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ACCELERATOR-BASED NEUTRINO BEAMS

K. Hübner

Abstract

The design principles of accelerator-based neutrino beams are outlined and the beams currently in operation or under construction are briefly described. The concepts and basic features of the different types of advanced neutrino beams which are under study are summarized.

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The design principles of accelerator-based neutrino beams are outlined and the beams currently in operation or under construction are briefly described. The concepts and basic features of the different types of advanced neutrino beams which are under study are summarized.

1 INTRODUCTION

A significant effort has been made in the past by the major accelerator laboratories (BNL, CERN, FNAL, KEK, LANL, and RAL) to provide high-energy neutrino beams for particle physics experiments [1]. At present, KEK operates one of these beams for the K2K experiment [2] and the new experiment MiniBooNE [3] will start in mid-summer of this year. Two new facilities are under construction: one at FNAL called NuMI [4] which will deliver the beam to the MINOS experiment [5] under construction in the Sudan mine in Minnesota; another one at CERN called CNGS [6] which will provide a beam for two experiments also under construction (OPERA and ICARUS) in the Gran Sasso Laboratory of INFN in Italy [7]. The distance between the source and the detector is about 250 km in the case of K2K, 0.5 km for MiniBooNE, and 730 km for OPERA and ICARUS.

In addition, a continuing major effort is being made in all three regions to study and design advanced neutrino beams: one approach is to push existing technology to its limits which results in the so-called “superbeams” [8,9]. The other approach uses new concepts based on the decay of unstable particles in a storage ring, the so-called “neutrino factories” [10,11,12].

This paper briefly summarizes the physics motivation [see 13,14]; describes the principle of a conventional facility, summarizes the ideas on superbeams and outlines the basic concepts of a neutrino factory.

2 PHYSICS MOTIVATION

There is strong evidence for neutrino flavor oscillations, e.g. ν_μ neutrinos created in the atmosphere by cosmic rays get transformed into ν_τ neutrinos, and ν_e neutrinos produced in the sun transform into ν_μ neutrinos. The experiments providing evidence for these phenomena use large detectors, deep underground in order to reduce the background by cosmic rays. Also experiments observing the anti- ν_e flux from nuclear power stations have significantly contributed to constrain the parameter space in which the oscillations might occur.

Experiments with ν_μ beams produced at accelerators have contributed with supplemental information either by constraining as null experiments the parameters or providing evidence for oscillations (LNSD [15] at LANL and K2K at KEK). These experiments are either conceived as appearance experiments, i.e. the aim is to detect neutrinos of a different flavour at the detector than the neutrinos which are sent to the detector; or they are disappearances experiments, i.e. the flux at the far-detector is compared to the flux at the near-detector with high precision. LNSD, MiniBooNE and OPERA belong to the first group; K2K belongs to the second group; ICARUS and MINOS will attempt to do both. Since it is difficult to reconcile the results of LNSD with the current hypothesis, the experiment will be repeated by MiniBooNE with better sensitivity. The results of K2K are in agreement with the evidence from cosmic ray experiments and fit quite well into the overall picture.

The main issues and open questions which have to be answered in order to discriminate between the various hypotheses are:

- Find the proof that neutrinos oscillate and change flavour, find $\nu_\mu \rightarrow \nu_\tau$ or ν_e;
- Does a sterile neutrino exist?
- Find the mixing angles in case each neutrino is composed of a linear combination of three eigenstates (three parameters);
- Find the parameters determining the mass hierarchy (two parameters);
- Do neutrino interactions violate charge-parity (CP) invariance and, if yes, what is the value of the parameter being the measure of this violation (CP phase)?

Thus, in total six parameters can be determined or constrained in oscillation experiments (3 mixing angles, 2 parameters of the mass hierarchy, CP-violation phase). Note that only the mass differences between the neutrinos can be found by these experiments. The absolute offset needs high-resolution β-decay experiments. The sensitivity of the experiments to the mass differences between the neutrinos depends on the ratio L/E_ν where L is the distance between neutrino source and detector, and E_ν is the neutrino energy. Large L and small E_ν allow to explore the parameter space where the mass differences are small. The intensity of the neutrino beam and its purity determine the sensitivity to small mixing angles.

3 FUTURE EXPERIMENTS AND FACILITIES

3.1 Medium Term

All the experiments in operation and those planned for the medium-term future use ν_μ beams generated from pion, respectively kaon decay. A typical decay pattern is e.g.

$$\begin{array}{ll} p + \text{target} \rightarrow \pi^{+} \rightarrow \mu^{+}, \nu_\mu & \\ \qquad\qquad\qquad\quad \downarrow & \\ \qquad\qquad\qquad\quad \rightarrow e^{+}\ \overline{\nu_\mu}\ \nu_e & \end{array} \tag{1}$$

The π and K are produced by high-energy protons hitting a metal or carbon target. In order to maximize the ν_μ flux, the π and K are focused in the direction of the detector and a vacuum tube with a length of the order of the decay length after the focusing elements minimizes the losses.

Note that the neutrinos from the μ decay and the three-body K decays create background in the experiments. The μ has a much longer lifetime than the π and, therefore, most of the μ are absorbed in the hadron stop and the soil. Since these background neutrinos stem from a three-body decay, they have a large divergence which further reduces this background. The negative secondary particles which are also produced in the target produce the charge conjugate tertiary particles, in particular the anti- ν_μ. The latter contribute also to the background though they have a large divergence as their parent particles (π^- and K^-) are defocused. In total, the background flux is typically around a few percent of the ν_μ flux. Note that this type of background is inherent in this type of the beam and cannot be completely suppressed, though this would be very desirable e.g. in the appearance experiments $\nu_\mu \rightarrow \nu_e$.

All the experiments use existing accelerators with the exception of nu-JHF [16] which will use the accelerator chain of the Japan Hadron Facility (JHF) under construction [17]. They are all approved except nu-JHF which has been formally proposed and hopefully will be approved this year. If MiniBooNE detects a ν_μ to ν_e oscillation in the parameter space where it is sensitive and, therefore, confirms the result of LNSD, which could only partially be excluded by Karmen at RAL [15], a second detector will be built, i.e. the full Boone.

3.2 Long Term

In the long term one considers increasing the physics reach by either upgrading both the existing facilities and detectors, or by constructing new more powerful facilities and/or more sensitive detectors. In particular, one would like to find the oscillation $\nu_\mu \rightarrow \nu_e$ and measure the parameters more precisely. The process used to create the required ν_μ beams would be the same as in the present facilities but the proton drivers should reach beam power in the MW range. This is the reason why these beams are called "superbeams".

An even more challenging idea is to possibly find CP-violation in the lepton sector by comparing the former process with anti-ν_μ $\rightarrow$ anti-ν_e This would require switching the polarity of the secondary particle focusing in order to collect e.g. π^- instead of π^+. Since the antineutrino cross-sections are about half those of the neutrino and less π^- are produced per proton than π^+, the run with negative polarity will be three times longer than the run with positive polarity. Typical running times under discussion are 2 years followed by 6 years with inverted polarity.

In order to increase the sensitivity it may be necessary to increase the distance from source to detector depending on the energy of the neutrino beam. Base lines of about 3000 to 4000 km have been considered. This implies a strong inclination of the beam line and, consequently, much more complicated civil engineering and installation.

i) Facilities for which an upgrading has been studied comprise nu-JHF, CNGS and NuMI.

A number of options for upgrading JHF have been studied [18]. The injected beam power could be increased by raising the injection energy of the booster which requires an extension of the linac to reach 0.6 or 1 GeV compared to the present 0.4 GeV. A further measure is the later replacement of the booster, a 3 GeV (25 Hz) Rapid-Cycling Synchrotron (RCS) which is under construction. In phase II, it could be replaced by either two to three 1 GeV (50 Hz) RCS or two 4 GeV (25 Hz) RCS. This would result in a beam power of 4 to 5 MW of the 50 GeV synchrotron compared to the presently planned 1 MW and a concurrent increase of the neutrino fluxes.

At FNAL, the intensity of the 120 GeV Main Injector (MI) could be increased by a factor four to 1.6 MW with a new booster and some upgrades in MI itself to provide a superbeam (SnuMI) [9]. A further step in the beam power could be achieved by raising the proton linac energy from 0.4 to 1 GeV and constructing a 16 GeV booster replacing the present 8 GeV booster [8].

A more modest increase of about a factor 1.5 to 1.8 in intensity per pulse of the PS and SPS has been studied at CERN for CNGS [19]. The factor 1.5 may be reached with double–batch injection into the PS from the PS-Booster and a new, less lossy ejection from the PS; the higher factor requires a new linac of about 120 MeV replacing the present 50 MeV linac in order to overcome the space charge limit at PS injection.

Also the use of off-axis neutrinos has been considered for NuMI and CNGS as a future option [20]. The off-axis neutrino beams are of interest in case intense low-energy beams are required, e.g. for $\nu_\mu \rightarrow \nu_e$ searches. The high-intensity at small angles relative to the direction of the parent π is a peculiarity of the $\pi \rightarrow \nu$ kinematics relating E_ν to the decay angle in the laboratory frame. Of course, this set-up also requires new detector positions. Such a beam is foreseen for nu-JHF from the beginning [16].

ii) New facilities providing superbeams are also being considered: a facility at CERN based on a superconducting linac and one at BNL using an upgraded AGS.

At CERN, a 2.2 GeV superconducting linac (SPL) [21] feeding an accumulator and a combiner ring is under study for a neutrino factory [22]. It was soon realized [23] that this proton driver providing 4 MW on the target could produce a very intense, conventional low-energy ν_μ beam for an experiment located about 100 km from the source [24]. It is proposed that the linac reuse LEP rf components to reduce the investment cost. SPL feeds an accumulation ring located in the ISR tunnel with H-minus. The ions are stripped by a foil at injection into the accumulation ring and many linac pulses are accumulated by using multi-turn injection before the proton beam is transferred to the compressor ring also housed in the ISR tunnel where the bunch length is reduced to about 3 ns. Since the proton energy is only 2.2 GeV, i.e. below the K production threshold, the ν_e contamination in the beam is much reduced, which is welcome for the $\nu_\mu \rightarrow \nu_e$ search. A further advantage of this proposal is the low duty cycle of the source (2.5×10^{-4}) due to the compression of the proton bunches, which makes atmospheric backgrounds negligible for the detector. However, at present, the estimate of the neutrino flux is hampered by the very limited knowledge of the proton cross-sections at these low energies (up to 50% systematic errors). The HARP experiment [25] at the CERN PS taking data in 2001 and 2002 will hopefully clarify this issue and establish whether SPL is a viable proposition for neutrino research.

A programme of experiments [26] has been proposed at BNL which is based on the AGS as a proton driver and which would involve a detector somewhere between 350 km and 2500 km from BNL. The upgrade plan of the AGS would raise the beam power from the present 0.14 MW at 24 GeV up to 1.3 MW at 28 GeV. The first step provides 0.54 MW by increasing the linac energy from 200 MeV to 400 MeV, the booster energy from 1.8 GeV to 2.5 GeV, the repetition rate of the AGS from 0.6 Hz to 1.0 Hz, and adding an 2.5 GeV accumulation ring in the AGS tunnel fed by the booster. The repetition frequency of AGS is further increased to 2.5 Hz in phase II, resulting in a beam power of 1.3 MW. Since the beam line must be above the water table (which is at about 20 m below surface), it will be constructed on a hill built with the appropriate slope (up to 13 degrees).

3.3 Longer Term

In order to push the sensitivity to the parameters of the mixing matrix, establish the mass hierarchy, and, possibly, measure the CP violation parameters with some precision, a more powerful facility is needed producing high intensity and, possibly, high-energy neutrino beams of great purity and detectors of larger mass with higher resolution are required. Two methods have been conceived to obtain such advanced beams:

i) store μ of 20 to 50 GeV in a storage ring and use the neutrinos resulting from the μ decaying according to (1). The μ are generated from π respectively K using the same process. Thus, the necessary ingredients for such a facility are a proton driver with a beam power in the MW range; a target standing the thermal shocks; a short decay channel; a μ capture section followed by a chain of accelerators. The latter have to accelerate the μ as fast as possible in order to minimize the μ loss by decay. Muons have a limited lifetime as the decay length is only $0.66\,\gamma\,\mathrm{km}$ where γ is their Lorentz factor. Only the neutrinos resulting from the μ decaying in the straight sections of the storage ring are useful to the experiments. Therefore, the ratio of straight section length to circumference is maximized by using superconducting bending magnets in order to reduce the total length of the arcs. Since the typical baselines to the detectors are between 1000 to 3000 km, the whole ring has to be tilted between about 6 to 13 degrees. The rings have either a racetrack shape for serving one detector or a bow-tie shape in the case where two beams are aimed at two different detectors. The unique feature of these facilities is that they can provide ν_e and anti- ν_μ beams (or anti- ν_e and ν_μ if μ^- are captured) of high purity whose divergence is only $1/\gamma_\mu$, given by the decay kinematics.

Facilities of this type [10,11] have been studied for FNAL [27], at CERN with the SPL as proton driver [22], in Japan with JHF Phase II as driver [28], and for BNL [29]. Layouts for a neutrino factory at RAL [30] have been studied with an upgraded ISIS at proton drive [31]. All studies except for JHF consider ionisation cooling to increase the transverse phase space density of the μ beam; the approach for JHF uses FFAG accelerators for the μ beam which have the unique feature of a very large aperture and momentum acceptance so that no cooling is required.

ii) the second method to produce a well collimated neutrino beam is to produce, accelerate and store radioactive beta-emitter ions in a storage ring. The neutrinos created in the decays have a typical angle of $1/\gamma_{\mathrm{parent}}$ which yields a beam with low divergence. Examples of suitable beta-emitters are ${}^6\mathrm{He}^{++} \rightarrow {}^6\mathrm{Li}^{+++}e^-$ anti-ν_e or ${}^{18}\,\mathrm{Ne} \rightarrow {}^{18}\,\mathrm{F}\ e^+\ \nu_e$ [12]. In a CERN study, the ions are produced in a target by protons of about 1 GeV by the so-called ISOL-process [32]. After proper mass separation and pre-acceleration, the ions are accelerated in PS and SPS to 150 GeV/n and decay in a new storage ring of about 2.5 km circumference. Since these ions have a lifetime of the order of 1 s at rest, the losses during acceleration can be limited. However, they would still produce a significant activation of the accelerators if the beam is not properly collimated. This method provides a rather low-energy neutrino beam which is important for long-baseline neutrino studies. It is not excluded that one large-mass detector could get served by two neutrino factories of the two different types.

4 CONCLUSIONS

The accelerator-based neutrino beams are an interesting challenge for accelerator physics and technology. The physics issues are high-proton beam power, short proton bunches, transverse emittance cooling and design of beam channels and accelerators with large admittance. The technology issues are the components of the proton drivers, targets standing the thermal shocks, magnets and rf in high radiation environment, absorbers and cavities for the transverse cooling, cavities with high gradients for fast acceleration and a number of operational issues such as reliability and maintenance. Since the field of neutrino physics will remain exciting, it is very likely that a significant part of the available resources in the large accelerator laboratories will remain assigned to these beams for quite some time as experiments in this field will need long running times due to the elusive nature of the neutrinos.

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6. ACKNOWLEDGEMENTS

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