NOVEL IDEAS AND R&D FOR HIGH INTENSITY NEUTRINO BEAMS

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Abstract

Recent developments in neutrino physics, primarily the demonstration of neutrino oscillations in both atmospheric neutrinos and solar neutrinos, provide the first conclusive evidence for physics beyond the Standard Model of particle physics. The phenomenology of neutrino oscillations, for three generations of neutrino, requires six parameters - two squared mass differences, 3 mixing angles and a complex phase that could, if not 0 or π, contribute to the otherwise unexplained baryon asymmetry observed in the Universe. Exploring the neutrino sector will require very intense beams of neutrinos, and will need novel solutions.

INTRODUCTION

The “Standard Model” of particles and their interactions provides a stunningly accurate description of a huge volume of experimental data, from LEP, HERA and the Tevatron, as well as precision experiments on particle properties, such as the g-2 experiment. However, there is now very convincing evidence [1] for the phenomenon of neutrino oscillations, in which neutrinos created in a particular flavour eigenstate (for example, as electron neutrinos in the sun) are subsequently found to be a mixture of flavours. This is only possible if the neutrinos have a mass (however small), contrary to one of the assumptions of the Standard Model, in which the neutrinos must be strictly massless.

So far, most of the measurements of the oscillation parameters have come from natural sources of neutrinos (solar and atmospheric), with some of the parameters constrained by experiments with reactor neutrinos. The present generation of neutrino beams, and the existing baselines for the experiments, are insufficient to make precision measurements. Neutrino beams with an intensity several orders of magnitude greater are needed to make more precise measurements of those parameters that are already known, and to make precision measurements of the others, in particular of the CP-violating phase. This will require novel approaches to the generation of neutrino beams, and considerable research and development into new technologies.

NEUTRINO OSCILLATIONS

In the Standard Model, the neutrinos are massless. It is difficult just to add a mass term for the neutrinos into the Standard Model Lagrangian, in analogy to the quarks and charged leptons, basically for two reasons. Firstly, the (maximal) violation of parity makes it difficult to write down the usual mass-term in a self consistent way. Secondly, the fact that (unlike all of the other matter particles in the Standard Model) the neutrino is electrically neutral means that there are other Lorentz invariant mass-like terms that can be written using the conjugate fields (Majorana terms) that cannot be easily excluded. For these reasons, neutrino oscillations require physics “beyond the Standard Model”.

Allowing the most general description of massive neutrinos introduces nine new parameters to the Standard Model that need to be measured, and which will eventually provide clues to the origin of the neutrino masses. The 3 flavour eigenstates (ν_e, ν_μ, ν_τ) are related to the 3 mass eigenstates (ν_1, ν_2, ν_3) through the Maki-Nakagawa-Sakata matrix U_{MNS} (equation (1)) .

$$\left[\nu_e, \nu_\mu, \nu_\tau\right] = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \qquad (1)$$

The *frequency* of the neutrino oscillations is governed by two independent parameters:– the two *differences* in the squared masses of the neutrinos. These can be chosen as $\Delta m_{12}^2 = m_1^2 - m_2^2$ (essentially governing the solar neutrino oscillation frequency) and $\Delta m_{23}^2 = m_2^2 - m_3^2$ (essentially governing the atmospheric neutrino oscillation frequency).

The oscillation amplitude is governed by the mixing matrix (see equation (2)).

$$\begin{aligned} U_{MNS} \equiv & \begin{bmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} \text{Solar} \\ \text{sector} \end{pmatrix} \\ \times & \begin{bmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{bmatrix} \begin{pmatrix} \text{3 - generation} \\ \text{sector} \end{pmatrix} \\ \times & \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{bmatrix} \begin{pmatrix} \text{Atmospheric} \\ \text{sector} \end{pmatrix} \\ \times & \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{bmatrix} \begin{pmatrix} \text{Majorana} \\ \text{sector} \end{pmatrix} \qquad (2) \end{aligned}$$

The Majorana phases α and β play no part in the neutrino oscillations, but their influence can be observed through for example, neutrinoless double β decay.

The *amplitude* of the neutrino oscillations is determined by the appropriate combination of the mixing angles θ_{12}, θ_{23}, and θ_{13}. The phase angle δ violates both CP and T invariance, and might be related to the, so far unexplained, baryon asymmetry of the Universe, through a process known as leptogenesis..

The final parameter needed to describe fully the neutrino sector is to set the absolute mass scale, for example by measuring the electron neutrino mass, or (through neutrinoless double β decay) by measuring a weighted average mass, or (through astrophysical measurements) the sum of the neutrino masses.

The present state of knowledge [2] of these parameters is summarised in Table 1. So far, there are only limits [1] on the absolute mass scale. Direct measurements of the tritium β decay place an upper limit of 2.2 eV on the electron neutrino mass. The neutrino oscillation parameters mean that at least one neutrino has a mass greater than about 0.04 eV. Finally, limits from cosmology imply that the mass scale is less than 0.7 eV.

Table 1: Neutrino Parameters

Parameter	Value	Comment
Δm_{12}^2	$6.9_{-0.40}^{+0.75} \times 10^{-5}\ \mathrm{eV}^2$	SuperKamiokande SNO and KAMLAND
θθ_{12}	$\left(33.2_{-1.6}^{+1.8}\right)^\circ$	
$\left\|\Delta m_{23}^2\right\|$	$2.3_{-0.45}^{+0.35} \times 10^{-3}\ \mathrm{eV}^2$	SuperKamiokande and K2K
θ_{23}	$\left(46.1_{-5.0}^{+4.1}\right)^\circ$	
θ_{13}	$< 11^\circ$	CHOOZ
Sign Δm_{23}^2	Unknown	
δ	Unknown	
α,β	Unknown	Neutrinoless double β decay

Now that the phenomenon of neutrino oscillations is established, and there are reasonably precise values for the parameters governing the leading transitions, it is possible to define the future programme of experiments that are required to explore fully the neutrino sector. The goal of the experimental programme has to be to measure all of the parameters with comparable precision, and this will require neutrino beams of significantly higher intensity, known spectrum and composition and lower (or better known) backgrounds from other (unwanted) neutrino flavours. This requires novel approaches to the generation of neutrino beams.

To gain some idea of why a variety of neutrino beams is required, it is instructive to examine a *simplified* (i.e. ignoring matter effects) oscillation formula (equation (3)). The presence of so many trigonometric functions means that there are several equivalent solutions for the fit to any given distribution, particularly if the statistics are limited.

$$
\begin{aligned}
P(\nu_\mu \Rightarrow \nu_e) = {} & \\
& 4c_{13}^2 s_{12}^2 \left(c_{12}^2 c_{23}^2 - s_{12}^2 s_{13}^2 s_{23}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\right) \\
& \sin^2\left(\tfrac{\Delta m_{21}^2 L}{4E}\right) \\
& + 8c_{13}^2 s_{12}s_{13}s_{23}\left(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23}\right) \\
& \cos\left(\tfrac{\Delta m_{32}^2 L}{4E}\right)\sin\left(\tfrac{\Delta m_{31}^2 L}{4E}\right)\sin\left(\tfrac{\Delta m_{21}^2 L}{4E}\right) \\
& + 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\left(\tfrac{\Delta m_{13}^2 L}{4E}\right) \\
& - 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23} \\
& \sin\delta \sin\left(\tfrac{\Delta m_{32}^2 L}{4E}\right)\sin\left(\tfrac{\Delta m_{31}^2 L}{4E}\right)\sin\left(\tfrac{\Delta m_{21}^2 L}{4E}\right) \qquad (3)
\end{aligned}
$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$.

NEUTRINO BEAMS AND EXPERIMENTS RUNNING OR UNDER CONSTRUCTION

So far, the evidence for neutrino oscillations from an accelerator derived neutrino beam comes from the LSND experiment [3] at LAMPF at Los Alamos, and the K2K experiment [4] at the 12 GeV proton synchrotron at KEK directed at the SuperKamiokande detector some 250 km distant. K2K has produced evidence for ν_μ oscillations with parameters consistent with the atmospheric neutrino oscillation data. This is a “state of the art” conventional neutrino beam. The LSND result is controversial, and should be either confirmed (which would be a major discovery) or refuted by the MiniBooNE experiment [5] underway at Fermilab. Both are conventional horn-focussed neutrino beams.

A new neutrino beam (NuMI – Neutrinos at the Main Injector) is under construction at Fermilab, which should receive its first beam later this year [6]. This is a conventional design, with two magnetic horns which can, by reconfiguring geometrically, produce beams of neutrinos with different peak energies. This is the first high-power (0.3 MW) neutrino beam, and represents a very significant increase in beam power. This is essential because the baseline is 735 km. Even though the target mass is only about 20% of that of K2K, the event rate in MINOS is about 30 times that of K2K. The principal physics goals of MINOS are a precision measurement of the atmospheric (ν_μ or “23”) oscillation parameters, and to improve the limits on (or make a measurement of) θ_{13}.

The “CERN to Gran Sasso” (CNGS) beam is also a conventional neutrino beam which, unlike the K2K and NUMI beams, is at a relatively high energy (above the threshold for production of ν_τ). This will start commissioning in 2006. The main objective is to demonstrate $\nu_\mu \rightarrow \nu_\tau$ appearance.

THE “OFF-AXIS” TRICK

So far, neutrino beams have been “on-axis”; this gives the highest flux of neutrinos, but inevitably has a broad momentum spectrum, with a long high energy tail, even for the so-called “narrow-band beams”. However, essentially because of the small Q-value in π-decay, the neutrino energy spectrum at small (few degrees) angles to the direction of the proton beam [7] has a narrower momentum spread, smaller high energy tail and (perhaps more surprisingly) higher flux at the peak energy, than the on-axis beam (see Figure 1).

The "Tokai to Kamiokande" (T2K) experiment [8] now under construction at the new Japan Proton Accelerator Research Complex (J-PARC) uses this feature, combined with a high-energy (50 GeV), high power (0.75 MW, upgradeable to 4 MW) proton beam to produce the first neutrino long-baseline (295 km) super-(conventional)-beam, with the principal objective of measuring θ_{13}. Because the initial proton energy is well above the kaon production threshold, it will be important to *measure* the flavour composition of the beam reasonably close (~2km) to the production target.

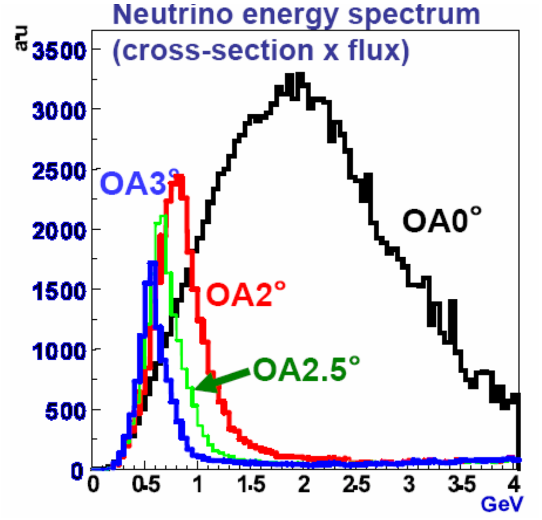

Figure 1: The "Off-axis" trick (from [8]).

Of course, any existing neutrino beam can exoploit the off-axis trick, and there are ideas for exploiting this technique for both the NuMI and CNGS beams. There is, however, a catch; the high power neutrino beams have very stringent requirements on the proton beam loss, and it is not easy (!) to steer the primary proton beam off axis. The T2K beam is *designed* to be off axis, but for the NuMI and CNGS beams, it is necessary to construct a new *detector* off-axis. A new collaboration has proposed the *NuMI Off-Axis* ν_e *Appearance (NO*ν_e*A)* experiment. Similarly, there is a developing proposal to utilise the CNGS neutrino beam off-axis, which means in practice using a large underwater detector in the Gulf of Taranto; the detector technology is challenging. Again, the principle objective of these experiments is $\nu_\mu \rightarrow \nu_e$ appearance, to measure or further constrain θ_{13}.

NEUTRINO "SUPERBEAMS"

There is no universally agreed definition of a neutrino superbeam, but perhaps a working definition is that it is a conventional horn-focussed neutrino beam with a proton power of a megawatt or more. The physics reach of such beams was originally studied to see whether they were suitable as an alternative to a neutrino factory at lower cost – the proton driver, target and pion/muon collection and decay being essentially the front-end of a neutrino factory.

Because these are obtained from conventional (if high power) targets, they are predominantly muon neutrinos, with a very small contamination at low energy (below the kaon production threshold) of electron neutrinos. Originally, the proton drivers were designed as rapid cycling proton synchrotrons [9], which allows a wide range of proton driver energies (from 2 GeV to more than 20 GeV) to be used. More recently, it has been realised that, with the advent of high-gradient superconducting cavities, it is possible to use superconducting proton linacs. CERN has proposed a 4 MW 2.2 GeV Superconducting Proton Linac (SPL) [10] as part of an upgrade, part of which could be used to create a low energy neutrino beam directed towards a new underground laboratory being considered at Frejus. More recently, Fermilab has considered [11] a 2 MW 8 GeV Superconducting Proton Linac (the Proton Driver), using TESLA cavities, as a replacement for the Booster, which could also drive a high-intensity neutrino beam. Both of these would be multi-function high power proton sources, with the neutrino beam being just one option. These are very attractive machines that could provide a flexible neutrino source. When combined with other experiments, such beams could provide better information on θ_{13} and (through the matter effects in the longer baselines) determine the sign of Δm^2_{23}. With a suitably large detector (say, a megaton water-Cherenkov detector), it might also be possible to observe CP-violation (if the phase δ is very large) through comparison of the appearance rates for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. The main technical challenges concern the design and construction of the high-power targets that are required.

"BETA BEAMS"

So far, all of the neutrino beams have been derived primarily from the decay of pions, and so are predominantly muon neutrinos (or antineutrinos, depending upon the polarity of the focussing horn). The electron neutrinos form a contamination or background that must be evaluated. Apart from reactors, which provide large fluxes of low energy electron antineutrinos, there have been no experimental sources of *high energy* electron neutrinos or antineutrinos. However, recent advances in radioactive ion beams mean that it is now possible to consider accelerating such ions to high energy, and so produce beams of pure electron neutrinos or antineutrinos [12].

There are a number of suitable β^- and β^+ emitters, with lifetimes of order 1 second [13], of which ^{6}He and ^{18}Ne seem suitable. These can then be accelerated to high energy, and stored in a ring with long straight sections pointing to a suitable distant detector. One option that has been extensively studied (see Figure 2) builds upon the development of the CERN SPL and the EURISOL project, and uses the CERN PS and SPS to post-accelerate the ions. Ion production rates of 2×10^{13}/s (^{6}He) and 8×10^{11}/s (^{18}Ne) are feasible [14].

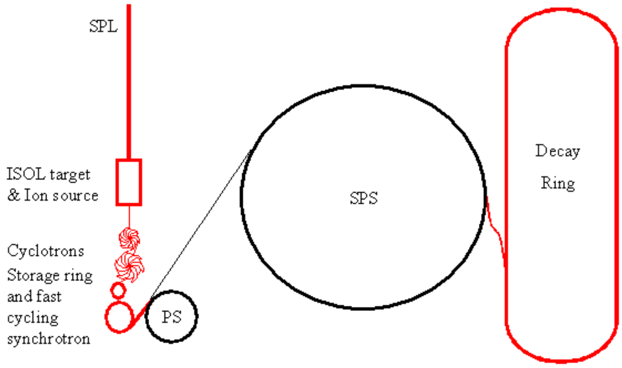

Figure 2: The CERN Beta Beam [14] with EURISOL.

It is possible to store both ^{6}He and ^{18}Ne concurrently in the same ring, provided that the ratio of the relativistic factors is given by equation (4).

$$\frac{\gamma_{Neon}}{\gamma_{Helium}} = \frac{A_{Helium}}{A_{Neon}} \times \frac{q_{neon}}{q_{Helium}} \cong 1.67 \qquad (4)$$

The SPS can currently accelerate ions up to a γ of about 150, which implies (given the Q-value of the decays) that the mean energy of the neutrino beam is about 600 MeV (^{6}He) and 1 GeV (^{18}Ne), comfortably above the muon production threshold. To get above the τ production threshold would require acceleration in something like the LHC (γ>1000).

While this is a beautiful concept, there are a number of significant technological problems to be solved before it can be realised.

THE NEUTRINO FACTORY

The basic idea of the neutrino factory is very simple [15] – the neutrinos come from the decay of muons in a long straight section of a storage ring, directed to a detector hundreds or thousands of kilometres away. This gives simultaneously beams of muon neutrinos and electron antineutrinos (or muon antineutrinos and electron neutrinos) of roughly equal and well-known intensity and spectrum and no background from other neutrino favours. The principal features of a neutrino factory are shown in Figure 3. A suitably shaped and inclined muon storage ring could serve two detectors at different distances, adding significantly to the resolving power of the neutrino factory. For example, the optimum sensitivity to the CP-violating phase δ is 2000 km to 3000 km, where matter effects are significant. However, these can be resolved if there is a second detector at either a significantly shorter (< 1000 km) or greater (> 6000 km) distance.

While there are several different schemes for realising a neutrino factory, they all share the same basic features. There are also clear synergies with other uses of high power proton drivers and targets, such as spallation sources, neutrino superbeams, radioactive beams, accelerator transmutation of nuclear waste etc.

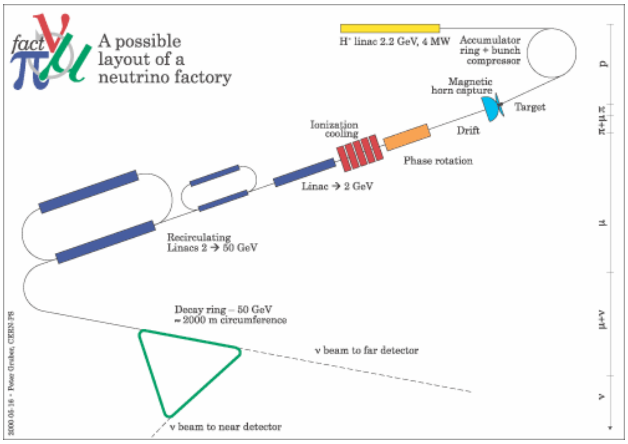

Figure 3: Schematic layout of a Neutrino Factory.

A crucial parameter that drives the design of the neutrino factory is the muon lifetime of 2.2 μsec, which imposes very significant demands upon the RF systems, although time dilation helps (at 400 MeV, the lifetime is already ~10 μsec, and at 20 GeV it is nearly 0.5msec).

A Multi-MW Proton Driver

There are several other applications for high power proton drivers, but the particular feature for the neutrino factory is the very short (~1 nsec) bunch structure that is required. The final stage of the proton driver is then an accumulator/compressor ring, which may be fed by either a high-energy linac or a series of rapid-cycling synchrotrons. Critical to the design is the choice of the proton energy. The pion yield within the acceptance of the capture system is fairly flat as a function of energy, and so the optimum is likely to be a compromise between the cost and complexity of the proton driver (which points to a lower energy) and that of the target (which may be somewhat easier at a higher energy).

Target and Pion Capture

Multi-MW targets are a new domain. There are a number of designs, but there are basically two options – liquid metal (mercury) and cooled solid metal. There is a need for greater theoretical understanding, and empirical work, on the behaviour of materials under extreme shock. There have been some studies of the impact of high intensity proton bunches on liquid mercury, and on the behaviour of liquid mercury jets in magnetic fields, and some studies on the resilience of metals under shocks similar to those of a neutrino factory target. Solid target configurations include radiation cooled rotating rings and liquid cooled metal beads.

The pions (and early decay muons) are widely distributed in angle and energy, and need to be collected, focussed, and sign-selected. There are two basic schemes – magnetic horns and large open solenoids. In practice, the geometry for both is highly constrained, and is intimately related to the target design.

After the production target and preliminary focussing, there are two broad lines of development. The first approach uses a variety of techniques to reduce the phase space spread of the resultant muon beam (cooling) before acceleration to the final energy in conventional (but demanding) accelerating sections. The second approach uses a cascade of Fixed Field Alternating Gradient (FFAG) rings to accommodate the large initial acceptance of the beam. There are also schemes that mix these two approaches. The first scheme is described detail below.

Decay, Phase Rotation and Cooling

The pions are allowed to decay downstream of the target, after which they are phase rotated to reduce the energy dispersion by decelerating the early (higher energy) muons and accelerating the later (lower energy) muons. At the end of the phase rotation, the peak of the muon energy distribution is around 200 MeV, with a dispersion of ±10%. However, the emittance is still too large for conventional acceleration to the final energy (10-50 GeV), although this would be acceptable for a FFAG-based machine. Most designs therefore include a cooling section to compress still further the emittance of the beam. Conventional cooling techniques are too slow. Ionisation cooling, in which energy lost through ionisation is replaced longitudinally through RF acceleration, is sufficiently fast to be appropriate. However, there is also a heating term coming from the multiple scattering, so that the performance of a cooling channel is critically dependent upon the delicate balance between these two. While ionisation cooling clearly works, it is essential that the *efficiency* of ionisation cooling is shown to be understood, and so a Muon Ionisation Cooling Experiment (MICE) is proposed [16] to test these ideas. This is critical to the neutrino factory design since there are a large number of cooling sections, and small differences between the calculated and actual performance of the cooling channel would have a serious effect on the performance of the neutrino factory.

Muon Acceleration and Storage Ring

There are two options, depending upon the amount of cooling – with modest cooling, an FFAG for both acceleration and storage might be attractive. However, with adequate cooling, the better option is probably one or more Recirculating Linacs (RLAs) and separate storage ring. The cost of the neutrino factory depends critically upon the final energy chosen for the storage ring. Because the neutrino cross-section increases linearly with energy in this range, and the scope for non-oscillation physics at detectors close to the storage ring is much greater, a higher energy (~50 GeV) might be preferred, although this adds significantly to the cost compared with a stored muon energy of, say, 20 GeV.

The original configuration for the muon storage ring was a simple inclined “racetrack” design. By using an inclined triangular shape, it is possible to direct beams to detectors at two very different baselines, although this means that the storage ring is inclined at angles between 20° and 70°.

With such a facility, it is possible (in principle) to study the disappearance through oscillation of both electron and muon neutrinos and antineutrinos, and the appearance of electron (muon) and tau neutrinos in muon (electron) neutrino and antineutrino beams, providing the most complete set of measurements of the neutrino oscillations. There will also be an enormous range of conventional neutrino and muon physics possible at such a facility.

SUMMARY

The experimental observation of neutrino oscillations has provided the first clear evidence for physics “Beyond the Standard Model”, and has stimulated an exciting search for new ways of creating very high intensity, high purity, high energy, low background neutrino beams. There is a large and active community of accelerator and particle physicists working in this field, whose dedication and work I acknowledge.

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