REQUIREMENTS FOR ACCELERATOR-BASED NEUTRINO FACILITIES

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Abstract

The study of neutrino oscillations offers promises of great discoveries including leptonic CP violation. The experimental programs that are under discussion pose considerable challenges to accelerator builders. Extremely high intensities are needed for classical on- and off-axis pion decay beams; novel ideas such as beta-beams and muon decay beams have been invented and are being studied. The experiments to be performed require outstanding predictability and monitoring of the neutrino flux. The challenges are reviewed and a list of requirements is proposed.

INTRODUCTION

The discovery of neutrino oscillations implies that they have mass and mix and constitutes the first experimental evidence for new physics beyond the standard model. The conceptual consequences are fascinating, with the possibility that the dominance of matter over anti-matter in the universe is finally explained. The experimental consequences are just as exciting with a new set of fundamental parameters (the mixing matrix and hierarchy of masses, **Figure 1**) to be measured precisely and the prospect for discovery of fermion number violation and leptonic CP violation. The latter definitely requires precise measurements with accelerator based neutrino beams. The accelerator requirements of this new programme of experiments are considerable. More details on this subject can be found in [1], and [2].

NEUTRINO OSCILLATIONS

The best process to search for CP violation is the $\nu_e \rightarrow \nu_\mu$ oscillation, and its charge or time conjugates. The transition probability is illustrated in **Figure 2**. One can see that it is dominated by two oscillations: i) the well known 'solar' oscillation with a large amplitude and a first maximum at a distance given by $\sin^2(1.27\Delta m^2_{12}\ L/E)=\pi/2$, ($\Delta m_2$ in eV_2, L in km, E in GeV) i.e. L/E~16000 km/GeV, ii)on top of this, the 'atmospheric' oscillation, driven by the unknown but small angle θ_{13}, at a value of L/E=500km/GeV. CP violation, by interference of the two oscillations, is maximal around the first atmospheric maximum, which is where the energy weighted flux should be maximized. Neglecting matter effects, the CP or T asymmetry reads:

$$A_{CP} = \frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \approx A_T = \frac{P(\nu_e \to \nu_\mu) - P(\nu_\mu \to \nu_e)}{P(\nu_e \to \nu_\mu) + P(\nu_\mu \to \nu_e)}$$
$$\approx \frac{\sin\delta\ \sin\vartheta_{13} \sin(\Delta m^2_{12}\ L/4E)\ \sin\vartheta_{12}}{\sin^2\vartheta_{13} + \textbf{solar term}} + \ldots$$

The facility must therefore provide both ν_e and either anti-ν_e or ν_μ, or both, in conditions which allow a precise comparison of the two. Since anti-neutrinos have a cross-section which is about half to a third of that of neutrinos, efficient production of antineutrinos is necessary. An alternative way to measure the CP effect is precisely measure the difference of the appearance probability between the first and second maxima.

The other facts to consider are: i) neutrino cross-section grows linearly with energy; ii) the small oscillation probability requires a pure and well-defined beam.

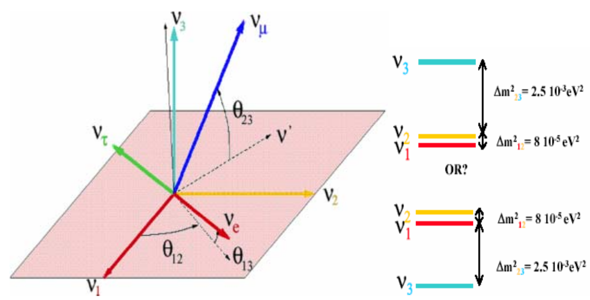

Figure 1: Left: present knowledge of the neutrino mixing matrix. The best values are, for the angles $\theta_{12}=32^0$, $\theta_{23}=45^0$, $\theta_{13}<13^0$, and for the masses $\Delta m^2_{12}=+8\ 10^{-5}\ eV^2$, $\Delta m^2_{23}=\pm 2.5\ eV^2$. The unknown phase δ would, if non-vanishing, generate CP and T violation in neutrino oscillations; right: the neutrino mass hierarchy could be different from that of charged leptons.

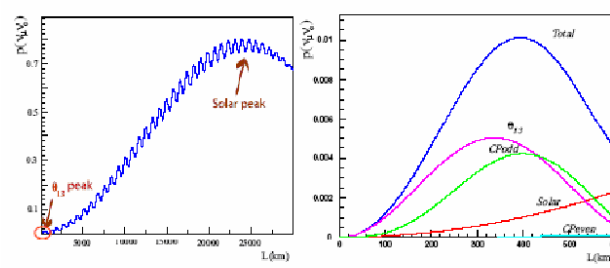

Figure 2: Description of neutrino oscillations for 1 GeVneutrinos as a function of distance to the source. The oscillation parameters are $\sin^2 2\theta_{13} = 0.01$, $\delta = 0$ for the left plot, $\delta = -\pi/2$ for the one on the righ, which shows the CP violating terms at the first oscillation.

NEUTRINO FACILITIES

The facilities considered for CP violation studies are: a conventional superbeam $\pi \rightarrow \mu\nu_\mu$ of the right energy, aimed at large detector(s) (e.g. T2HK, T2KK, NOvA) Figure 3;ii) a Beta-Beam combined with a Superbeam aimed at a Megaton detector (SB+BB+MD)

Fréjus) Figure 4. iii) a Neutrino Factory + magnetic detector(s) situated at a farther distance, Figure 5.

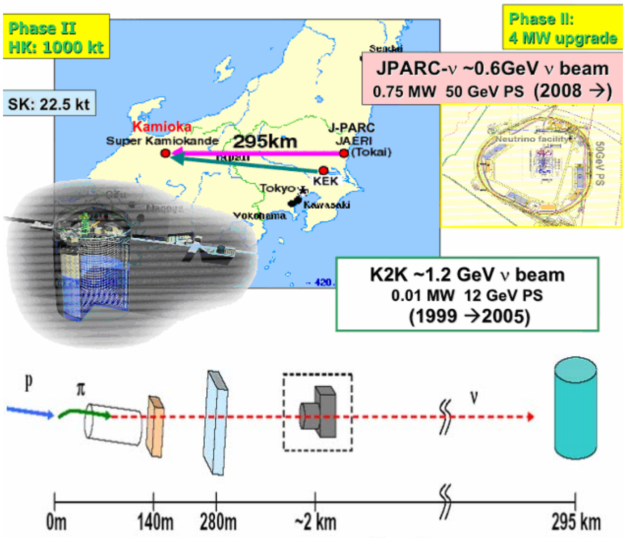

Figure 3: Top: Overview of the J-PARC to SuperKamiokande long baseline experiment foreseen from 2009. Bottom: Schematic description of the detectors along the T2K beam line.

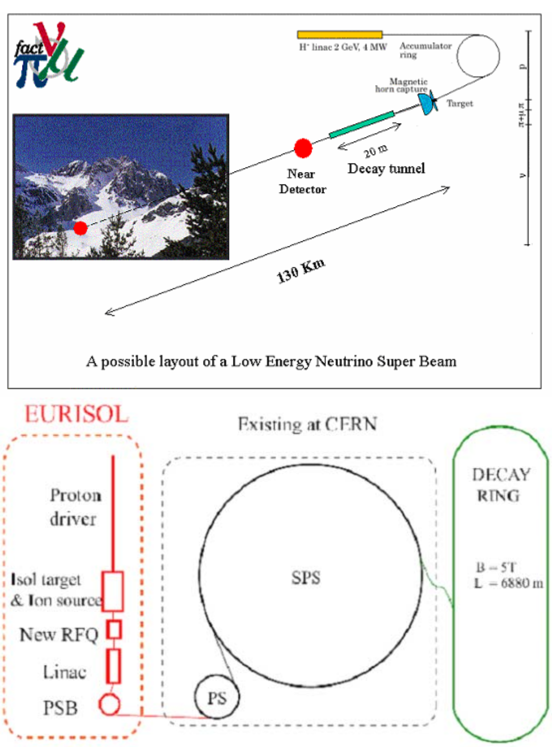

Figure 4: the CERN to Frejus complex: top: the superbeam; bottom: possible implementation of the beta beam concept on the CERN site.

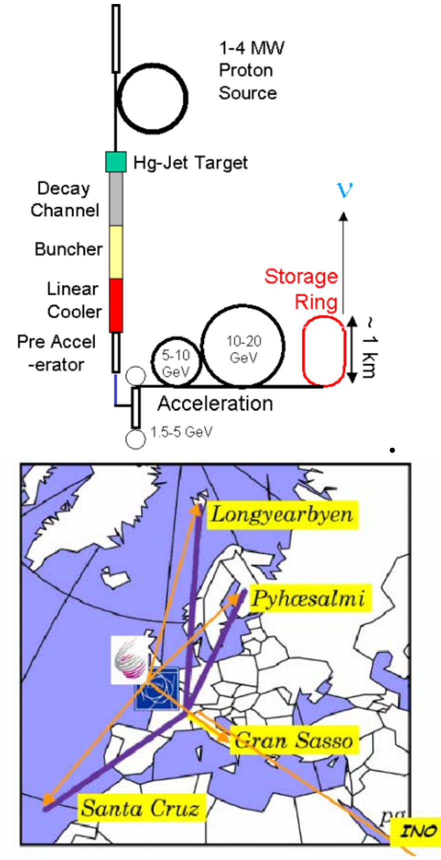

Figure 5 Top: the neutrino factory accelerator complex; bottom: possible beam lines in Europe.

EXPERIMENTAL CONSTRAINTS

The first and foremost requirement by experiments is *to provide the largest possible flux at the lowest possible cost*. This exercise being performed, the limitations on flux will originate from the maximum power that can be delivered on a target. Once the maximum flux of a given facility is established, a physics sensitivity estimate can be studied taking into account the feasibility of large mass detectors. The final comparison has to take into account the feasibility and cost and nthe estimated R&D effort left on each facility. This delicate investigation will require a very vigorous programme of R&D, to be defined for instance in the context of the ongoing scoping study [3].

The other experimental constraints are as follows:

1. Requirements on the neutrino beam energy and resulting constraints on the primary proton beam energy
2. Constraints on the time structure of the neutrino beam
3. Constraints resulting from the requirement of precise knowledge of the flux

The neutrino beam energy needs to satisfy L/E~500km/GeV for a first maximum experiment, and three times this for a second maximum experiment. The neutrino beam line has a dip angle of $\sin\lambda = L/2R_{earth}$, a possible challenge.

For a conventional *on-axis* pion decay beam, the energy is 5-10% of the primary proton beam energy. This can be modified by moving the location and current in the horns, as in the case of the NUMI beam. The *off-axis* beam technique, as in the case of T2K provides a reduced, but more monochromatic flux, at an energy which is given by the off-axis angle: $\mathbf{E}_\nu = \dfrac{\mathbf{m}_\pi^2 - \mathbf{m}_\mu^2}{2(\mathbf{E}_\pi - \mathbf{p}_\pi \cos\boldsymbol{\theta})}$

The high energy tail and the contamination of beam by ν_es from kaon and muon decay are is a problem. This can be cured with a low parent proton beam energy, where kaon production is suppressed.

The Beta-beam gives a typical beta spectrum (**Figure 6**) with an end point $E_{max} = 2\ \gamma E_0$ with E_0~2.6 MeV. At CERN- SPS the maximum for ^{6}He is γ=150. When comparing $\nu_\mu \rightarrow \nu_e$ to $\nu_e \rightarrow \nu_\mu$ one must know flux and cross-section for both appearance channels. The superbeam and betabeam energies should be as similar as possible, **Figure 6** shows the CERN case. Both superbeam and beta-beam will produce neutrino beams in the range of 0.25 to ~1.5 GeV.

The neutrino factory uses $\mu^+ \rightarrow \mathbf{e}^+ \nu_\mathbf{e} \bar{\nu}_\mu$ leading to a similar spectrum but with a maximum neutrino energy equal to that of the muons. It is thus the only high energy future facility under consideration. This allows uniquely the detection of tau neutrinos. For the longest baseline considered, 7000 km from Europe to US or India, the first maximum is at 14 GeV, thus a muon energy above 20 GeV does not seem necessary unless $\sin^2 2\theta_{13}$ is <<10^{-4}..

The required time structure of the beam stems from the properties of neutrino detectors. To fight natural backgrounds the smallest possible duty factor is desirable. For sub-GeV neutrinos a duty factor of <10^{-3} is required. For the neutrino factory, events have no natural background and this requirement does not apply. If one wishes to run simultaneously two different neutrino parents (betabeam and superbeam, or ^{6}He and ^{18}Ne, or $\mu^+$and μ^- simultaneously) the arrival times in the neutrino detectors should be such that they can be separated unambiguously, i.e. Δt >~100ns.

Flux monitoring and alignment. The need to monitor the beam leads to requirements on the near detectors and instrumentation and alignment.

For the pion superbeam, knowledge of the absolute flux requires a pion production measurement such as HARP, or MIPP or the NA49/T2K experiment). To achieve an absolute precision of 1% on the neutrino flux requires detailed angular and momentum distributions. The measurement of neutrino cross-sections requires a dedicated near detector experiment situated at a distance sufficient to assure that the geometrical effects due to the decay tunnel length are under control (a few times the decay tunnel length). Alignment has to be provided for the beam at the level of 0.1-0.3 mrad; this latter requirement is more stringent for the off-axis beam.

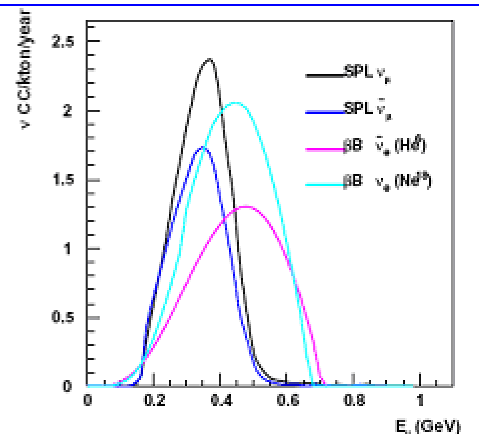

Figure 6 Beta spectrum compared to that of superbeam in the CERN-Fréjus scheme.

The situation is more better for the neutrinos produced by stored beams of ions or muons. The decay spectrum is very well known; the parameters to measure are

- The parent beam energy and energy spread
- The parent beam angular divergence
- The parent beam intensity.

This analysis was performed in [2] for the neutrino factory.

A key element in the muon storage ring is the possibility to observe the spin precession of muons. The energy and energy spread of the beam can thus be determined. The parent beam divergence needs to be determined by a dedicated beam monitor.

The angular divergence should be smaller than $0.1/\gamma$ where γ is E/m of the muons not to reduce the beam intensity by more than about 5%. It should be measured with a precision of 10% of its value. A ring-imaging He Cherenkov has been considered, although questions were raised concerning the feasibility.

If these conditions can be achieved a precision of 10^{-3} on the neutrino flux should be achievable. The beta beam does not offer direct energy calibration, but is otherwise similar; a flux uncertainty of 0.5% should be achievable.

CONCLUSIONS

The facilities considered to discover and study CP violation in neutrino oscillation are extremely challenging, mostly from the point of view of delivering the maximum possible flux of a pure flavour of neutrinos. The requirements on alignment, beam divergence and monitoring are hard work but reasonably straightforward.

REFERENCES

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