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Monochromatic neutrino beams

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Abstract: In the last few years spectacular results have been achieved with the demonstration of non vanishing neutrino masses and flavour mixing. The ultimate goal is the understanding of the origin of these properties from new physics. In this road, the last unknown mixing $[U_{e3}]$ must be determined. If it is proved to be non-zero, the possibility is open for Charge Conjugation-Parity (CP) violation in the lepton sector. This will require precision experiments with a very intense neutrino source. Here a novel method to create a monochromatic neutrino beam, an old dream for neutrino physics, is proposed based on the recent discovery of nuclei that decay fast through electron capture. Such nuclei will generate a monochromatic directional neutrino beam when decaying at high energy in a storage ring with long straight sections. We also show that the capacity of such a facility to discover new physics is impressive, so that fine tuning of the boosted neutrino energy allows precision measurements of the oscillation parameters even for a $[U_{e3}]$ mixing as small as 1 degree. We can thus open a window to the discovery of CP violation in neutrino oscillations.

Keywords: Neutrino Physics.

Contents

1. Introduction

Neutrinos are very elusive particles that are difficult to detect. Even so, physicists have over the last decades successfully studied neutrinos from a wide variety of sources, either natural, such as the sun and cosmic objects, or manmade, such as nuclear power plants or accelerated beams. Spectacular results have been obtained in the last few years for the flavour mixing of neutrinos obtained from atmospheric, solar, reactor and accelerator sources and interpreted in terms of the survival probabilities for the beautiful quantum phenomenon of neutrino oscillations [1, 2]. The weak interaction eigenstates ν_α $(\alpha = e, \mu, \tau)$ are written in terms of mass eigenstates ν_k $(k = 1, 2, 3)$ as $\nu_\alpha = \sum_k U_{\alpha k}(\theta_{12}, \theta_{23}, \theta_{13}; \delta)\nu_k$, where θ_{ij} are the mixing angles among the three neutrino families and δ is the CP violating phase. Neutrino mass differences and the mixings for the atmospheric θ_{23} and solar θ_{12} sectors have thus been determined. The third connecting mixing $|U_{e3}|$ is bounded as $\theta_{13} \leq 10^\circ$ from the CHOOZ reactor experiment [3]. Next experiments able to measure this still undetermined mixing and the CP violating phase δ, responsible for the matter-antimatter asymmetry, need to enter into a high precision era with new machine facilities and very massive detectors. The observation of CP violation needs an experiment in which the emergence of another neutrino flavour is detected rather than the deficiency of the original flavour of the neutrinos. The appearance probability $P(\nu_e \to \nu_\mu)$ as a function of the distance between source and detector (L) is given by [4]

$$P(\nu_e \to \nu_\mu) \simeq s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{13}^2\, L}{4E}\right) + c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{12}^2\, L}{4E}\right) + \\ + \tilde{J} \cos\left(\delta - \frac{\Delta m_{13}^2\, L}{4E}\right) \frac{\Delta m_{12}^2\, L}{4E} \sin\left(\frac{\Delta m_{13}^2\, L}{4E}\right), \tag{1.1}$$

where $\tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$, s_{ij} and c_{ij} are the corresponding *sin* and *cos* functions of θ_{ij} and Δm_{ij}^2 the square mass differences. The four measured parameters $(\Delta m_{12}^2, \theta_{12})$ and $(\Delta m_{23}^2, \theta_{23})$ have been fixed throughout this paper to their mean val-

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ues [5]. The three terms of eq. (1.1) correspond, respectively, to contributions from the atmospheric and solar sectors and their interference. As seen, the CP violating contribution has to include all mixings and neutrino mass differences to become observable. Neutrino oscillation phenomena are energy dependent (see figure 1) for a fixed distance between source and detector, and the observation of this energy dependence would disentangle the two important parameters: whereas $|U_{e3}|$ gives the strength of the appearance probability, the CP phase acts as a phase-shift in the interference pattern. These properties suggest the consideration of a facility able to study the detailed energy dependence by means of fine tuning of monochromatic neutrino beams. In an electron capture facility, the neutrino energy is dictated by the chosen boost of the ion source and the neutrino beam luminosity is concentrated at a single known energy, which may be chosen at will for the values in which the sensitivity for the (θ_{13}, δ) parameters is higher. This is in contrast to beams with a continuous spectrum, where the intensity is shared between sensitive and non sensitive regions. Furthermore, the definite energy would help in the control of both the systematics and the detector background. In the CERN Joint Meeting of BENE/ECFA for Future Neutrino Facilities in Europe, the option of a monochromatic neutrino beam from atomic electron capture in ^{150}Dy was considered and discussed both [6] in its Physics Reach and the machine feasibility. This idea was conceived earlier [7] by the authors and presented together with the beta beam facility. The analyses showed that this concept could become operational only when combined with the recent discovery of nuclei far from the stability line, having super allowed spin-isospin transitions to a giant Gamow-Teller resonance kinematically accessible [8]. Thus the rare-earth nuclei above ^{146}Gd have a small enough half-life for electron capture processes. Some preliminary results for the physics reach were presented in [9]. A subsequent paper [10] has appeared in the literature with the proposal of an EC-beam with fully stripped long-lived ions. This option would oblige recombination of electrons with ions in the high energy storage ring. Such a process has a low cross section and would lead to low intensities at the decay point. Even if the production rate would be considerably higher for these long-lived nuclei it would result in extremely high currents in the decay ring, something which already in the present beta-beam proposal is a problem due to space charge limitations and intra-beam scattering. We discuss the option of short-lived ions [6].

In section 2, the electron capture process is described with reference to the new existing cases of fast decay. In section 3, the Neutrino Flux emerging from the facility with boosted decaying ions is calculated and the main characteristics discussed. In section 4, we show the sensitivity which can be reached with the proposed facility for the parameters (θ_{13}, δ) of neutrino oscillations. Some conclusions and outlook are given in section 5.

2. Electron Capture

Electron Capture is the process in which an atomic electron is captured by a proton of the nucleus leading to a nuclear state of the same mass number A, replacing the proton by a neutron, and a neutrino. Its probability amplitude is proportional to the atomic wavefunction at the origin, so that it becomes competitive with the nuclear β^+ decay at

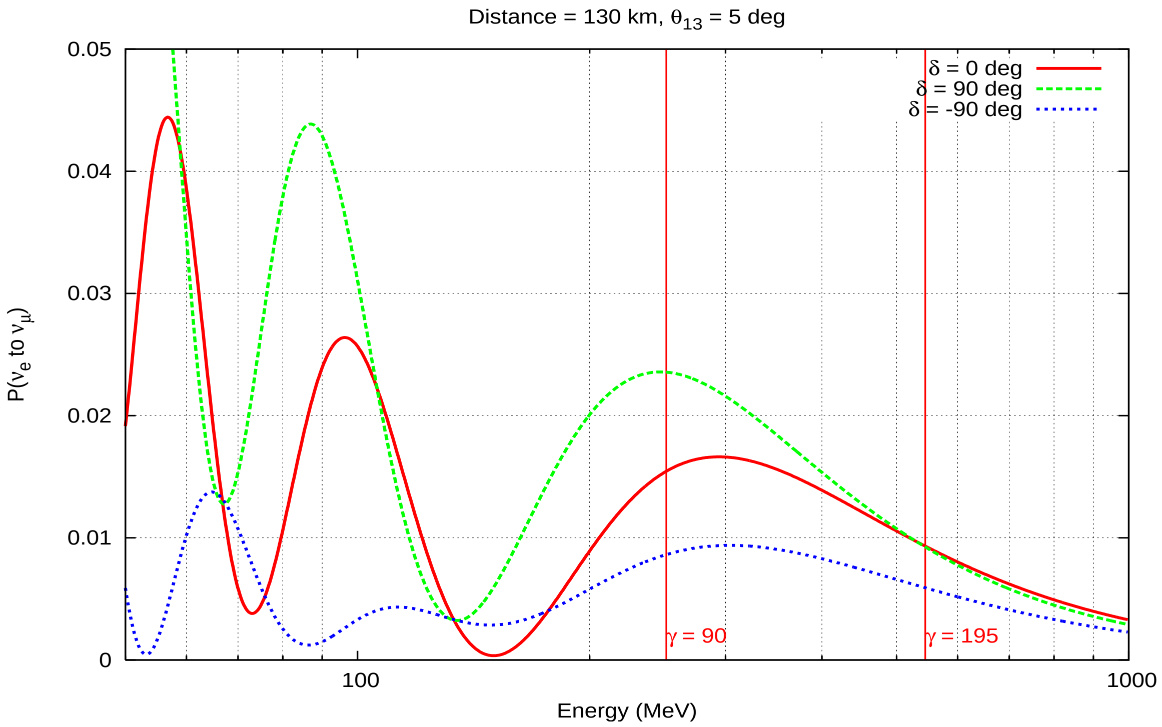

Figure 1: The appearance probability $P(\nu_e \to \nu_\mu)$ for neutrino oscillations as a function of the LAB energy E, with fixed distance between source and detector and connecting mixing. The three curves refer to different values of the CP violating phase δ. The two vertical lines are the energies of our simulation study.

Decay	$T_{1/2}$	BR_ν	EC/β^+	E_{GR}	Γ_{GR}	Q_{EC}	E_ν	ΔE_ν
$^{148}Dy \rightarrow ^{148}Tb^*$	$3.1m$	1	96/4	620	≈ 0	2682	2062	≈ 0
$^{150}Dy \rightarrow ^{150}Tb^*$	$7.2m$	0.64	100/0	397	≈ 0	1794	1397	≈ 0
$^{152}Tm2^- \rightarrow ^{152}Er^*$	$8.0s$	1	45/55	4300	520	8700	4400	520
$^{150}Ho2^- \rightarrow ^{150}Dy^*$	$72s$	1	77/33	4400	400	7400	3000	400

Table 1: Four fast decays in the rare-earth region above ^{146}Gd leading to the giant Gamow-Teller resonance. Energies are given in keV. The first column gives the life-time, the second the branching ratio of the decay to neutrinos, the third the relative branching between electron capture and β^+, the fourth is the position of the giant GT resonance, the fifth its width, the sixth the total energy available in the decay, the seventh is the neutrino energy $E_\nu = Q_{EC} - E_{GR}$ and the eigth its uncertainty.

high Z. Kinematically, it is a two body decay of the atomic ion into a nucleus and the neutrino, so that the neutrino energy is well defined and given by the difference between the initial and final nuclear mass energies (Q_{EC}) minus the excitation energy of the final nuclear state. In general, the high proton number Z nuclear beta-plus decay (β^+) and electron-capture (EC) transitions are very "forbidden", i.e., disfavoured, because the energetic window open Q_β/Q_{EC} does not contain the important Gamow-Teller strength excitation seen in (p,n) reactions. There are a few cases, however, where the Gamow-Teller resonance

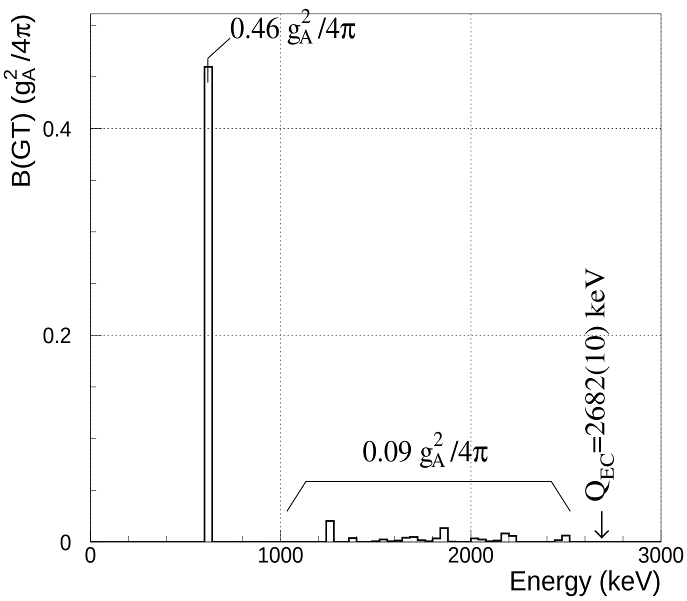

Figure 2: Gamow-Teller strengh distribution in the EC/β^+ decay of ^{148}Dy.

can be populated (see figure 2) having the occasion of a direct study of the "missing" strength. For the rare-earth nuclei above ^{146}Gd, the filling of the intruder level $h_{11/2}$ for protons opens the possibility of a spin-isospin transition to the allowed level $h_{9/2}$ for neutrons, leading to a fast decay. The properties of a few examples [11] of interest for neutrino beam studies are given in table 1. A proposal for an accelerator facility with an EC neutrino beam is shown in figure 3. It is based on the most attractive features of the beta beam concept [12]: the integration of the CERN accelerator complex and the synergy between particle physics and nuclear physics communities.

3. Neutrino flux

A neutrino (of energy E_0) that emerges from radioactive decay in an accelerator will be boosted in energy. At the experiment, the measured energy distribution as a function of angle (θ) and Lorentz gamma (γ) of the ion at the moment of decay can be expressed as $E = E_0/[\gamma(1-\beta\cos\theta)]$. The angle θ in the formula expresses the deviation between the actual neutrino detection and the ideal detector position in the prolongation of one of the long straight sections of the Decay Ring of figure 3. The neutrinos are concentrated inside a narrow cone around the forward direction. If the ions are kept in the decay ring longer than the half-life, the energy distribution of the Neutrino Flux arriving to the detector in absence of neutrino oscillations is given by the Master Formula

$$\frac{d^2N_\nu}{dSdE} = \frac{1}{\Gamma}\frac{d^2\Gamma_\nu}{dSdE}N_{\rm ions} \simeq \frac{\Gamma_\nu}{\Gamma}\frac{N_{\rm ions}}{\pi L^2}\gamma^2\delta(E-2\gamma E_0)\,, \tag{3.1}$$

with a dilation factor $\gamma \gg 1$. It is remarkable that the result is given only in terms of the branching ratio and the neutrino energy and independent of nuclear models. In equation (3.1), N_{ions} is the total number of ions decaying to neutrinos. For an optimum choice

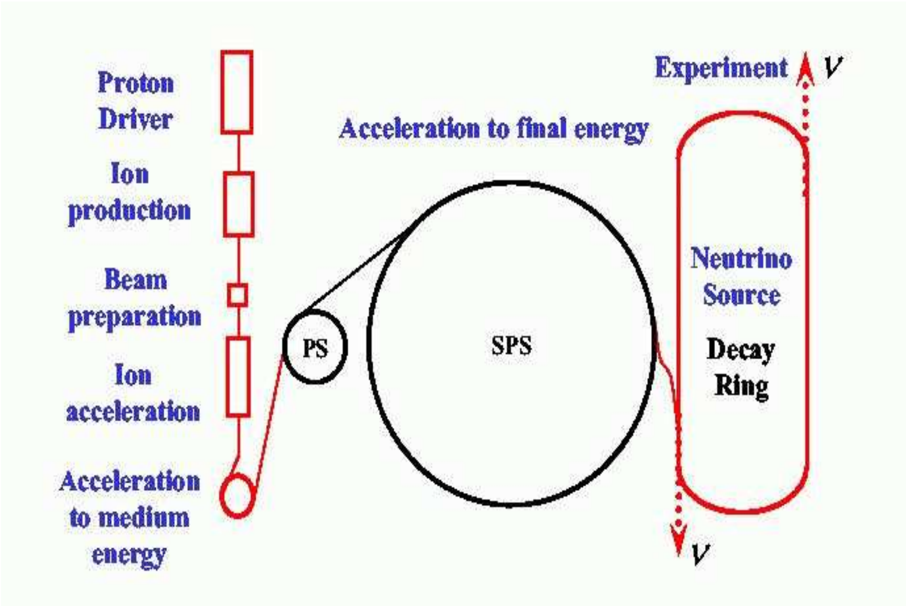

Figure 3: A proposal for the CERN part of a CERN to Frejus ($130km$) EC neutrino beam facility.

with $E \sim L$ around the first oscillation maximum, eq. (3.1) says that lower neutrino energies E_0 in the proper frame give higher neutrino fluxes. The number of events will increase with higher neutrino energies as the cross section increases with energy. To conclude, in the forward direction the neutrino energy is fixed by the boost $E = 2\gamma E_0$, with the entire neutrino flux concentrated at this energy. As a result, such a facility will measure the neutrino oscillation parameters by changing the γ's of the decay ring (energy dependent measurement) and there is no need of energy reconstruction in the detector.

4. Physics reach

We have made a simulation study in order to reach conclusions about the measurability of the unknown oscillation parameters. Some preliminary results for the Physics Reach were presented [9] before. The ion type chosen is ^{150}Dy, with neutrino energy at rest given by 1.4 MeV due to a unique nuclear transition from 100% electron capture in going to neutrinos. Some 64% of the decay will happen as electron-capture, the rest goes through alpha decay. We have assumed that a flux of $10^{18}/y$ neutrinos at the end of the long straight section of the storage ring can be obtained (e.g. at the future European nuclear physics facility, EURISOL). We have taken two energies, defined by $\gamma_{max} = 195$ as the maximum energy possible at CERN with the present accelerator complex, and a minimum, $\gamma_{min} = 90$, in order to avoid background in the detector below a certain energy. For the distance between source and detector we have chosen $L = 130\ km$ which equals the distance from CERN to the underground laboratory LSM in Frejus. The two values of γ are represented as vertical lines in figure 1. The detector has an active mass of 440 $kton$ and the statistics is accumulated during 10 years, shared between the two runs at different γ's, by detecting both appearance ($\nu_e \to \nu_\mu$) and disappearance ($\nu_e \to \nu_e$) events. Although the survival

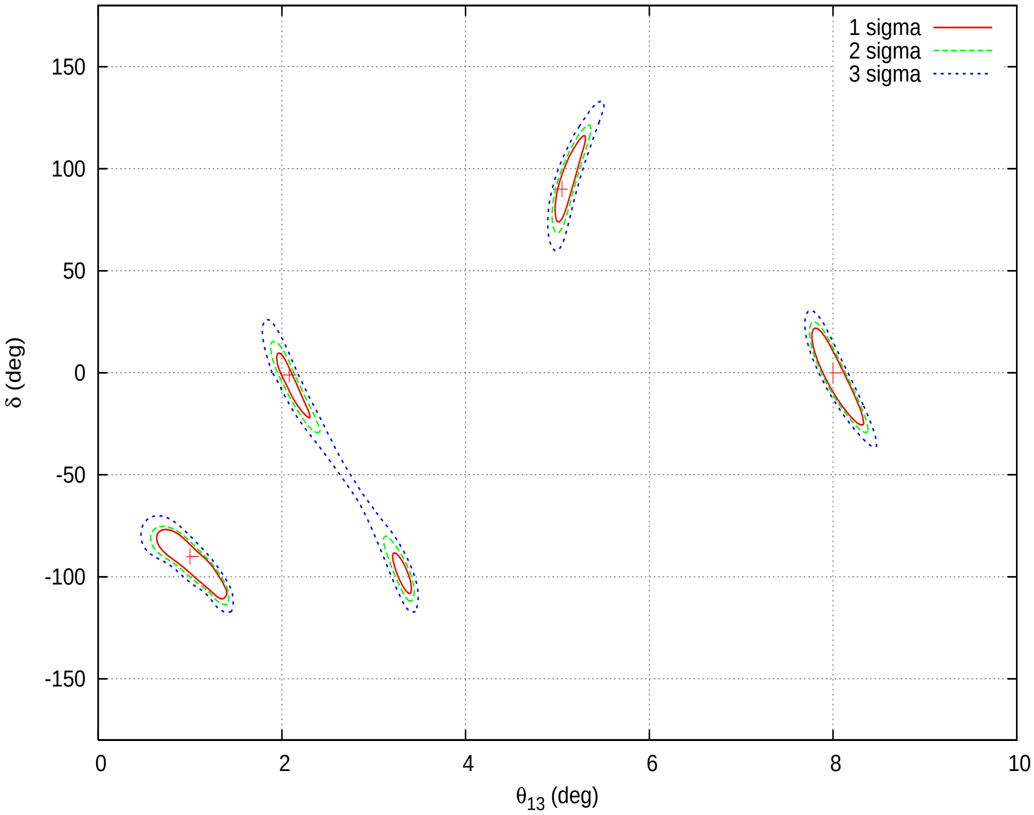

Figure 4: Physics Reach for the presently unknown (θ_{13}, δ) parameters, using two definite energies in the electron-capture facility discussed in this paper.

probability does not contain any information on the CP phase, its measurement helps in the cut of the allowed parameter region. The systematics will affect this cut, but one can expect a smaller level of systematic error than in conventional neutrino beams or beta-beams, due to the precise knowledge of the event energy. This is a subject for further exploration. The Physics Reach is represented by means of the plot in the parameters (θ_{13}, δ) as given in figure 4, with the expected results shown as confidence level lines for the assumed values $(8°, 0°)$, $(5°, 90°)$, $(2°, 0°)$ and $(1°, -90°)$. The improvement over the standard beta-beam reach is due to the judicious choice of the energies to which the intensity is concentrated (see figure 1): whereas $\gamma = 195$ leads to an energy above the oscillation peak with almost no dependence of the $\delta-$phase, the value $\gamma = 90$, leading to energies between the peak and the node, is highly sensitive to the phase of the interference. These two energies are thus complementary to fix the values of (θ_{13}, δ).

The main conclusion is that *the principle of an energy dependent measurement is working and a window is open to the discovery of CP violation in neutrino oscillations*, in spite of running at two energies only. The opportunity is better for higher values of the mixing angle θ_{13}, the angle linked to the mixing matrix element $|U_{e3}|$ and for small mixing one would need to enter into the interference region of the neutrino oscillation by going to higher distance between source and detectors.

5. Prospects

The electron-capture facility, proposed in this work, will require a different approach to acceleration and storage of the ion beam compared to the standard beta-beam [13], as the ions cannot be fully stripped. Partly charged ions have a short vacuum life-time [14] due to a large cross-section for stripping through collisions with rest gas molecules in the accelerators. The isotopes discussed here have a half-life comparable to, or smaller than, the typical vacuum half-life of partly charged ions in an accelerator with very good vacuum. The fact that the total half-life is not dominated by vacuum losses will permit an important fraction of the stored ions sufficient time to decay through electron-capture before being lost out of the storage ring through stripping. A detailed study of production cross-sections, target and ion source designs, ion cooling and accumulation schemes, possible vacuum improvements and stacking schemes is required in order to reach a definite answer on the achievable flux. The discovery of isotopes with half-lives of a few minutes or less, which decay mainly through electron-capture to Gamow-Teller resonances in super allowed transitions, certainly opens the possibility for a monochromatic neutrino beam facility which is well worth exploring. The Physics Reach that we have shown here is impressive and demands such a study.

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References

[1] Super-Kamiokande collaboration, Y. Fukuda et al., *Evidence for oscillation of atmospheric neutrinos*, *Phys. Rev. Lett.* **81** (1998) 1562 [hep-ex/9807003].

[2] SNO collaboration, Q.R. Ahmad et al., *Direct evidence for neutrino flavor transformation from neutral-current interactions in the sudbury neutrino observatory*, *Phys. Rev. Lett.* **89** (2002) 011301 [nucl-ex/0204008]; *Measurement of day and night neutrino energy spectra at sno and constraints on neutrino mixing parameters*, *Phys. Rev. Lett.* **89** (2002) 011302 [nucl-ex/0204009].

[3] CHOOZ collaboration, M. Apollonio et al., *Limits on neutrino oscillations from the CHOOZ experiment*, *Phys. Lett.* **B 466** (1999) 415 [hep-ex/9907037].

[4] A. Cervera et al., *Golden measurements at a neutrino factory*, *Nucl. Phys.* **B 579** (2000) 17 [hep-ph/0002108].

[5] M.C. Gonzalez-Garcia, *Global analysis of neutrino data*, hep-ph/0410030.

[6] J. Bernabeu and M. Lindroos, *Monochromatic neutrino Beam from electron-capture*, in *EU CARE-BENE meeting*, 16–18 March 2005, CERN, Geneva, Switzerland (http://bene.na.infn.it/).

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[7] M. Lindroos, *Neutrino beta beam facility*, in *Workshop on Terrestrial and Cosmic Neutrinos, Leptogenesis and Cosmology*, 4-23 July 2004, Benasque Center for Science, Spain (`http://benasque.ecm.ub.es/benasque/2004neutrinos/`).

[8] A. Algora et al., *beta decay of* ^{148}Dy*: study of the Gamow-Teller giant state by means of total absorption spectroscopy*, *Phys. Rev.* **D 70** (2004) 064301.

[9] J. Burguet-Castell, *Electron capture*, in *JOINT UK Nuclear and Particle Physics meeting on the beta-beam and FIRST meeting of the EURISOL beta-beam task*, 17-18 January 2005, Rutherford Appleton Laboratory, UK (`http://beta-beam.web.cern.ch/beta-beam/RAL05/RAL05-presentations.htm`).

[10] J. Sato, *Monoenergetic neutrino beam for long baseline experiments*, *Phys. Rev. Lett.* **95** (2005) 131804 [`hep-ph/0503144`].

[11] E. Nacher, *Beta decay studies in the* $N \sim Z$ *and the rare-earth regions using Total Absorption Spectroscopy techniques*, Ph. D. Thesis, Univ. Valencia, 2004.

[12] P. Zucchelli, *A novel concept for a* $\bar{\nu}_e$ *neutrino factory: the beta beam*, *Phys. Lett.* **B 532** (2002) 166.

[13] B. Autin et al., *The acceleration and storage of radioactive ions for a neutrino factory*, *J. Phys. G* **29** (2003) 1785.

[14] B. Franzke, *Vacuum requirements for heavy ion synchrotrons*, Proc. 1981 Particle Accelerator Conference, IEEE Trans. Nucl. Sci. **NS-28** (1981) 2116.