

Physics with a very first low-energy beta-beam

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We describe the importance of having low-energy (10-100 MeV) neutrino beams produced through the decay of boosted radioactive ions (“beta-beams”). We focus on the interest for neutrino-nucleus interaction studies and their impact for astrophysics, nuclear and particle physics. In particular, we discuss the relation to neutrinoless double-beta decay. Finally, we mention the status as far as the feasibility of low-energy beta-beams is concerned.

1. INTRODUCTION

Nuclei are a wonderful laboratory for searches on fundamental issues, such as the knowledge of the neutrino mass scale, or of the Majorana versus Dirac nature of neutrinos. Nuclei can also be a beautiful tool for the search of new physics. The original idea of “beta-beams”, first proposed by Zucchelli [1], enter in this category. Beta-beams use the beta-decay of boosted radioactive ions to produce well known electron (anti)neutrino beams, while the conventional way exploits the decay of pions and muons. This simple but intriguing idea has opened new strategies, thanks to the future radioactive ion beams, at present under study, in various nuclear physics laboratories. In fact, the planned intensities of 10^{11-13} ions/s can actually render neutrino accelerator experiments using ions, feasible.

In the original paper [1], a new facility is described, based on the beta-beam method, the central motivation being the search for CP violation in the lepton sector – the Maki-Nakagawa-Sakata-Pontecorvo (MNSP) matrix, relating the neutrino flavor and mass basis, might indeed be complex. With this aim the ions would be accelerated to 60-100 GeV/A (or $\gamma = 60 - 100$, where γ is the Lorentz factor), requiring accelerator infrastructure like the PS and SPS at CERN, as well as a large storage ring pointing to an (enlarged) Fréjus Underground Laboratory, where a big detector would be located.

Very soon the interest of this new concept for the production of low-energy neutrino beams has been recognized [2]. Here the ions are boosted to a much lower γ , i.e. 5-15. High energy scenarios have been proposed [3] afterwards, requiring different (or revised) accelerator infrastructures to boost the ions at very high γ ($\gamma \gg 100$). (Note that for this reason the original scenario [1] is sometimes referred to in the literature as “standard”, or misleadingly “low-energy”.) Detailed works exist at present both on the feasibility [4] as well as on the physics potential of the standard [5] scenario, contributing to determining the conditions for the best CP violation sensitivity, in possible future searches. A feasibility study is now ongoing within the Eurisol Design Study [6]. Here we will focus on the physics potential of low-energy beta-beams.

2. LOW-ENERGY BETA-BEAMS

2.1. Physics Motivations

The idea of establishing a facility producing low-energy neutrino beams, based on beta-beams, has been proposed in [2]. This opens new opportunities, compared to the original scenario. First one might use the ion decay at rest as an intense neutrino source in order to explore neutrino properties that are still poorly known, such as the neutrino magnetic moment [7]. In fact direct measurements achieving improved limits are precious, since the observation of a large magnetic moment

points to physics beyond the Standard Model.

The interest of low-energy beta-beams in the tens of MeV, to perform neutrino-nucleus interaction studies, has been discussed in [2,8]. At present, there is a limited number of measurements available in this domain (essentially on three light nuclei), so that theoretical predictions are of absolute necessity. Getting accurate predictions can be a challenging task, as the discrepancies on the ^{12}C [9] and ^{208}Pb [10] cross sections have been demonstrating. Neutrino-nucleus applications are numerous and span from a better knowledge of neutrino detector response using nuclei, like supernova observatories or in oscillation experiments, to nuclear astrophysics, for the understanding of processes like the nucleosynthesis of heavy elements. (More information can be found e.g. in [11,12].)

In [2] we have pointed out that performing neutrino-nucleus interaction studies on various nuclei would improve our present knowledge of the “isospin” and “spin-isospin” nuclear response (the nuclear transitions involved in charged-current reactions are in fact due to the isospin, like e.g. t_{\pm} , and spin-isospin, like e.g. σt , operators). A well known example is given by the super-allowed Fermi transitions (due to the isospin operator), which are essential for determining the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, the analog of the MNSP matrix in the quark sector. Another (less known but still intriguing) example is furnished by the so-called Gamow-Teller transitions (these are due to the spin-isospin operator) in mirror nuclei, which can be used to observe second class currents, if any. These terms transform in an opposite way under the G -parity transformation – the product of charge-conjugation and of a rotation in isospin space – as the usual vector and axial-vector terms [13], and are not present in the Standard Model. In [2] we have pointed out that spin-isospin and isospin states of higher multipolarity (than those just mentioned) contribute significantly to the neutrino-nucleus cross sections, as the energy of the neutrino increases. Such contributions are larger when the nucleus is heavier. Since low-energy beta-beams have the specificity that the average energy can

be increased by increasing the Lorentz boost of the ions (more precisely $\langle E_{\nu} \rangle \approx 2\gamma Q_{\beta}$), they appear as an appropriate tool for the study of these states. Apart from their intrinsic interest, neutrino-nucleus interaction measurements would put theoretical predictions for the extrapolation to exotic nuclei useful for astrophysical applications, on really solid grounds. They are also important for the open question of the neutrino nature.

One of the crucial issues in neutrino physics is to know if neutrinos are Dirac or Majorana particles. The answer to this question can be furnished for example by the observation of neutrinoless double beta decay in nuclei, since this lepton violating process can be due to the exchange of a Majorana neutrino. While the present limit is of about 0.2 eV [14], future experiments aim at the challenging 50 meV energy range. However, it has been longly debated that the theoretical situation, as far as the half-life predictions are concerned, should be clarified: different calculations present significant variations for the same candidate emitters. Reducing these differences certainly represents an important theoretical challenge for the future, and one might hope that dedicated experiments will help making a step forward [15]. One way to constrain such calculations is by measuring related processes, such as beta-decay [16], muon capture [17], charge-exchange reactions [18] and double-beta decay with the emission of two neutrinos [19] (the latter process is allowed within the Standard Model and does not tell us anything about the neutrino nature). Such a procedure has been used since a long time. However each of these processes bring part of the necessary information only.

Recently we have been showing that there is a very close connection between neutrinoless double-beta decay and neutrino-nucleus interactions [20]. In fact, by rewriting the neutrino exchange potential in momentum space and by using a multiple decomposition, the two-body transition operators, involved in the former, can be rewritten as a product of one-body operators, which are essentially the same as the ones involved in neutrino-nucleus interactions. (Note, however, that there keep being some differences

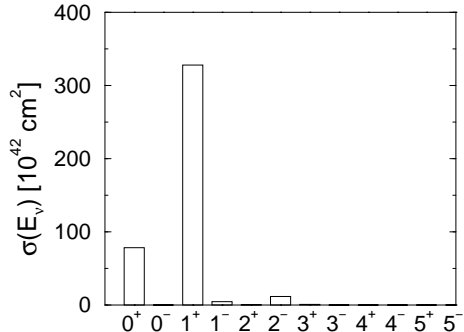


Figure 1. Contribution of the states of different multipolarity to the total charged-current $\nu_e + {}^{48}\text{Ca}$ cross section for neutrino energy $E_\nu = 30$ MeV. The histograms show the contribution of the Fermi ($J^\pi = 0^+$), the Gamow-Teller (1^+) and the spin-dipole ($0^-, 1^-, 2^-$) states and all higher multipoles up to 5 [20].

like for example short range correlations which can play a role in the two-body process, but not in the one-body one.) Therefore, besides the above-mentioned processes an improved knowledge of the nuclear response through either low-energy beta-beams or conventional sources (decay of muons at rest) could help constraining the neutrinoless half-life predictions as well. Figures 1 and 2 show the contribution of different states for two impinging neutrino energies on ${}^{48}\text{Ca}$ taken just as an illustrative example. One can see that the Gamow-Teller transition is giving the dominant contribution at low neutrino energies, while many other states become important when the neutrino impinging energy increases. These states are an essential part of the neutrinoless double-beta decay half-lives as well [2].

2.2. A small storage ring

The main aim of the work in Ref.[8] has been to calculate exactly: *i*) the neutrino-nucleus interactions rates expected at a low-energy beta-beam facility, by using parameters from the first feasibility study [4]; *ii*) to study how these scale by changing the geometry of the storage ring. In particular, two sizes have been considered: a small

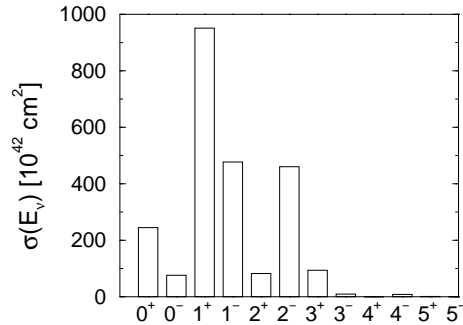


Figure 2. Same as Fig.1 for $E_\nu = 60$ MeV [20].

one, i.e. 150 m straight sections and 450 total length, like the one planned for the future GSI facility [21]; a large one, having 2.5 km straight sections and 7 km total length, such as the one considered in the original beta-beam baseline scenario [1]. Table I shows the events for deuteron, oxygen, iron and lead, taken as typical examples, the detector being located at 10 m from the storage ring. One can see that interesting interaction rates can be obtained on one hand and that clearly a small devoted storage ring is more appropriate for such studies on the other hand. The physical reason is simple. Since the emittance of the neutrino fluxes is inversely proportional to the γ of the ions, only the ions which decay close to the detector contribute significantly to the number of events, while those who decay far away see the detector under a too small opening angle. The complementarity between a low-energy beta-beam and conventional source is discussed in [22].

3. CONCLUSIONS

The use of the beta-beam concept to produce neutrino beams in the tens of MeV energy range is very appealing. If both electron-neutrino and electron (anti)neutrino beams of sufficiently high intensities can be achieved, low-energy beta-beams can offer a flexible tool, where the average neutrino energy can be varied by varying the γ of the ions. The studies realized so far indicate

Table 1

Reaction	Ref.	Mass (tons)	Small Ring	Large Ring
ν +D	[11]	35	2363	180
$\bar{\nu}$ +D	[11]	35	25779	1956
ν + ¹⁶ O	[23]	952	6054	734
$\bar{\nu}$ + ¹⁶ O	[23]	952	82645	9453
ν + ⁵⁶ Fe	[24]	250	20768	1611
ν + ²⁰⁸ Pb	[25]	360	103707	7922

Neutrino-nucleus interaction rates (events/year) at a low-energy beta-beam facility [8]: Rates on deuteron, oxygen, iron and lead are shown as examples. The rates are obtained with $\gamma = 14$ as boost of the parent ion. The neutrino-nucleus cross sections are taken from referred references. The detectors are located at 10 meters from the storage ring and have cylindrical shapes ($R=1.5$ m and $h=4.5$ m for deuteron, iron and lead, $R=4.5$ m and $h= 15$ m for oxygen, where R is the radius and h is the depth of the detector). Their mass is indicated in the second column. Rates obtained for two different storage ring sizes are presented: the small ring has 150 m straight sections and 450 total length, while the large ring has 2.5 km straight sections and 7 km total length. Here 1 year = 3.2×10^7 s.

clearly that a small devoted storage ring is more appropriate to obtain such beams in particular for performing neutrino-nucleus interaction studies, a promising axis of research. We have particularly discussed the interest of such measurements for a better knowledge of the nuclear response relevant for neutrinoless double-beta decay searches. The feasibility study of the small storage ring is now ongoing within the Eurisol Design Study. Several issues need to be addressed (e.g. stacking ion method, duty factor). The realization of low-energy beta-beams would be a *proof-of-principle* that the beta-beam concept works.

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REFERENCES

1. P. Zucchelli, Phys. Lett. B 532 (2002) 166.
2. C. Volpe, Jour. Phys. G 30 (2004) L1 [hep-ph/0303222].
3. J. Burguet-Castell *et al*, Nucl. Phys. B 695 (2004) 217 [hep-ph/0312068].
4. B. Autin *et al*, J. Phys. G 29 (2003) 1785 [physics/0306106]. See also <http://beta-beam.web.cern.ch/beta-beam/> and the contribution of M. Lindroos to this volume.
5. M. Mezzetto, J. Phys. G29 (2003) 1771 [hep-ex/0302007]; J. Bouchez, M. Lindroos, M. Mezzetto, AIP Conf. Proc. 721, (2004) 37 [hep-ex/0310059]; M. Mezzetto, Nucl. Phys. Proc. Suppl. 143 (2005) 309 [hep-ex/0410083]; A. Donini *et al*, Nucl. Phys. B 710 (2005) 402 [hep-ph/0406132]; A. Donini *et al*, Phys. Lett. B 621 (2005) 276 [hep-ph/0411402]; C. Volpe, Nucl. Phys. A 752 (2005) 38 [hep-ph/0409357]; J. Burguet-Castell *et al*, Nucl. Phys. B 725, 306 (2005) [hep-ph/0503021]; J. Bernabeu, J. Burguet-Castell, C. Espinoza, M. Lindroos, hep-ph/0505054 ; P. Huber, M. Lindner, M. Rolinec, W. Winter, [hep-ph/0506237]; see also contributions of J. Burguet-Castell and M. Mezzetto to this volume.
6. See <http://www.ganil.fr/eurisol/>.
7. G.C. McLaughlin and C. Volpe, Phys. Lett. B 591 (2004) 229 [hep-ph/0312156].
8. J. Serreau and C. Volpe, Phys. Rev. C 70 (2004) 055502 [hep-ph/0403293].
9. E. Kolbe *al*, Phys. Rev. C 52 (1995) 3437; S.K. Singh, N.C. Mukhopadhyay and E. Oset,

- Phys. Rev. C 57 (1998) 2687; E. Kolbe, K. Langanke and P. Vogel, Nucl. Phys. A 613 (1997) 382; A.C. Hayes and I.S. Towner, Phys. Rev. C 61 (2000) 044603; C. Volpe *et al*, Phys. Rev. C 62 (2000) 015501; N. Jachowicz *et al*, Phys. Rev. C 65 (2002) 025501; A. Brotugno and G. Cò, nucl-th/0506028.
10. G.M. Fuller, W.C. Haxton and G.C. McLaughlin, Phys. Rev. D 59 (1999) 085005; E. Kolbe and K. Langanke, Phys. Rev. C 63 (2001) 025802; C. Volpe *et al*, Phys. Rev. C 65 (2002) 044603; N. Jachowicz, K. Heyde and J. Ryckebush, Phys. Rev. C 66 (2002) 055501; M. Sajjad Athar *et al*, nucl-th/0506046.
 11. K. Kubodera and S. Nozawa, Int. J. Mod. Phys. E 3 (1994) 101.
 12. A.B. Balantekin, Prog. Theor. Phys. Suppl. 146 (2003) 227 [nucl-th/0201037]; A.B. Balantekin and G.M. Fuller, J. Phys. G 29 (2003) 2513 [astro-ph/0309519]; C. Volpe, Nucl. Phys. B 143 (2005) 43 [hep-ph/0409249]; E. Kolbe *et al*, J. Phys. G 29 (2003) 2569, and references therein.
 13. N.A. Smirnova and C. Volpe, Nucl. Phys. A 714 (2003) 441, and references therein.
 14. L. Baudis *et al.*, Phys. Rev. Lett. **83**, 41 (1999); H.V. Klapdor-Kleingrothaus *et al.*, Eur. Phys. J. A 12 (2001) 147; C.E. Aalseth, Phys. Rev. D 65, (2002).
 15. K. Zuber *et al*, article in preparation.
 16. K. Muto, E. Bender and H.V. Klapdor, Z. Phys. A 334, 177 (1989); M. Aunola, J. Suhonen, Nucl. Phys. A 602, 133 (1996).
 17. M. Kortelainen and J. Suhonen, Europhys. Lett. 58, 666 (2002); M. Kortelainen and J. Suhonen, Phys. Atom. Nucl. 67, 1202 (2004).
 18. J. Bernabeu *et al*, IPNO/TH-88-58, FTUV-88/20; H. Akimune *et al*, Phys. Lett. B 394, 23 (1997); S. Rakers *et al*, Phys. Rev. C 70, 054302 (2004) and 71, 054313 (2005).
 19. V.A. Rodin, A. Faessler, F. Simkovic, P. Vogel, Phys. Rev. C 68, 044302 (2003).
 20. C. Volpe, J. Phys. G 31 (2005) 903 [hep-ph/0501233].
 21. See <http://www.gsi.de/>.
 22. G.C. McLaughlin, Phys. Rev. C 70 (2004) 045804 [nucl-th/0404002].
 23. E. Kolbe, K. Langanke, P. Vogel, Phys. Rev. D 66 (2002) 013007; W.C. Haxton, Phys. Rev. D 36 (1987) 2283.
 24. E. Kolbe and K. Langanke, Phys. Rev. C 63 (2001) 025802.
 25. J. Engel, G.C. McLaughlin, C. Volpe, Phys. Rev. D 67 (2003) 013005.