PHYSICS LETTERS B

ELSEVIER

Physics Letters B 532 (2002) 166–172

www.elsevier.com/locate/npe

A novel concept for a $\bar{\nu}_e/\nu_e$ neutrino factory: the beta-beam

P. Zucchelli [1]

CERN, Geneva, Switzerland

Received 3 July 2001; received in revised form 8 February 2002; accepted 7 March 2002

Editor: L. Rolandi

Abstract

The evolution of neutrino physics demands new schemes to produce intense, collimated and pure neutrino beams. The current neutrino factory concept implies the production, collection, and storage of muons to produce beams of muon and electron neutrinos at equal intensities at the same time. Research and development addressing its feasibility are ongoing. In the current Letter, a new neutrino factory concept is proposed that could possibly achieve beams of high intensity, known energy spectrum and a single neutrino flavour (electron–antineutrino or electron–neutrino). The scheme relies on existing technology. © 2002 Elsevier Science B.V. All rights reserved.

1. Introduction

The demand for better neutrino beams is correlated with the considerable improvement in neutrino detectors, and to the recent exciting claims of evidence for neutrino oscillations by various experiments. In particular, solar, atmospheric and accelerator neutrinos appear today to oscillate (and therefore should have non-zero masses) in a way that it is hard to accommodate in a unique picture, given current theoretical understanding. Speculation and *ad-hoc* theories abound in the absence of decisive experiments. Obviously, a high intensity neutrino source of a single flavour, improved backgrounds and known energy spectrum and intensity could be decisive both for oscillation searches and precision measurement of the lepton mixing parameters.

2. The concept

It is proposed to produce a collimated $\bar{\nu}_e$ beam by accelerating, to high energy, radioactive ions that will decay through a beta process (the beta-beam).

Radioactive ion production and acceleration to low energy (several MeV) have already been performed for nuclear studies, and various techniques have been developed [1], e.g., at CERN ISOLDE.

Acceleration of the positively charged atoms to about 150 GeV/nucleon is already done in the CERN PS/SPS accelerators for the heavy-ion programme.

Storage of the radioactive ion bunches in a storage ring could be very similar, in principle, to what

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E-mail address: piero.zucchelli@cern.ch (P. Zucchelli).

[1] On Leave of Absence from INFN-Sezione di Ferrara.

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PII: S0370-2693(02)01576-9

is being studied for the muon-based neutrino factory scheme [2].

The resulting neutrino beam has three distinctive and novel features:

- a single neutrino flavour, essentially background-free;
- well-known energy spectrum and intensity;
- low energy combined with strong collimation, resulting from the low neutrino energy in the centre-of-mass system and the large Lorentz boost of the parent ions. This feature is particularly important for long-baseline neutrino studies.

2.1. Nuclear beta decays

As a guideline, a textbook atomic β^- decay which has well-known characteristics and good features for neutrino production is considered:

$${}^{6}_{2}\mathrm{He}^{++} \to {}^{6}_{3}\mathrm{Li}^{+++}\mathrm{e}^{-}\bar{\nu}_{\mathrm{e}}.$$

Its half-life $T_{1/2}$ is 0.8067 s and the Q value of the reaction is 3.5078 MeV [3]. These two quantities are, unfortunately, correlated by the 'Sargent rule' [4]. In substance, the width of the unstable initial state is proportional to the fifth power of the reaction energy, so that a low Q value implies an almost stable atom. For neutrino production and long-baseline studies, contemporaneous low value of Q and $T_{1/2}$ would be the best solution, in contradiction with nature. The energy spectrum of the electron produced in the ^{6}He beta decay has been extensively measured and is well described theoretically (without corrections due to the Coulomb attraction between the nucleus and the electron) by the simple analytic formula

$$N(E)\,\mathrm{d}E \approx E^2(E-Q)^2\,\mathrm{d}E,$$

where E is the electron kinetic energy. The neutrino spectrum is therefore completely known by the laboratory measurement of the associated electron (without involving a neutrino measurement) since $E_{\mathrm{e}} + E_{\nu} \approx Q$ because of the large mass of the nucleus. The average energy of the neutrino from ^{6}He decay is 1.937 MeV. The neutrino is isotropically emitted since the parent ion is spinless.

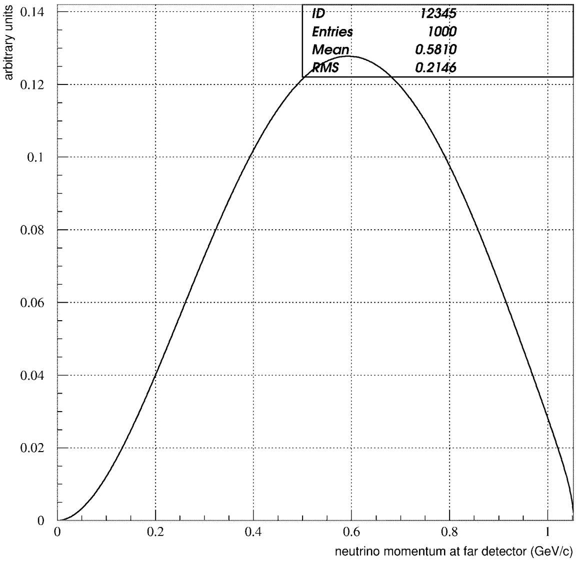

Fig. 1. 'Boosted' spectrum of the neutrinos at the far detector.

2.2. The relativistic effect

Suppose that the ^{6}He atom is accelerated up to a value of $\gamma = 150$, achieving a typical energy per nucleon currently obtained in the heavy-ion runs of the CERN SPS. In the laboratory frame, the neutrino transverse momentum (with respect to the beam axis) is identical to that observed when the atom is at rest: 1.937 MeV on average. In contrast, the average longitudinal momentum is multiplied by a factor corresponding to γ and therefore neutrinos have typical decay angles of $1/\gamma$, in our case 7 mrad. In the forward direction, the centre-of-mass neutrino energy is multiplied by the factor 2γ, so that the average neutrino energy on a 'far' detector is 581 MeV (Fig. 1).

As the lateral dimensions of the far detector are typically much smaller than $1/\gamma$ multiplied by the distance L, the neutrino spectrum has essentially no radial dependence. The neutrino flux per parent decay and unit area is obtained by a Lorentz transformation of the centre-of-mass distribution of neutrino emission into the laboratory system. For a value of $\gamma = 150$, the relative neutrino flux computed at distances above ≈ 1 km varies according to the $1/L^2$ scaling law, and at 100 km distance (corresponding to $\langle E\rangle/L = 5.9 \times 10^{-3}$ GeV/km) its value is $\Phi = 7.2 \times 10^{-7}\mathrm{m}^{-2}$. It is important to compare the focusing properties of a beta-beam with those of a muon-based neutrino factory beam. The comparison should be made for identical values of $\langle E\rangle/L$: if we choose arbitrarily the value $\langle E\rangle/L = 5.9 \times 10^{-3}$ GeV/km previously mentioned, the neutrino factory detector sits at 5750 km from the 50 GeV muon storage ring [2]. The relative flux of neutrinos reaching the far detector of the muon-based neutrino factory is $5.7 \times 10^{-9}/\mathrm{m}^2$, 128 times less than in a beta-beam. After this, it has to be said that the relative neutrino flux comparison is essentially independent of the γ factor if the comparison is made under identical $\langle E\rangle/L$ conditions, since both fluxes are proportional to $1/L^2$. This is strictly correct if the polarization effects due to the muon spin are neglected. The polarization of the muon affects the energy spectrum and the relative flux of both neutrino flavours produced in the muon decay [5].

Another significant neutrino beam parameter is the number of neutrino interactions when $E/L \approx \Delta m^2$. In fact, this parameter determines the overall statistics collected by an oscillation disappearance experiment, and is also indicative of the appearance signal intensity since

$$I \propto \sin^2\left(1.27\frac{\Delta m^2\ [\mathrm{eV}^2]\ L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]}\right).$$

Assuming the neutrino cross-sections to be proportional to the neutrino energy,[2] and taking into account that the focusing properties of the neutrino beam depend solely on the γ factor, the neutrino interaction rate in the far detector N_{int} is

$$N_{\mathrm{int}} \propto \left(\Delta m^2\right)^2 \times \frac{\gamma}{E_{\mathrm{cms}}},$$

where E_{cms} is the neutrino energy in the frame where its parent is at rest.

The 'quality factor' γ/E_{cms} characterizes the neutrino beam and now includes the interaction probability in the approximation previously described. It is straightforward to see that—despite the larger probability of the high-energy neutrinos from muon decay to interact—a ^{6}He beta-beam accelerated at $\gamma = 150$ is more than five times more efficient than a neutrino beam from muons accelerated at $\gamma = 500$.

3. Feasibility

Here, the challenges to the feasibility of beta-beams are reviewed aspect by aspect, and possible objections are discussed.

3.1. Radioactive ion production

Various techniques have been developed in the nuclear physics community in order to produce unstable, radioactive nuclei. For a detailed review, the interested reader is referred to Ref. [1]. Probably, the technique developed at CERN ISOLDE, called ISOL ion production, is the most suitable for high intensity ^{6}He production. Today ISOLDE can produce up to $\approx 10^8$ ^{6}He ions per second [6], without a specific optimization for this atomic state. ^{6}He production by spallation is an understood and measured process [7], and the target technology at high-intensity has already been studied [8]. Release efficiencies have been measured [9], as well as the ionization efficiency to electrostatically collect the ^{6}He ions [10]. A recent estimate, based on the previous data, indicates that $o(5 \times 10^{13})$ ^{6}He ions per second can be produced with a 100 μA proton beam at an energy of 2.2 GeV [11]. This proton intensity would be perfectly possible, for example, with the 2 mA CERN Superconducting Proton Linac (SPL) which is in an early planning stage. The necessary radioactive ion production facility has already been advocated and studied by the ISOLDE team [12] with the goal of nuclear physics experiments utilizing a radioactive ion beam. The low proton intensity required to produce the radioactive ions could allow the beta-beam to be operated at the same time as a conventional neutrino super-beam [13] of comparable energy. The two beams could be directed towards the same detector and would permit the contemporaneous study of ν_μ, $\bar{\nu}_\mu$, $\bar{\nu}_{\mathrm{e}}$ and ν_{e} (see later) interactions.

3.2. Post-acceleration

Post-acceleration of ^{6}He ions does not differ significantly from non-radioactive ion acceleration. Unlike the muon-based neutrino factories, the acceleration time to reach the relativistic regime (where the dilatation of the decay time in the laboratory frame occurs) is not critical, the ratio of the lifetimes being 4×10^5, and for example, the acceleration cy-

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[2] This approximation is correct for electron and muon neutrinos at the energies under discussion.

cles of the CERN PS multi-purpose synchrotron are affordable. REX-ISOLDE is indeed a CERN facility for post-acceleration of a wide spectrum of radioactive ions, and the post-acceleration of ^{26}Na ($T_{1/2} = 1.07$ s) has been recently demonstrated.

Once the relativistic regime is achieved (PS), the injection into a larger machine, for example the CERN SPS, could take the beam to the required energy before it is sent to the storage ring. The high-energy acceleration cycle, of the order of 8 s, is the limiting factor in the ion intensity delivered into the storage ring.

Given that the beam is radioactive, one could object that the radioactive pollution in the accelerator would seriously compromise the beta-beam's feasibility. In fact, the acceleration losses have been evaluated [14] to be 35% overall, given a standard acceleration cycle of the CERN PS and SPS complex. It was noticed that the losses in the high-energy accelerator are reasonably low, and for example are within limits set today for the CERN SPS. This is not the case, today, for the CERN PS stage. The limitation, however, concerns more the characteristics of the specific machine than an intrinsic technology limit: the BNL AGS, for example, routinely withstands higher proton losses than those discussed here. In a newly built machine, the radioactive decay could be tolerable because its characteristics are significantly different from those of pure losses, and moreover it decreases at high energy because of the relativistic time dilatation due to the energy boost. Without giving a proof, obtainable only by a detailed study of the specific accelerator, a possible argument in favour of it is presented below.

A beta-beam induced radioactivity is a perfectly known process, where an accelerated ion nucleus decays into a harmless neutrino, a negative electron, and an ion whose charge differs by one unit from that of its parent (in the case of ^{6}He, $\Delta q/q =$ 50%). The decay rate decreases linearly with the increasing energy because of the boost, therefore the average decay occurring during acceleration has a low-energy parent and is in the low-energy section of the accelerator. The average energy of the escaping electron is about 300 times lower than that of its parent, while the lithium ion has of course the same energy as the decaying helium. The electrons can be easily stopped by thin metallic shields, and produce no secondary neutrons. The lithium ions have a different charge. Their trajectories will therefore change and follow different and well-known orbits; the collisions of the decayed nuclei will thus occur in well-localized places, i.e., the inner part of the dipoles. Therefore it is probably possible to shield the machine where the trajectories of the daughter ions are expected, or to use 'C-like' magnets with the iron coil on the external part of the ring.

3.3. *The storage ring*

The storage ring must:

- have a straight section which, relative to the total length, is as long as possible;
- store the maximum number of bunches, to allow the ions time to decay;
- be immune from the radioactive ion decays.

The first two of these requirements are similar to those of a muon-based neutrino factory storage ring, and detailed studies have already been performed. To store ions accelerated to the maximum SPS energy, a bending strength of 1500 Tm is required. By means of super-conducting magnets, a field of 5 T can be achieved, resulting in a radius of curvature of 300 m. It has to be noted that—from the energetic loss point of view—the decay losses of the beam do not harm the magnets significantly. The maximum possible energy loss, in static conditions and with the intensity figures described here, is already below the 'allowed steady losses' evaluated for the 7 T LHC super-conducting dipoles [15].

A relative length of the straight section towards the detector of 36% can be assumed, resulting in a straight section length of 2500 m and an overall decay ring length of 6880 m. It essentially corresponds to the SPS circumference constrained in a rectangular field of 600×3100 m^2.

Because of the ring topology, radioactive decays could constitute a problem at the end of the straight sections where the strong focusing transports a large fraction of ^{6}Li towards the first dipole. But the first dipole is, in itself, a spectrometer capable of separating $^6_3$Li from $^6_2$He. Therefore a specific design could transport the ^{6}Li ions outside the trajectory and, for example, direct them onto an appropriate beam dump. As an interesting possibility, the high-energy lithium ions could even be recycled to activate the ion source and therefore improve the efficiency of the radioactive ion production, or used for other purposes (for example, a conventional neutrino target).

The ^{6}Li ions which are lost in the storage rings could have undesired hadronic interactions, with subsequent production of ν_μ and $\bar{\nu}_\mu$. These neutrinos could be an irreducible background of the beta-beam for appearance experiments. A Geant simulation [16] has been performed in the simple approximation of dumping all ^{6}Li ions produced in the beta decay onto an iron dump. For simplicity, a ^{6}Li ion is assumed to be equivalent to six protons, and the simulation has been made for a proton beam. An angle of 100 mrad between the beam-dump direction and the beta-beam axis is assumed, as if all the ^{6}Li ions would be lost in the first dipole following the straight section of the storage ring. The conclusion is that this beam-related background is below $o(10^{-4})$ the neutrino flux from beta decay.

The optimal scheme to inject the accelerated bunches into the storage ring is still under study. In particular, attention is being put on the filling fraction of the ring, since it is reflected in the neutrino time-structure on the far detector. The neutrino arrival time, is particularly, important for the rejection of neutrino interactions produced by atmospheric neutrinos that could possibly mimic the signature of beta-beam neutrinos. A scheme where bunches from the accelerator are stored on top of a single storage-ring bunch, which is therefore never extracted and dumped, appears to be possible. This would allow a minimal length of the beam particles inside the ring [14]. The maximum number of particles that can exist in the storage ring is, in the approximation of no beam losses,

$$N_{\mathrm{TOT}} = \frac{N_{\mathrm{BUNCH}}}{1 - e^{\frac{T}{\gamma T_{1/2}}}}$$

where N_{BUNCH} is the number of the particles, coming from the accelerator, entering the storage ring every T seconds.

3.4. Baseline, energy and intensity considerations

Order-of-magnitude performances of the acceleration scheme can be based on current efficiencies of existing machines. A transmission efficiency of 65% in the accelerator is assumed, but the neutrino interaction rate is *not* included. Table 1 shows the possible neutrino flux of a beta-beam, which can be easily scaled to different detector distances as already discussed.

Table 1
Possible characteristics of a beta-beam

^{6}He ions production	5×10^{13}/s every 8 s
^{6}He collection efficiency	20%
^{6}He accelerator efficiency	65%
^{6}He final energy	150 GeV/nucleon
$\bar{\nu}_e$ average energy	581 MeV
Storage ring total intensity	1×10^{14} ^{6}He
Straight section relative length	36%
Running time/year	10^7 s
Detector distance	100 km
$\langle E\rangle/L$	5.9×10^{-3} GeV/km
$\bar{\nu}_e$ flux	2.1×10^{12} m^{-2} yr^{-1}
$\bar{\nu}_e$ interaction rate on H_2O	69 kt^{-1} yr^{-1}

4. Impact on possible measurements

To evaluate the physics impact of a beta-beam, the physics goal has to be specified in view of the low maximum energy, the focusing property and the different neutrino flavour with respect to other accelerators.

4.1. Oscillation physics: appearance and disappearance

Disappearance measurements are particularly attractive in a beta-beam since both intensity and spectrum of the source are perfectly known on the basis of a non-neutrino measurement. These disappearance experiments have the advantage of being sensitive to oscillation also if the value of Δm^2 is much larger than the typical $\langle E\rangle/L$ of the experiment. For the case in which Δm^2 is comparable to $\langle E\rangle/L$, the experiment is ideally suited to a precision measurement of the $\bar{\nu}_e$ disappearance, with a sensitivity only limited by statistics. When Δm^2 is smaller than $\langle E\rangle/L$, i.e., the experiment is too near to the source, the sensitivity of a disappearance experiment is typically seriously compromised and does not appear to be competitive with appearance detection for the same $\langle E\rangle/L$ value.

A typical disappearance beta-beam experiment could be a very large, simple electromagnetic calorimeter capable of measuring the energy of one electron and located at a distance that makes $\langle E\rangle/L$ comparable to the Δm^2 value to be measured. This detector, by timing, could be synchronized to the pulsed structure of the storage ring in order to minimize backgrounds. It is impossible not to think of the large water Cherenkov detectors, such as SuperKamiokande, and the next-generation studies like UNO [17] and Hyper-K [18].

Appearance experiments with beta-beams probably have to be limited to muon neutrino appearance. Even if it was possible to increase the ion energy to achieve the cross-section threshold necessary for tau production (ν_τ appearance), it would imply a very large storage ring and an increased storage time because of the lifetime dilatation.

Muon neutrino appearance experiments with beta-beams provide two interesting possibilities connected with the absence of other flavours in the beam.

The first is related to the long-baseline measurements, since the far detector can be very similar to those envisaged for proton decay experiments. In both cases the aim is to differentiate a minimum ionizing track from an electron shower, without the need of charge identification of the final-state lepton. In a muon-based neutrino factory experiment, in fact, a magnetic field is required in order to separate the huge background induced by neutrinos of the same flavour but opposite lepton number. Again, also for appearance experiments it is impossible not to think of the large water Cherenkov detectors under study [17,18], as already studied in Ref. [19]. In addition to proton decay, the very same detector could detect neutrinos from supernovae, from the sun, from the atmosphere, from a super-beam and from a beta-beam.

The second possibility is connected with short-baseline measurements: if the MiniBoone experiment validates the LSND oscillation claim, a beta-beam experiment looking to $\bar{\nu}_e \to \bar{\nu}_\mu$ oscillation could allow unprecedented measurements of oscillations in the region of Δm^2 relevant to astrophysics and cosmology. At the moment, no pure sources of ν_μ or ν_e are available to appearance experiments which have to explore the region characterized by $\sin^2\theta_{12} \approx 10^{-4}$. The technology developed for the ICARUS experiment [20] would probably be suitable for this domain of investigation.

4.2. Precision physics

The high intensity and the purity make a beta-beam very interesting in the domain of nuclear studies with neutrinos. The small maximum energy, however, excludes the study of the deep inelastic neutrino interactions, and limits the scope of the investigations to the low-energy domain, which nevertheless could be very relevant in order to measure the cross section on different target materials of $\bar{\nu}_e$ and ν_e neutrinos from astrophysical sources.

4.3. Are CP-violation measurements still possible?

An obvious advantage of the muon-based neutrino factory beams is the possibility to accelerate muons or antimuons to produce neutrinos of opposite lepton number. This opens the possibility to measure CP-violation effects in the leptonic sector. Despite the difficulty in identifying the experiment parameters which will allow an effect to be observed, this measurement is clearly of maximum importance. A beta-beam has the crucial advantage of a lower energy and better focusing, which is reflected in a larger explorable domain of $\langle E\rangle/L$ values. But anti-helium atoms are impossible to produce. The solution is to accelerate a different atom, which has a superallowed β^+ transition [21]; for example,

$$ {}^{18}_{10}\mathrm{Ne} \to {}^{18}_{9}\mathrm{F} e^+ \nu_e, $$

which has a half-life $T_{1/2}$ of 1.7 s and an average neutrino energy at rest of $E_{\mathrm{cms}} = 1.86$ MeV. In this case, without modifications to the previously mentioned acceleration and decay scheme, the maximum acceleration energy of the radioactive ion corresponds to $\gamma = 250$. In fact, the fully stripped ${}^{18}_{10}\mathrm{Ne}$ ion has a charge-over-mass ratio of $10/18$ e/a.m.u. while for ${}^{6}_{2}\mathrm{He}$ the same ratio is only $2/6$. As previously exposed, the larger acceleration is reflected in a higher neutrino beam energy ($\langle E\rangle = 930$ MeV), and a 'quality factor' γ/E_{cms} of the machine almost doubled ($1.7\times$). As the Z/A ratio of the β^+ emitters is larger than the same quantity for β^- emitters, the conclusion is general, and has to be considered in the evaluation of other possible candidates.

4.4. An exercise: interaction rates in a water detector

Despite being beyond the scope of the present Letter, it is interesting to evaluate the neutrino interaction rates in a possible detector, which is assumed to be made of H_2O and positioned at a distance of 130 km—the distance of the Frejus laboratory from CERN [22]. Antineutrino cross-sections have been extracted from Refs. [23,24], and convoluted with the neutrino spectrum already described. The interaction rate is 69 $\bar{\nu}_e$ interactions $\mathrm{kt}^{-1}\,\mathrm{yr}^{-1}$, and in the hypothesis of $\sin^2 2\theta_{13} = 1$ (given $\Delta m_{13} \approx \Delta m_{23} = 2.4 \times 10^{-3}\ \mathrm{eV}^2$ from the atmospheric neutrino measurements) the $\bar{\nu}_\mu$ interaction rate is 25 $\bar{\nu}_\mu$ interactions $\mathrm{kt}^{-1}\,\mathrm{yr}^{-1}$. For a fiducial mass of 440 kt, as estimated for UNO [17], about 30, 300 $\bar{\nu}_e$ interactions can be collected in a single year.

5. Conclusions

An alternative neutrino factory scheme can produce $\bar{\nu}_e$ or ν_e beams from the beta decay of boosted ions. The efficient focusing makes it very suitable for explorations at low Δm^2 values. The unprecedented beam flavour, the known spectrum and the purity make it attractive for both appearance and disappearance oscillation experiments, and for new precision neutrino physics. The technology to produce, accelerate and store radioactive ions has already been explored.

Recent discoveries in neutrino physics probably represent the most important opportunity to probe the Standard Model understanding. Any improvement of the current artificial neutrino acceleration technology should therefore be investigated. Up to now, many have considered focused low-energy neutrino beams impossible.

Acknowledgements

The author is indebted to A. Blondel, J.J. Gomez-Cadenas, D. Casper, U. Koester, M. Lindroos, M. Mezzetto, T. Nilsson, J. Panman and B. Saitta for their help, ideas, attention, comments and suggestions. Special and sincere thanks to F. Dydak for his stimulating and constructive criticism.

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