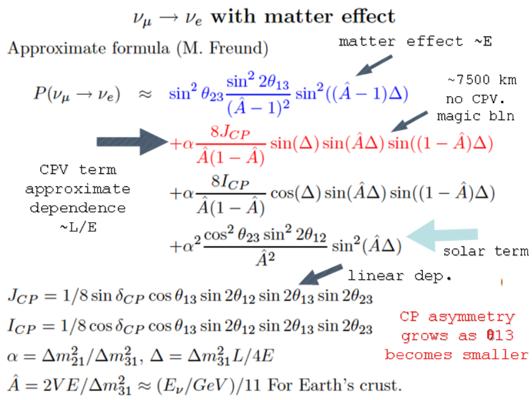

Figure 3:

As noted earlier the exciting experimental challenge in the lepton sector is to obtain more precise values of the neutrino masses mass differences, mixing angles and CP phase. With our present knowledge we are in a position to determine the neutrino mass hierarchy, and the values of the unknown missing angle θ_{13} and the CP violating phase δ. However, we are also now convinced that in order to do so requires very large detectors, very long neutrino beam baselines and high intensity beams. This was first pointed out in 2003 in an article by M. Diwan and collaborators entitled "Very Long Baseline Neutrino Oscillation Experiment for Precise Measurement of

Mixing Parameters and CP Violating Effects" Phys. Rev. D. 68, 120002 (2003). But what is very large, very long and high intensity With respect to detectors, there are three candidates. The most well known and utilized large neutrino detector is the water Cherenkov detector. The minimum size required for this new physics is 300 ktons with a desired target of 1 Mton. The largest such detector built to date is 50 ktons. One can visualize constructing 100 - 150 Kton modules to attain the large desired volumes. Another very promising technique is the liquid argon TPC. Due to its greater resolution, a minimum 50 Kton detector is required with 100 Ktons being a more desirable target. At present a 0.6 Kton exists with plans for 5 Kton liquid argon detector having recently been approved. The third option would be a liquid scintillator detector of a 50 Kton size with the largest built to date being of the order of 1 Kton.

In order to achieve adequate event rates even in these very large detectors, requires high proton beam intensities of the order of one megawatt. Present accelerators can produce beam intensities of 100 - 200 Kwatts - with modest upgrades one can attain 700 - 1,000 Kwatts and with major upgrades 2,000 Kwatts. As noted earlier neutrino energies between 0.5 GeV and 10 GeV are desirable. The known mixing angles and mass differences then require neutrino flight paths of the order of 1,000 - 2,500 kilometers. Such possibilities are being explored in the U.S., Europe and Japan. Finally cosmic ray conditions make it desirable to place the detectors underground at depth of 3,000 - 5,000 meters water equivalent.

As noted earlier there are two types of accelerator based neutrino experiment being considered. The first is called a disappearance experiment where a muon neutrino doesn't produce a muon, thereby disappearing; and the second being an appearance experiment when a muon neutrino produces an electron (indicative of a muon neutrino having oscillated into an electron neutrino). Those two approaches are utilized to extract values for mixing angles, mass differences, mass hierarchy and CP violation in the neutrino sector. A rather detailed study has been undertaken to determine the requirements, in beams, detector baseline etc. for ascertaining those important physics quantities. In particular the baseline considered was 1300 km. Fermilab to Homestake; two detectors, a 300 Kton water Cherenkov and a 100 Kton liquid argon TPC; a proton beam of 7×10^{13} ppp at a 4/3 sec rep rate, yielding 10×10^{20} POT/yr at 60 GeV and 120 GeV. The results are graphically displayed in the following figures. First it would be gratifying to see an oscillation. In the past we have clearly seen a depletion in the expected number of neutrino events. Now in a few years of running time one would observe two oscillation nodes in a disappearance experiment. This is shown in Fig 4. for a 60 GeV, 0 degree beam which would yield a 1 per cent measurement of $\sin^2 \theta_{23}$ and $\Delta\ m^2{}_{31}$. One also notes the drastic reduction of expected event rates from the case of the expected neutrino oscillations (a factor of two).

In Fig. 5 we display the expected spectra for an electron appearance experiment for normal and inverted hierarchy, and for different values of the CP violating phase (note the energy log scale, -.3 is .5GeV 0.5is 3 GeV and 1.0 is 10 GeV) Clear oscillations are again observed with at least two nodes being experimentally accessible. The position

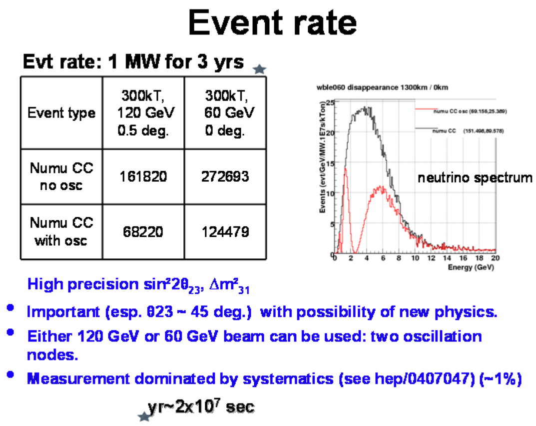

Figure 4:

of the node, and their amplitudes are clearly dependent on both the mass hierarchy as well as the CP phase and it is clearly useful to span neutrino energies form 0.5 GeV to 10 GeV.

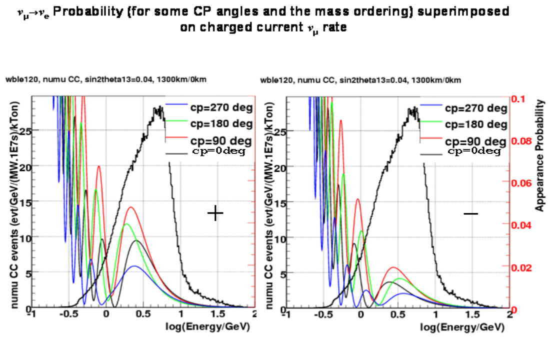

Figure 5:

Electron neutrino appearance spectra for a 300 Kton water Cherenkov detector and a 100 Kton liquid argon detector are shown in Fig 6 and Fig 7 respectively.

Plots are displayed for normal and revised hierarchy, for neutrino anti-neutrino running and for a 30×10^{20} POT exposure, and curves for two values of the CP phase δ and projected data points for zero phase. It is apparent that investigating the normal hierarchy, neutrino running is preferred and for reversed hierarchy anti-neutrino is preferred. There are clear signals above background for both detectors, however, the

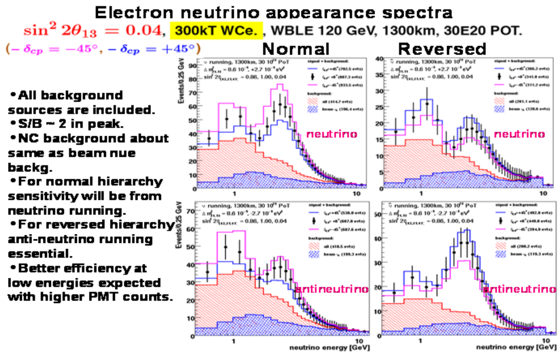

Figure 6:

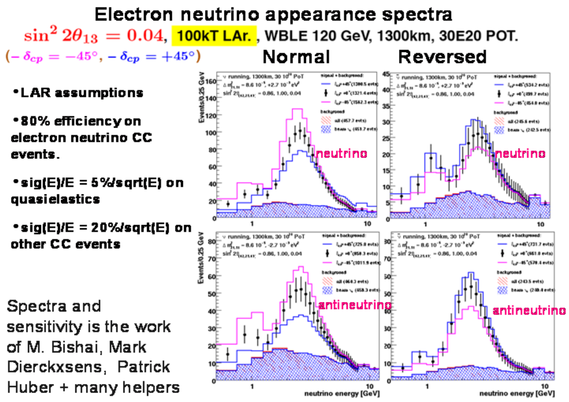

Figure 7:

backgrounds are lower for the liquid argon TPC due to is better resolution. The strength and power of this technique is shown in Fig. 8 where the sensitivity to different values of θ_{13} and δ are displayed for a water Cherenkov detector.

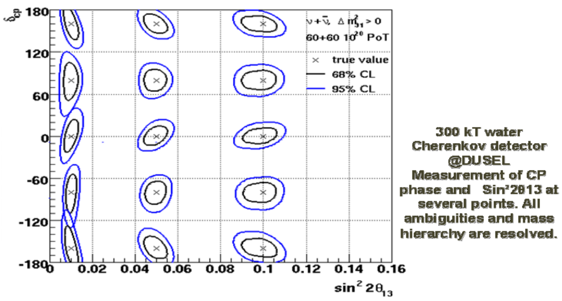

Figure 8:

CP measurement to within plus/minus 20° are attainable for nearly all values of δ and θ_{13}. As such, we can deduce that a program utilizing large detectors, intense beams and long baselines can in a period of 6 years yield dramatic results for determining the mass hierarchy, a 3-5 σ effect if $\sin^2 2\theta_{13} > .008$; measure $\sin^2 2\theta_{13}$ if its value is of the order of .004 and detect CP violation if $\sin^2 2\theta_{13} > .01$. This physics opportunity is so extraordinary that it is being pursued in the U.S., Fermilab to Homestake; in Japan J PARC to Super K/Island/South Korea, and Europe with CERN to Finland/Great Britain.

One of the great dreams in physics is that of Grand Unification, the combining of strong, weak, electro-magnetic and gravitational forces under one Grand Unified Theory (GUT). The energy scale at which this may occur is 10^{15} GeV to 2×10^{16} GeV, much higher than any present or visualized accelerator. A most interesting consequence of such conjectures concerns the stability of the proton, namely whether it decays and at what rate. The earliest theory foray was minimal SU (5) which predicted proton decay into both $e^+\pi^0$ and $K^+\nu$ with rates of the order of $10^{28} - 10^{30}$ years. Many searches for proton decay have been carried out over the past years. These involved IMB, Kolar Gold Mine, Homestake, Soudan, Frejus and more recently Kameokande and Super Kameokande. Experimental limits on proton decays have been obtained by Superkameokande, data equivalent to 141 Kton years. The limiting values are 8.2×10^{33} yrs for proton decaying into a positron and a π^0 meson and $> 1.6 \times 10^{33}$ years for the neutrino K plus decay mode. This clearly rules out minimal SU (5). More recent theoretical conjectures are centered around Supersymmetric Grand Unified Theories - (SUSY-GUT) and theories involving extra dimensions. Utilizing all our present knowledge, these newer conjectures place the proton decay lifetimes at 2×10^{35} years for the $e^+\pi^0$ mode and 10^{34} years for $K^+\nu$ mode, one or two orders of magnitude beyond present limits. With the realization of a long baseline neutrino program and its accompanying large detectors, one would automatically be in a position to greatly extend the search for proton decay into a region where there is a reasonable probability of discovery (one megaton for 10 years yielding a 10,000 Kton years/exposure).

A similar opportunity is afforded to the study of Supernova neutrinos. Since rates are estimated to be small, large detectors of Megaton scale are required for proper exploration of this phenomenon. What is measured is the number, energy and arrival time of neutrino coming from supernova explosions. With such data one can explore the core of supernova, the hydrodynamics of supernova and even possible fundamental neutrino properties. We all recall the excitement of SN87A when the IMB and Kameokande detectors found 19 supernova initiated neutrino events. Galactic supernova events are estimated to occur once every forty years. Such events can be detected via the reaction $\bar{\nu}$ p $\rightarrow$ n e^+ with 100,000 events occurring in 10 kpc. The energy range is 5-20 Mev with a time window of seconds. Of similar interest is the study of diffuse (relic) supernova. Their flux is constant with the 5-30 Mev energy range and expected rates just beyond the reach of Superkameokande. As such the projected large detector should be able to accumulate sufficient events to study the properties of these relic, diffuse supernovae.

I conclude by noting that we are entering a new era in neutrino physics. It is characterized by large scale detectors, intense beams and long distances. It provides a grand opportunity to greatly improve our knowledge of neutrinos, their masses and mixing angels, a strong possibility of observing CP violation, proton decay and supernova. It would also be very gratifying and advantageous if genetic engineering could increase our longevity to be commensurate with the times that it requires to explore this exciting physics.