Neutrino Properties and Low-energy Beta-beams

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(Dated: September 15, 2004)

We propose to use the beta-beam concept to establish a beta-beam facility producing low-energy neutrinos. We discuss neutrino properties that can be studied with such a facility, like the neutrino magnetic moment and neutrino-nucleus interactions of interest for nuclear physics, particle physics and astrophysics. We show that present limits on the magnetic moment can be improved by almost one order of magnitude and that interesting neutrino-nucleus interaction rates can be obtained. Among possible sites for such a facility, CERN is particularly attractive for the neutrino energies and intensities that can be attained.

PACS numbers:

Neutrino physics is traversing an exciting era : several experiments have recently found a positive oscillation signal showing that neutrinos are massive particles contrary to what was believed so far [1]. This discovery has important implications in various fields of physics like cosmology or astrophysics. Many questions are still open such as the Majorana or the Dirac nature of neutrinos, their electromagnetic properties, or the possible existence of CP violation in the leptonic sector. The availability of very intense neutrino beams will offer the opportunity to address some of the open issues. In particular, beta-beams have attracted a strong interest recently: it is a new method to produce neutrino beams which exploits the beta-decay of boosted radioactive ions [2]. In the first baseline scenario the beams are produced, stored and accelerated first at several hundred MeV per nucleon then to several tens of GeV per nucleon by injection in the PS and SPS. The ion production and acceleration steps before injection in the PS presents a strong overlap with the EURISOL project. Finally the ion bunches are accumulated in a storage ring with long straight sections [2, 3] to be fired to a gigantic Cherenkov detector [4], located in an upgraded Fréjus Underground Laboratory, about 130 km from CERN with the aim of studying very small values of the neutrino mixing angle θ_{13} and CP (and T) violation in the lepton sector [2, 4, 5]. The gigantic detector can also be used to improve present sensitivities on proton decay and to detect neutrinos emitted in a core-collapse supernova explosion in and outside our galaxy [4]. Other interesting scenarios are now proposed where beta-beams would have even higher energies and would be sent to further distances, like e.g. the Gran Sasso Laboratory [6, 7].

A. Low-energy Beta-beams

We have recently proposed to exploit the beta-beam concept to establish a facility producing neutrinos with low energies (i.e. several tens of MeV up to a hundred and more) [8]. Two configurations are possible : *i)* the ions are produced, collected and used as an intense neutrino source; *ii)* the ions are produced, accelerated to low energy and stored in a storage ring. This idea presents two new points with respect to the original project : *i)* it opens new axis of research since other neutrino properties can be studied; *ii)* besides CERN other sites are possible for a low-energy beta-beam facility since intense exotic ion beams will be available in the future at various laboratories [8]. Here we give two examples of the rich physics program that one can perform with such a facility. In particular, we show that one can study intrinsic neutrino properties like the neutrino magnetic moment [9], and neutrino-nucleus interaction interactions, which is a topic of current great interest for various domains of physics [10].

1. *Prospects for the neutrino magnetic moment*

The observation of a large neutrino magnetic moment would represent an outstanding discovery. In fact the indirect evidence that neutrinos are massive particles, provided by oscillation experiments, implies that neutrinos have a small magnetic moment. In the case of a Dirac mass, standard model interactions give the neutrino a magnetic moment of $3 \times 10^{-19}(m_\nu/\text{eV})$ in units of Bohr magnetons, μ_B. The observation of a large magnetic moment would indicate interactions beyond the Standard Model and provide valuable information for understanding the neutrino mass mechanism. So far, the best limits from direct measurements have been obtained with reactor experiments and are in the range $\mu_\nu < 1.0 - 4 \times 10^{-10}\mu_B$ at 90 % C.L. [11]. Similar upper bounds have recently been deduced from solar events [12]. Indirect limits in the range $10^{-11} - 10^{-12}\mu_B$ have been obtained by using astrophysical considerations [13], although the exact values for these limits are model-dependent.

The direct measurements exploit neutrino-electron scattering where the neutrinos are detected by measuring the recoil of the electrons. In fact, the weak and

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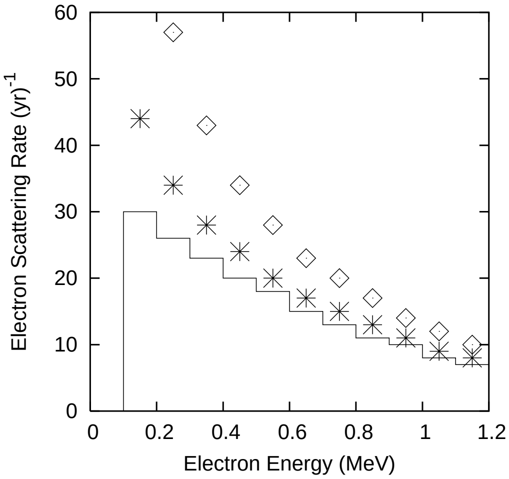

FIG. 1: *Prospects on the neutrino magnetic moment:* Number of neutrino-electron scattering events from a Helium-6 as a beta-beam emitter produced at the rate 10^{15} per second, and a 4π detector. (Similar results are obtained if Neon-18 is used instead.) Results corresponding to electron recoil energies of [0.1,1.2] MeV are shown. The diamonds show the number of scatterings if the neutrino has a magnetic moment of $\mu_\nu = 10^{-10}\mu_B$, the stars present the number of events if $\mu_\nu = 5\times10^{-11}\mu_B$. The histogram shows the expected number of events for a vanishing neutrino magnetic moment.

electromagnetic cross section is given by [11]

$$\frac{d\sigma}{dT} = \left(\frac{d\sigma}{dT}\right)_W + \left(\frac{d\sigma}{dT}\right)_M \tag{1}$$

where

$$\left(\frac{d\sigma}{dT}\right)_W = \frac{G_F^2 m_e}{2\pi}\left[a^2 + b^2\left(1-\frac{T}{E_\nu}\right)^2 + c\frac{m_e T}{E_\nu^2}\right], \tag{2}$$

and

$$\left(\frac{d\sigma}{dT}\right)_M = \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\frac{1-T/E_\nu}{T}, \tag{3}$$

where E_ν is the neutrino impinging energy, T is the electron recoil energy, the constants are $a = g_V + g_A$, $b = g_V - g_A$, $c = g_A^2 - g_V^2$ $g_V = 2\sin^2\theta_W + 1/2$, θ_W is the Weinberg angle, $g_A = 1/2$ (-1/2) for ν_e ($\bar{\nu}_e$), m_e is the electron mass and G_F is the Fermi coupling constant. From Eqs.(1)-(3) one can see that a non-zero neutrino magnetic moment dominates the neutrino-electron cross section particularly for very low electron recoils ($T \to 0$). This fact is exploited in direct measurements to set a limit on μ_ν.

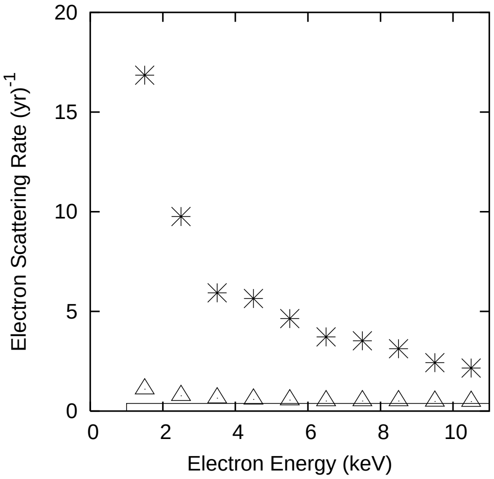

FIG. 2: Same as Figure 1 but for electron energy recoils within [1,10] keV. The triangles give the number of events if the neutrino has a magnetic moment of $\mu_\nu = 10^{-11}\mu_B$.

We have studied possible strategies to improve present direct limits on the neutrino magnetic moment. To reach this aim one needs : *i)* very intense neutrino sources of well-known fluxes; *ii)* very low threshold detectors. A static source as well as low-energy beta-beams seem particularly attractive since the neutrino fluxes can be very accurately calculated. With a static source, as proposed by various authors [14–16], one might be able to improve present limits. In particular, with the use of a tritium source the upper bound might be improved by about two orders of magnitudes [9, 15, 16] reaching the range which is presently covered by indirect considerations. Here we present the results for low-energy beta-beams obtained by averaging the cross section Eq.(1) with the neutrino fluxes produced by collecting 10^{15} Helium-6/s inside a 4π detector (Figs. 1,2). If there is no magnetic moment, this intensity will produce about 170 events in the 0.1 MeV to 1 MeV range per year and 3 events in the 1 keV to 10 keV range per year. These numbers increase to 210 and 55 respectively in the case of a magnetic moment of $5 \times 10^{-11}\mu_B$.

In conclusion the results obtained in [9] show that with the use of low-energy beta-beams the present limit can be improved by almost an order of magnitude, the precise value requiring a detailed simulation of the detector response. These results give the important indication that reaching higher production rates as compared to those evaluated in the first feasibility study [3], for at least one beta-beam emitter, would be extremely helpful for such applications. These experiments need the development of detectors with a very low threshold as well as a careful knowledge of the background below 1 MeV. Such detectors are currently investigated [15, 17].

2. *Neutrino-nucleus interaction rates*

We have studied the neutrino-nucleus interaction rates which can be attained at a low-energy beta-beam facility. In order to show how the number of events changes, as a function of the storage ring length two scenarios are envisaged, where the detector is placed close either to a small or to a large storage ring. We take as typical sizes those of the ring planned for the future GSI facility [18], and of the one considered in the beta-beam baseline scenario at CERN [3]. The total number of events per unit time is obtained by integrating over the useful decay path of the storage ring and over the volume of the detector [10]:

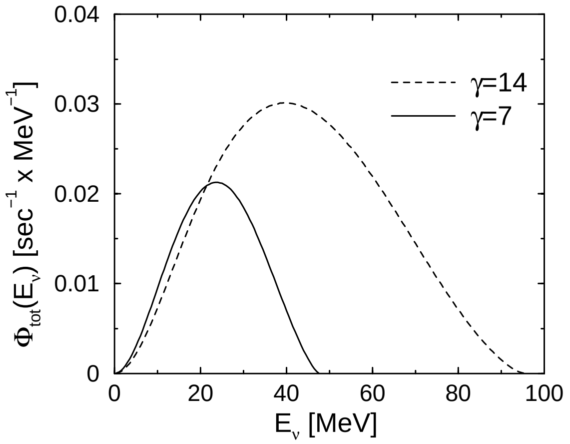

FIG. 3: Neutrino fluxes $\Phi_{tot}(E_\nu)$ as a function of energy for ^{18}Ne nuclei boosted at $\gamma = 7$ and $\gamma = 14$. This corresponds to the small ring and small detector configuration.

$$\frac{dN_{ev}}{dt} = g\tau n h \times \int_0^\infty dE_\nu \, \Phi_{tot}(E_\nu) \, \sigma(E_\nu) \, , \qquad (4)$$

where n is the number of target nuclei per unit volume, $\sigma(E_\nu)$ is the relevant neutrino-nucleus interaction cross-section, and where

$$\Phi_{tot}(E_\nu) = \int_0^D \frac{d\ell}{L} \int_0^h \frac{dz}{h} \int_0^{\bar\theta(\ell,z)} \frac{\sin\theta d\theta}{2} \, \Phi_{lab}(E_\nu, \theta) \, , \qquad (5)$$

with

$$\tan\bar\theta(\ell, z) = \frac{R}{d + \ell + z} \, , \qquad (6)$$

where g is the number of injected ions per unit time, τ the half-life of the parent nucleus, L the total length of the storage ring with straight sections D, R is the radius of the cylindrical detector of depth h placed at distance d from the storage ring. Figure 3 shows the neutrino fluxes used. Table I presents the results obtained for four nuclei, i.e. deuteron, oxygen, iron and lead as typical examples. Note that in [10] an analytical formula is given which allows one to scale the present exact rates for storage rings of different lengths. An interesting study is also performed in [23] for the case of lead. The rates presented in Table I are very promising and show that one can perform neutrino-nucleus interaction studies of interest for e.g. :

Reaction	Ref.	Mass	Small Ring	Large Ring
ν+D	[19]	35	2363	180
$\bar\nu$+D	[19]	35	25779	1956
ν+^{16}O	[20]	952	6054	734
$\bar\nu$+^{16}O	[20]	952	82645	9453
ν+^{56}Fe	[21]	250	20768	1611
ν+^{208}Pb	[22]	360	103707	7922

TABLE I: *Neutrino-Nucleus Interaction Rates* [10]: Number of events per year for the ion Lorentz factor $\gamma = 14$ in the small ($L = 450$ m, $D = 150$ m) and large ($L = 7$ km, $D = 2.5$ km) ring configurations. The detector is located at $d = 10$ m away from the ring and has dimensions $R = 1.5$ m and $h = 4.5$ m for the D (D_2O), ^{56}Fe and ^{208}Pb, and $R = 4.5$ m and $h = 15$ m for the case of ^{16}O (H_2O), where R is the radius and h is the depth of the detector having cylindrical shape. The corresponding masses are given in tons. The relevant cross-sections are taken from the indicated references. The results are obtained with 1 year = 3.2×10^7 s.

- *Neutrino detector response* Nuclei are often used as a neutrino detectors in neutrino experiments like oscillation measurements or in supernova neutrino observatories.

- *Nuclear structure* There are several open issues, for example in the neutrino-deuteron interaction, in understanding some of the isospin and spin-isospin modes which are excited in neutrino-nucleus reactions.

- *Nuclear astrophysics* These reactions play a role in various contexts like in the nucleosynthesis of heavy elements or neutrino nucleosynthesis.

Sites	Ion intensity (ions/s)	γ
GANIL	10^{12} [24]	1
EURISOL	10^{13}	1
CERN	2×10^{13} [3]	1-150

TABLE II: Examples of the ion intensities and the gamma of the parent ion which could be available at some of the possible sites for a low-energy beta-beam facility. In sites where $\gamma = 1$ the ions can be used as a neutrino source. The line corresponding to EURISOL refers to the case of the original EURISOL project without acceleration at high energy and a storage ring. The numbers refer to ^{6}He as an example [8].

B. Sites

We next discuss the neutrino energies and intensities that can be reached at various sites. Table II shows three examples of the ion intensities and the Lorentz γ factor that can be attained. Note that the neutrino energy is related to γ by $E_\nu \simeq 2\gamma Q_\beta$ where Q_β is the beta-decay Q-value. In sites like GANIL (without acceleration at GeV energies and a storage ring) the ions can be used as a neutrino source inside a 4π detector. In laboratories like GSI and CERN the ions can be accelerated and stored, producing neutrino beams. Lower intensities will be reached at GSI [25] if the fragmentation method is used to produce the ions. The neutrino energies will be in the 50 MeV energy region (Figure 2) [18]. However, the use of an ISOLDE technique would bring the intensities at the same level as those of Table II. From Table II one can see that CERN seems a promising site both for the neutrino intensities and energies. In particular one can vary the γ of the parent ion, thereby producing neutrino fluxes of variable energy, spanning from the tens of MeV to several hundred MeV. This feature is extremely attractive for neutrino-nucleus interaction studies.

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