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New neutrino experiments

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Abstract. Following incredible recent progress in understanding neutrino oscillations, many new ambitious experiments are being planned to study neutrino properties. The most important may be to find a non-zero value of θ_{13}. The most promising way to do this appears to be to measure $\nu_\mu \to \nu_e$ oscillations with an E/L near $\Delta m^2_{\rm atmo}$. Future neutrino experiments are great.

Keywords. Neutrino; particle detectors.

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1. Introduction

In the last few years we have seen remarkable progress in understanding the neutrino. Compelling evidence for the existence of neutrino mixing and oscillations has been presented by Super-Kamiokande [1] in 1998, based on the flavor ratio and zenith angle distribution of atmospheric neutrinos. That interpretation is supported by analyses of similar data [2] from IMB, Kamiokande, Soudan 2 and MACRO, and 2002 was a miracle year for neutrinos, with the results from SNO [3] and KamLAND [4] solving the long standing solar neutrino puzzle and providing evidence for neutrino oscillations with both neutrinos from the Sun and neutrinos from nuclear reactors. Finally, the K2K long-baseline neutrino oscillation experiment [5] has indications that accelerator neutrinos also oscillate.

In preparation for this meeting, I asked the previous speaker, Sandip Pakvasa from the University of Hawaii, "What are the outstanding issues in the neutrino sector for future experiments to address?" His list was:

(1) See the dip in atmospheric ν L/E distribution.
(2) Measure the whole solar ν energy spectrum.
(3) Determine the value of Ue3 (θ_{13}).
(4) Are CP violation effects large?
(5) If so, what is the CP phase δ?
(6) Can we see the τs in $\nu_\mu \to \nu_\tau$ oscillation?
(7) Can we settle the LSND question?

(8) Measure the absolute ν masses?
(9) Is the neutrino Majorana or Dirac?
(10) Is the mass hierarchy normal or inverse?
(11) Are there astrophysical sources of >TeV νs?

Indeed, those questions are just the ones that have motivated new neutrino projects, and a plethora of new proposals for future projects at underground laboratories and accelerators. These include the study of solar, atmospheric, reactor, accelerator and astrophysical sources of neutrinos. There is also the direct search for neutrino mass in tritium beta decay, and the search for Majorana masses in neutrinoless double beta decay.

2. The importance of θ_{13}

For all the fullness of the program, I share the view that the single most important task before the neutrino community is to measure a non-zero value for θ_{13} if it exists. While $\sin^2(2\theta_{23})$ is near 1, SNO data supports that $\sin^2(2\theta_{12})$ is approximately 0.7 and is clearly not maximal. Although we do not know what symmetries, if any, control the values of the MNS mixing angles, it is reasonable to expect that if θ_{12} is not maximal, θ_{13} is probably not exactly zero. The current limit on $\sin^2(2\theta_{13})$ is <0.1 [6]. Some of us hope that a new search which is sensitive down to 0.01 would have a 90% chance of measuring a non-zero value for θ_{13}.

Such a result would open up new possibilities for future neutrino research. If θ_{13} is not 0, search for matter effects and CP violation with accelerator neutrinos are feasible, in particular using $\nu_\mu \to \nu_e$ measurements as described in the last paragraph of this section. The observation of matter effects in ν or $\bar{\nu}$ tells us if Δm^2_{atmo} is positive (normal mass hierarchy) or negative (inverted mass hierarchy). Of even greater interest, the measurement of differences between ν and $\bar{\nu}$ oscillation parameters (after removing any matter effects) is sensitive to CP violating effects in the lepton sector. The measure of CP violation is the Jarlskog invariant, which is proportional to the product of all mixing angles and Δm^2 values. With the large mixing in the lepton sector, CP violation in the neutrino sector is poised to be 50 times larger than in the quark sector.

The probability in vacuum for $\nu_\mu \to \nu_e$ is [7]

$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & 2\sin(2\theta_{13}) s_{23} c_{13} s_{12} (s_{12} s_{23} s_{13} - c_{12} c_{23} c_\delta) \sin^2\phi_{32} \\ & + 2\sin(2\theta_{13}) s_{23} c_{13} c_{12} (c_{12} s_{23} s_{13} + s_{12} c_{23} c_\delta) \sin^2\phi_{31} \\ & - 2\sin(2\theta_{12}) c_{13}^2 [s_{12} c_{12} (s_{13}^2 s_{23}^2 - c_{23}^2) \\ & + s_{13} s_{23} c_{23} (s_{12}^2 - c_{12}^2) c_\delta] \sin^2\phi_{21} \\ & + \frac{1}{2}\sin(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23}) c_{13} s_\delta [\sin\phi_{32}\cos\phi_{32} \\ & - \sin\phi_{31}\cos\phi_{31} + \sin\phi_{21}\cos\phi_{21}], \end{aligned} \tag{1}$$

where $\phi_{ij} = \Delta m^2_{ij} L/(4E)$ and c_{ij} and s_{ij} refer to the cosine and sine of the mixing angle ij. The first two terms describe the behavior at L/Es corresponding to the large value of Δm^2 and the terms proportional to $\sin\delta(\cos\delta)$ are CP odd(even).

3. Underground laboratories for neutrino research

Since neutrino cross-sections are small, most neutrino experiments are located underground to reduce backgrounds from cosmic rays.

The Kamioka mine in the Japanese Alps is home to the 50 kiloton Super-Kamiokande water Cerenkov detector. In November 2002 it started running again, with half the photo-tube coverage that it had before its accident in December 2001. Nearby is the KamLAND detector which looks at reactor neutrino disappearance from 26 reactors throughout Japan. There are also early plans to put the one megaton Hyper-Kamiokande experiment in a cavern in the Tochibora mine, about 3 km south of the present Mozumi mine. That could pair with the present Super-Kamiokande facility as an off-axis site from the new JPARC accelerator at Tokai.

The Baksan facility is located in the Caucasus mountains in Southern Russia. The gallium solar ν experiment SAGE is located in a deep section with a minimum overburden of 4700 MWE. The gallium experiment was crucial in confirming the solar neutrino deficit. Also located at Baksan is the four-layer Baksan underground scintillation telescope (BUST) located at a minimum overburden of 850 MWE. BUST has been studying the zenith angle distribution of upward atmospheric induced neutrino events, which is relevant to the atmospheric-neutrino deficit.

The nicest facility for underground physics is located at the Gran Sasso Laboratory in a mountain road tunnel in Italy. It is operated there by INFN for experimentalists from throughout the world. There are three large halls in which a number of neutrino experiments have operated and are being built. These include the Gallex and GNO experiments which have measured the pp solar neutrinos; the MACRO experiment which measured the angular distribution of atmospheric neutrinos; Borexino which is being built to measure the solar neutrinos from ^{7}Be; the Heidelberg–Moscow neutrino-less $\beta\beta$ decay experiment on germanium, which is the most sensitive search to date; the LVD detector which search for neutrinos from supernovae; and the OPERA and ICARUS projects which will measure neutrinos associated with the CERN neutrinos to the Gran Sasso (CNGS) program starting in 2006.

The waste isolation pilot plant (WIPP) facility, in Carlsbad, New Mexico was built to store low-level radioactive waste from the US military. It is the world's first underground repository licensed to safely and permanently dispose of transuranic radioactive waste left from the research and production of nuclear weapons. After more than 20 years of scientific study, public input, and regulatory struggles, WIPP began operations on March 26, 1999. It is considered as a possible site for the supernova experiment OMNIS which will feature a measurement of the neutral current events from supernovae; the 400 kiloton proton decay experiment UNO; and EXO, a new neutrino-less $\beta\beta$ decay experiment which uses xenon. Experimental facilities located in the salt are sufficiently removed from the radioactive waste that they present no backgrounds to any of these experiments.

There is considerable interest in the United States in developing a national underground laboratory facility (NUSEL) for future neutrino experiments. A panel was appointed in 2002 by the US National Research Council to study future neutrino facilities, with an emphasis on NUSEL and also a neutrino telescope ICE-CUBE. In its conclusion section, they wrote [8]: 'In summary, our assessment is that a deep underground laboratory in the US can house a new generation of experiments that will advance our understanding of the fundamental properties of neutrinos and the forces that govern the elementary particles, as well as shedding light on the nature of the dark matter that holds the Universe together. Recent discoveries about neutrinos, as well as new ideas and technologies make possible a broad and rich experimental program. Considering the commitment of the US community and the existing scientific leadership in this field, the time is ripe to build such a unique facility.' The favored location for NUSEL is the Homestake, South Dakota mine where the famous Davis experiment ran for many years. There is also a proposal to locate the laboratory with horizontal access in a new facility near San Jacinto, California.

The Sudbury neutrino observatory (SNO) is taking data that has provided revolutionary insight into the properties of neutrinos and the core of the Sun. The detector is in INCO's Creighton mine near Sudbury, Ontario. SNO uses 1000 tons of heavy water, on loan from Atomic Energy of Canada Limited (AECL), contained in a 12 m diameter acrylic vessel. Neutrinos which react with the heavy water (D_2O) are detected by an array of 9600 photomultiplier tubes. The detector laboratory is extremely clean to reduce background signals from radioactive elements. Besides the heavy water detector, the Canadian government has recently funded a new international facility for underground science called SNOLAB which will provide a low background facility nearby.

India was home to one of the earliest and deepest underground facilities with the KGF mine and experiment from the sixtees through the early nineties. Now a group from several institutes throughout India is studying the possibility of a new neutrino observatory to measure atmospheric neutrinos and the possible site for a long-baseline neutrino program from a neutrino factory. Two sites which have hydro-electric projects near large hills are being considered. The PUSHEP (Pykara Ultimate Stage Hydro Electric Project) site near Ooty in Tamil Nadu is located in a vein of high quality rock, and is also close to a high-altitude cosmic ray facility. The RAMMAM Hydro Electric Project site is located in the Himalayas near Darjeeling, and has the possibility of a laboratory with a much greater overburden, suitable for solar neutrino experiments. A project team has got a grant to study both sites and to design a 30 kiloton iron/RPC calorimeter for atmospheric neutrinos.

4. Future non-accelerator experiments

In the past year, SNO and KamLAND have solved the solar neutrino problem by showing that the total rate of neutrinos coming from the Sun is equal to the long-expected value from the standard solar model [9], and that neutrino oscillations in the so-called 'large mixing angle' region of parameter space explains the apparent deficit of ν_e charged current events in the many experiments. SNO, which has provided us with two measurements of the neutral current event rate, will do it again with its salt data, and then yet again with its helium counters. Borexino will measure the rate of beryllium neutrinos, which have a lower energy than the boron neutrinos measured by Super-Kamiokande. A series of ambitious real-time *pp* neutrino experiments are also being considered, including HERON, LENS and HELLAZ, as well as a new experiment using iodine.

KamLAND has seen clear evidence for approximately 40% $\bar{\nu}_e$ disappearance from reactors throughout Japan. With more data, they will be able to further reduce the range of parameter space for $\sin^2(2\theta_{12})$ and particularly Δm_{12}^2. Other reactor experiments at about 10 km distance were being considered when there was a possibility that Δm_{12}^2 would be higher than its currently favored values. There has been a loss of interest in these experiments since the SNO data has been presented. But there is increasing interest in using reactors to search for a non-zero value of θ_{13}. The current best limit for θ_{13} comes from the reactor experiment Chooz [6]. One idea for a new, more precise experiment would be located at the Krasnoyarsk reactor in central Russia [10] and would carefully measure the difference from $1/L^2$ in the event rate from two detectors located at different distances from the core. Control of systematic errors to better than 1% will be the challenge for this type of experiment.

Most people attribute the discovery of oscillations to the 1998 results on atmospheric neutrinos by the Super-Kamiokande Collaboration [1]. Previous results from IMB and Kamioka as well as subsequent results from Soudan 2 and MACRO supported the oscillation interpretation [11], but Super-Kamiokande results are both qualitatively and quantitatively better than all other data put together. One feature of the Super-K data did lead to another proposal. The L/E resolution in Super-K was not good enough to see the dip in the oscillation. Early fits (now ruled out) showed that the distribution could be explained by neutrino decay as well as by oscillations. The proposed Monolith experiment was designed with the resolution to see that dip, or 'reappearance' at higher L/E, as demonstrated in figure 1. The large iron spectrometer was planned for the Gran Sasso but was not approved. Now that Super-Kamiokande is running again, they will have increased statistics which will be useful for improving the determination of Δm^2.

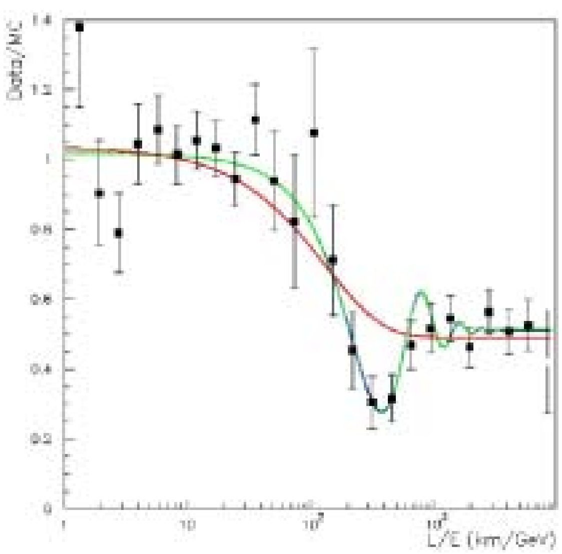

Figure 1. The L/E resolution that could have been expected with the Monolith or similar underground detector on atmospheric neutrinos.

Neutrino oscillations measure the difference of neutrino masses, $\Delta m^2 = m_1^2 - m_2^2$ but are not sensitive to the overall mass scale. The idea that neutrinos must be light was an original feature of their prediction from the kinematics of nuclear beta decay [12]. The most sensitive searches have been from tritium β decay. The best limit now comes from Mainz: $|m| < 2.2$ eV [13]. Since we now recognize that flavor neutrinos are not mass eigenstates, it is not correct to make statements such as $m(\nu_e) < 2.2$ eV. A new improved experiment, KATRIN, is being prepared to reach a sensitivity to neutrino mass of 0.35 eV. This will be achieved using a special type of spectrometer, the so-called MAC-E-Filters (magnetic adiabatic collimation combined with an electrostatic filter). This type of spectrometer was first proposed in ref. [14] and described in refs [15] and [16]. It combines high luminosity and low background with a high-energy resolution, both essential to measure the neutrino mass from the endpoint region of a β decay spectrum.

Another possible way to detect neutrino mass is in neutrino-less double β decay experiments. This process would exist if the neutrino mass were Majorana instead of Dirac. It is well-known that neutrinoless double β decay, $0\nu\beta\beta$ can proceed only if neutrinos are massive Majorana particles. If the $0\nu\beta\beta$ occurs, the effective Majorana neutrino mass is related to the half-life of the nuclear state and the nuclear matrix elements. Searches are proceeding in a number of nuclei, including germanium [17] and xenon [18].

The search for astronomical sources of neutrinos is a new endeavor which is more related to astronomy than the physics of neutrino oscillations. Arrays of well-separated phototubes called Nestor, Antares and Nemo in the Mediterranean are joining the Russian Baikal project and AMANDA at the South Pole in setting up large water/ice detectors to search for neutrino sources. The eventual goal is to have a km^3 array, either in the Mediterranean or the South Pole, to look for neutrinos from AGN's, γ-ray bursts, and WIMP annihilation in the Sun.

5. Future accelerator experiments

The MiniBooNe experiment is described in more detail at this conference [19]. That experiment, which is currently running, uses neutrinos made from 8 GeV protons accelerated in the Fermilab Booster. The average neutrino event energy is about 1 GeV. The experiment will search for $\nu_\mu \to \nu_e$ appearance in the regions of parameter space suggested by results from the LSND experiment [20], $\Delta m^2 \sim 1$ eV^2; $\sin^2(2\theta) > 0.001$. ν_e appearance will manifest itself as an excess of electrons from quasi-elastic scattering. Backgrounds include ν_e in the beam and neutral current events which look like single electrons.

The atmospheric neutrino oscillation signature has motivated long-baseline neutrino experiments in Japan, the US and Europe. The expression 'long-baseline' is of course an arbitrary designation. The dictionary [21] defines long as 'measuring much, or more than usual, from end-to-end in space or time'. The practical definition seems to be that the detector is located off-site with respect to the accelerator laboratory. There is a useful definition with respect to the beam, that the distance from the ν source to the detector is much greater than the length of the decay pipe. In that case, neutrino emission can be considered as coming from a point source and calculations predicting the beam spectra are simplified. There is a useful physics definition of long, i.e. $L \gg E_\nu/\Delta m^2$, which would imply that the neutrino beam was fully oscillated. When the present round of experiments were proposed, Δm^2 was unknown. Now that we know $\Delta m^2 \sim 3.0 \times 10^{-3}$ eV^2, none of the present experiments meet the physics definition of 'long-baseline'.

The K2K experiment [5] uses protons from the 12 GeV PS at KEK to make a neutrino beam aimed at the Super-Kamiokande detector with an average energy (in the absence of oscillations) around 1.3 GeV. The detector is located 250 km away. They observe indications of neutrino oscillation: a reduction of ν_μ flux together with a distortion of the energy spectrum. Fifty-six beam neutrino events are observed in Super-Kamiokande (SK), 250 km from the neutrino production point, with an expectation of $80.1^{+6.2}_{-5.4}$. Twenty-nine one ring μ-like events are used to reconstruct the neutrino energy spectrum, which is better matched to the expected spectrum with neutrino oscillation than without. The probability that the observed flux at SK is explained by statistical fluctuation without neutrino oscillation is less than 1%. They are now running again after the Super-Kamiokande accident and expect to double their statistics in another 3 years.

In the United States, the main injector neutrino oscillation search (MINOS) experiment is under construction to measure neutrinos from Fermilab's neutrinos at the main injector (NuMI) beamline. The beamline will use a 675 m long decay pipe aimed at the Soudan mine 730 km away. The 5.6 kiloton magnetized iron calorimeter will be able to separate most ν_μ charged current events from neutral current events and ν_e charged current showers. With 7.4 $\times 10^{20}$ protons on target, the experiment will be able to use the energy distribution of reconstructed events at the far detector to measure Δm^2 eight times more accurately than presently known. More than half of the detector is currently operating at Soudan and it should be completed in the early summer of 2003. The civil construction of the tunnel for the beamline at Fermilab is also complete, and first neutrinos are expected in December 2004.

Using a low-energy beam which peaks near 4 GeV, MINOS will measure a shift in the charged current energy distribution due to $\nu_\mu \to \nu_\tau$ oscillations. The magnitude of those shifts, and the ratios with the expected energy distributions in the absence of oscillation are shown in figure 2 for three allowed values of oscillation parameters: $\sin^2(2\theta) = 0.9$; and $\Delta m^2 = 0.002, 0.0035$ and 0.005 eV^2. The sensitivity for each of these three points including both statistical and systematic errors for the planned exposure is shown in figure 3.

A long-baseline neutrino program is also being constructed in Europe, and is known as CERN neutrinos to the Gran Sasso (CNGS). The neutrinos will travel the same distance as in the US, 730 km, but there will be higher-energy neutrinos in order to detect ν_τ appearance. Two detectors are under construction, ICARUS, a very-high resolution liquid argon time projection chamber, and OPERA, which is a lead-emulsion sandwich. A 600 ton version of ICARUS will be installed in Gran Sasso in 2003, with plans for 3000 tons operational by the summer of 2006 when the CNGS beam is expected to turn on. ICARUS will also be sensitive to solar neutrinos, atmospheric neutrinos, supernova neutrinos and nucleon decay. OPERA will measure evidence for the production of τ decays from ν_τ charged current interactions produced after oscillations. They expect a signal of $18.3 \times [\Delta m^2/(3.2 \times 10^{-3}\ \mathrm{eV}^2]^2$ events with a background of 0.57 events in two years.

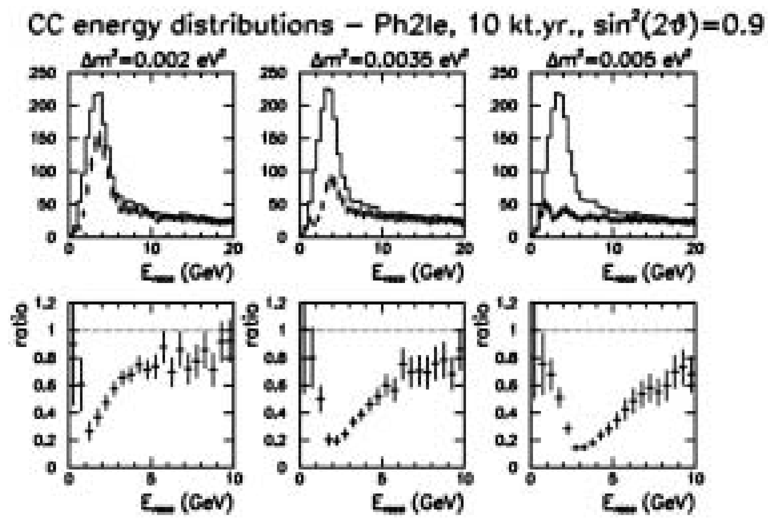

Figure 2. Expected reconstructed event energy distributions with and without oscillations for the three points in parameter space given in the text.

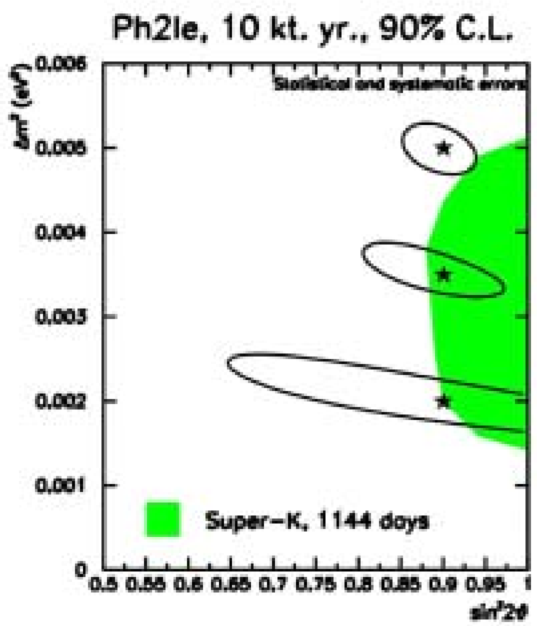

Figure 3. Parameter space sensitivity of MINOS for three points in parameter space, compared to the 1144 Super-Kamiokande allowed region.

A series of other near-detector neutrino experiments have also been proposed at Fermilab [22]. Experiments have been suggested on- and off-axis in the NuMI and MiniBooNE beamlines to measure neutrino cross-sections, understand neutrino spectra, and provide proof-of-principle for new detector technologies. Fermilab will be considering these proposals next year.

6. Off-axis experiments

The Japanese particle research center (JPARC) is a new 50 GeV proton synchrotron being built in Tokai, east of Tokyo. A neutrino beam is part of the planned facility, though it is not yet formally approved. In the first phase the accelerator would operate at 0.77 MW, but an upgrade to 4 MW driving a conventional neutrino beam is being considered. The 22.5 kiloton Super-Kamiokande detector is 295 km away, and the beam could be built to be simultaneously 2 degrees off-axis to that experiment and to the proposed site for a 1000 kiloton Hyper-Kamiokande detector in Tochibora. With a 5 year run of JPARC, and the proposed 2° off-axis beam, JPARCν would be able to measure θ_{13} or set a limit on $\sin^2(2\theta_{13}) < 0.006$ at 90% CL.

A study about an ambitious new neutrino program from Brookhaven focusing on θ_{13} has recently been presented [23]. A Brookhaven beam from the AGS cannot go deep into the Earth because of local groundwater, but a sufficient beampipe can be constructed by bending the beam up and then down in a new hill made with construction techniques similar to highway exit ramps. They considered the physics that could be done with a conventional horn-focused neutrino beam directed at a detector located in either Homestake, South Dakota at 2540 km or WIPP, New Mexico at 2880 km. They assumed a detector similar to UNO (described below) and get a physics reach similar to the NuMI off-axis project (described below).

At the NuMI beam, a letter of intent has been submitted to Fermilab to build a new 20–50 kiloton detector. It is known as P929. The challenge for this and other future long-baseline experiments is to observe $\nu_\mu \to \nu_e$ oscillations down to the level of a few parts per million. Charged current ν_e interactions can be identified by the presence of an electron in the final state. The experimental backgrounds arise from three sources:

(1) ν_e in the beam, primarily from μ and K_{e3} decays (both charged and neutral),
(2) electrons from τ decay following $\nu_\mu \to \nu_\tau$ oscillation,
(3) neutral current events which look like electrons, particularly single π^0 production.

In the MINOS experiment, each of these backgrounds exists at a level near 2%. These backgrounds can all be reduced by going about 2° off-axis of the center of the neutrino beam. The reason has to do with the kinematics of pion decay. As one goes off-axis, both the energy and the flux of the neutrinos that are produced is reduced. However, the energy spectrum of the remaining neutrinos is sharper. Thus in effect, one gets a narrow band beam (NBB). All three backgrounds mentioned above become smaller. The ν_e in the beam remain at a few per cent level, but mostly at higher energy. So an energy cut can reduce them to $\sim$0.2%. At the lower energies (below 4 GeV), the ν_τ cross-section is below threshold, and the fraction of neutral current events that look like an electron of the right energy is also greatly reduced, primarily through the reduction of the high-energy part of the beam spectrum. The price that one pays for these advantages is a much lower event rate, already a serious limitation in a long-baseline experiment. Thus a huge far detector, in the mass range of 20–50 kiloton is required. P929 is studying many possible detector configurations, as well as ways to increase the proton intensity, and plans to submit a proposal to Fermilab in 2003.

Considerable effort has been devoted to considering the most cost-effective detector technology for a new off-axis neutrino detector at Fermilab [24]. An R&D program could lead to cheaper detectors such as scintillator, streamer tubes, resistive plate chambers or even liquid argon. A huge water Cerenkov detector, while not optimum in the energy range above 2 GeV, might allow a simultaneous search for nucleon decay.

7. Farther future experiments

As described earlier, a signature for $\nu_\mu \rightarrow \nu_e$ in a conventional neutrino beam has to compete with various 1% backgrounds which also give signals which look like electrons. If one could make a high energy ν_e beam, however, the intrinsic muon background would be at the level of 10^{-5} from charm decay. This has been one of the strongest arguments for construction of a neutrino factory. In the last few years, there have been two design studies for a neutrino factory [25] and a physics study focusing on a 20–50 GeV stored muon energy with 10^{19}–10^{21} decays per year. Figure 4 shows an example of how an experiment at such a facility that could search for wrong sign muons in both $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ would be sensitive to both matter effects and CP violation as a function of baseline.

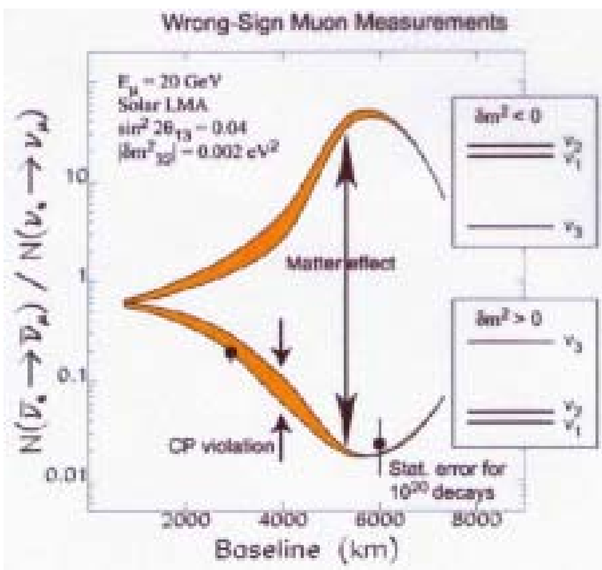

Figure 4. Predicted wrong sign muon rates at a 20 GeV neutrino factory. The range due to CP violation and matter effects is shown.

The idea of β beams has been studied at CERN. In a storage ring which accelerated heavy ions which beta decay, one could obtain a pure beam of ν_e in the 1 MeV region. Then θ_{13} could be determined with an accurate disappearance experiment. ^{6}He could be used to make νs and ^{18}Ne for $\bar{\nu}$s. These ions could be accelerated and stored using the ISOLDE heavy ion accelerator as a source, a new superconducting LINAC and accumulator, the PS, the SPS and a new storage ring.

8. UNO

Part of the recent progress in neutrino physics has come as a result of detectors such as Soudan 2 and Super-Kamiokande which were built to search for nucleon decay, as motivated by grand unified theories. While experimental searches for nucleon decay have produced no convincing evidence for its existence (there are presently not even any strong clues) nevertheless, the theoretical motivation for nucleon decay at some level is almost as strong as ever. Many specific theories constrain the proton life-time to be within one or two orders of magnitude of the present limits. This motivates an even larger detector, patterned after Super-Kamiokande. There are two similar ideas for building such a new proton decay detector; Hyper-Kamiokande in Japan, and UNO in the United States [26]. The UNO concept is for a 60 m $\times$ 60 m $\times$ 180 m volume of water, with two optical-only dividers making three similar cubes. There would be 40% phototube coverage in one cube, and perhaps 10% in the other two. The total volume would be 650 kiloton, with 445 kiloton of fiducial volume, which is 20 times larger than Super-Kamiokande. Such a detector could improve limits in $e\pi^0$ and νK^+ modes by about an order of magnitude in a short run, and a factor of 30 or so with a sufficiently long run, and as our experience has been in the recent past, such a detector would be a great laboratory for studying solar νs, atmospheric νs, supernova νs and possibly accelerator νs.

9. Summary

The tremendous range of new opportunities in neutrino physics is a curious result of the recent successes of neutrino physics. Relevant ranges of L/E for neutrinos have been exploited for solar, atmospheric, reactor and accelerator neutrino oscillation projects, with successful searches now being found in all types. Newer experiments are needed to exploit these earlier successes, and to fully determine the neutrino mass and mixing parameters. New neutrino experiments continue to be planned at accelerators and underground laboratories. Some of these searches continue to go hand-in-hand with the so-far unsuccessful search for proton decay.

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