What about a beta-beam facility for low-energy neutrinos ?

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A novel method to produce neutrino beams has recently been proposed : the beta-beams. This method consists in using the β decay of boosted radioactive nuclei to obtain an intense, collimated and pure neutrino beam. Here we propose to exploit the beta-beam concept to produce neutrino beams of low energy. We discuss the applications of such a facility as well as its importance for different domains of physics. We focus, in particular, on neutrino-nucleus interaction studies of interest for various open issues in astrophysics, nuclear and particle physics. We suggest possible sites for a low-energy beta-beam facility.

The recent discovery that neutrinos are massive particles has considerable impact on different domains of physics: in particle physics, where the description of non-zero masses and mixing requires the extension of the Standard Model of fundamental interactions; in astrophysics, for the comprehension of various phenomena such as nucleosynthesis; in cosmology with, for instance, the search for dark matter.

In the last few years positive oscillation signals have been found in a series of experiments using neutrinos produced with various sources [1,2]. In view of the importance of this discovery and its implications, a number of projects are running, planned in the near future, or under study in order to address many still open questions about neutrinos. Among them are those concerning their Majorana or Dirac nature, the mass hierarchy and absolute mass scale, the knowledge of the mixing angle θ_{13}, the possible existence of sterile neutrinos and of CP violation in the leptonic sector.

In a recent paper [3] Zucchelli has proposed an original method to produce intense, collimated and pure neutrino beams: the *beta-beams*. In contrast with the neutrino factory concept implying the production, collection and storage of muons to obtain muon and electron neutrino beams, the novel method consists in accelerating, to high energy, radioactive ions decaying through a β process. A beta-beam facility consists of a radioactive ion production and acceleration to low energy (like at CERN ISOLDE), further acceleration to about 150 GeV/nucleon (using for example the PS/SPS accelerators at CERN) and storing of the radioactive ion bunches in a storage ring. At present ^6He and ^{18}Ne seem to be the best candidates [3]. The resulting neutrino beam has three novel features, namely a single neutrino flavor (electron neutrino or anti-neutrino), a well-known energy spectrum and intensity, a strong collimation. Another important advantage: a beta-beam scheme relies on existing technology. The physics impact of such a beam has been discussed in [3,4] and includes for example oscillation searches, precision physics and CP violation measurements. The feasibility of beta-beams is at present under careful study [5].

In this letter we propose to exploit the beta-beam concept to produce intense, collimated and pure neutrino beams of low energies [6]. Low energies means here a few tens of MeV, like those involved in nucleosynthesis and in supernova explosions, up to about a hundred MeV. We argue that the physics potential of such a facility would have an important impact on hot issues in different domains, in particular nuclear physics, particle physics and astrophysics. To illustrate this we focus on the specific example of neutrino-nucleus interaction studies and discuss some open questions that could be addressed with a low-energy beta-beam facility [6]. Finally, we analyze possible sites for such a facility.

Nuclei are used to detect neutrinos in experiments designed to study neutrino properties, such as oscillation measurements, as well as experiments where neutrinos bring information from the interior of stars like our sun or from supernova explosions. As a consequence, a detailed understanding of neutrino induced reactions on nuclei is crucial both for the interpretation of various current experiments and for the evaluation of the feasibility and physics potential of new projects. Examples are given by the use of [1]: - deuteron in heavy water detectors like in SNO for solar neutrinos; - carbon in scintillator detectors such as in the LSND and KARMEN experiments using neutrinos from a beam dump [2,7]; - oxygen in Cherenkov detectors like in the Super-Kamiokande detector or in next-generation large water detectors like UNO and Hyper-K [8]; - lead-perchlorate [9] and lead in new projects for supernova neutrinos such as OMNIS and LAND [10]. Open issues in astrophysics provide important motivations for improving our present knowledge of neutrino-nucleus interactions. In particular, the role of these reactions for nucleosynthesis is under intense investigation [11].

So far, experimental data on neutrino-nucleus interactions are extremely scarce. The largest ensemble of data has been obtained for carbon [2,7] where discrepancies between experimental and theoretical values have been the object of intensive studies in the last years [12,13]. There is one measurement in deuteron [14] and one in iron [15]. In the case of deuteron, where theoretical predictions are very accurate, there is still an important unknown quantity, i.e. L_{1A} [16]. Theoretical calculations are therefore of absolute necessity. However, getting accurate predictions is a challenging task and necessitates as much experimental information as possible.

The general expression for the cross section of the $\nu_l +^A_Z X_N \rightarrow l +^A_{Z+1} X_{N-1}$ reaction (l is the outgoing lepton), as a function of the incident neutrino energy E_ν, is given by [17] :

$$\sigma(E_\nu) = \frac{G^2}{2\pi} cos^2\theta_C \sum_f p_l E_l \int_{-1}^{1} d(cos\,\theta) M_\beta, \qquad (1)$$

where $G\,cos\,\theta_C$ is the weak coupling constant, θ is the angle between the directions of the incident neutrino and the outgoing lepton, $E_l = E_\nu - E_{fi}$ is the outgoing lepton energy and p_l its momentum, E_{fi} being the energy transferred to the nucleus. The quantity M_β contains the nuclear Gamow-Teller and Fermi type transition probabilities [12].

The energy which can be transferred to the nucleus in a neutrino-nucleus interaction does not have any upper value since the neutrinos can have any impinging energy according to the specific neutrino source. Typical neutrino energies cover the range from the very low (up to about 10 MeV for reactor and solar neutrinos) to the low (tens of MeV for e.g. supernova neutrinos) energy regime, to the intermediate (about 100-300 MeV) and high (GeV and multi-GeV) energy range of accelerator and atmospheric neutrinos. The nuclear degrees of freedom relevant in these various energy windows are very different and the models used to describe the transition probabilities in (1) range from the Elementary Particle Model, Effective Field Theories, detailed microscopic approaches (Shell Model, Random-Phase Approximation and its variants) for low momentum transfer, to the Fermi Gas Model at high momentum transfer [18].

One of the difficulties in getting accurate theoretical predictions comes from the increasing role played by the forbidden transitions when the neutrino energy increases, as pointed out in [12,19]. The importance of the forbidden spin-dipole transitions in nucleosynthesis has been first pointed out in [20]. As an example Fig.1 shows the contribution of various states, excited in the ν_e(Pb,Bi)e^- reaction, to the total cross section and its evolution with increasing neutrino energy. In particular we see that already for 30-50 MeV neutrino energy the contribution of forbidden states ($J^\pi \neq 0^+, 1^+$) becomes significant.

The importance of forbidden states can also be seen directly in the flux-averaged cross sections – obtained by folding the cross sections (1) with the relevant neutrino flux – which are the relevant quantities for experiments. For low energy neutrino, such as supernova neutrinos, or neutrinos produced by the decay-at-rest of muons, the spin-dipole states ($J^\pi = 0^-, 1^-, 2^-$) contribute by about 40% in ^{12}C [12] and ^{56}Fe [15], and by about 68% in ^{208}Pb [19]. The contribution from higher forbidden states is about 5% and 25% in iron and lead respectively. Their role increases with increasing neutrino energy. Indeed, they contribute by about 30% in carbon [12] and 60% in lead [19] in the intermediate energy region corresponding, for example, to neutrinos produced from pion decay-in-flight.

Few data exists on the spin-dipole states, mainly from charge-exchange reactions [21] and practically none for the higher forbidden states*. More experimental information is needed to constrain theoretical calculations of the centroid, the width and the total strength of forbidden states. For example, one of the open questions concerning these states is the possible quenching of their strength. Note that understanding the quenching of the allowed Gamow-Teller ($J^\pi = 1^+$) strength, namely the reason why the observed strength is only a fraction of the predicted one, has been a longstanding problem in nuclear physics [22].

This has a direct impact on the physics potential of running experiments or projects under study. Let us consider the case of lead-based projects which aim at measuring supernova neutrinos. It has been shown, for example, that the a precise measurement of the energy of the electrons emitted in the charged-current neutrino-lead reaction can provide useful information about the temperature of the initial muon/tau neutrinos produced in a supernova explosion [23]. Although this result seems little sensitive to the details of the calculations, a measurement of the differential electron cross section would bring an important piece of information. Moreover, the number of charged current events in coincidence with neutrons produced in the des-excitation of Bi may be used to determine whether the mixing angle θ_{13} is much larger or much smaller than 10^{-3}. In the latter case, one would need – as far as the neutrino detection is concerned – a very precise knowledge of the reaction cross sections [23]. Similar studies have been performed in various other nuclei. In [24] it has been shown that in Cherenkov detectors the detection of γ rays produced in the inelastic neutrino scattering off oxygen allow to identify $\nu_{\mu,\tau}$.

A low-energy beta-beam facility would provide the possibility to perform neutrino-nucleus interaction studies with various nuclei and address the many open questions [18,25,26]. Examples are the measurements of reaction cross sections on deuterium, carbon, oxygen, iron and lead. In the latter case, the measurement of the differential electron cross section as well as of the neutral and charged current cross sections in coincidence with one- and two-neutron emission would be of great interest. A larger set of experimental data would allow us to make

*Some knowledge about the relevant states can be obtained through muon capture experiments.

reliable extrapolation from the low to the high neutrino energy regime. It would also provide important information for the extrapolation to the case of neutrino reaction on exotic nuclei, which are of astrophysical interest. Finally, one should reanalyze, in the context of a low-energy beta-beam facility, the feasibility of the experiments proposed for the ORLAND project (Oak Ridge Laboratory for Neutrino Detectors) [25] which has been proposed a few years ago (these include, for example, oscillation searches, measurement of the Weinberg angle at low momentum transfer). Another aspect of beta-beams should be stressed : the neutrons emitted from some beta-decay candidates also open other axes of research besides the one mentioned here.

The future availability of intense radioactive ion beams at several facilities offers various possible sites for a beta-beam facility producing low-energy neutrinos. Among these are GANIL, GSI, CERN or the EURISOL project. Table 1 shows the capabilities (energy and intensities) which can be attained at these sites. Concerning GSI, lower intensities will be reached with the presently envisaged upgrade [27]. We see that two configurations are possible. In sites like GANIL and for the EURISOL project (in the present shape where the ions are accelerated up to a 100 MeV/A and without a storage ring), the gamma of the parent ions is equal to one. Therefore, one can bring the ions in a 4π detector and dispose of intense neutrino sources. In sites like GSI and CERN, the ions will be accelerated and stored in a storage ring (at GSI with the future HESR). In particular, at GSI one will dispose of neutrinos spanning the tens of MeV energy range, whereas at CERN, one could span from tens to 100 MeV neutrino energy domain.

In conclusion, we propose to exploit the beta-beam concept to produce intense and pure low energy neutrino beams. Such a facility would have a considerable impact in different domains of physics. Possible sites include CERN, GSI and GANIL.

I am grateful to M. Lindroos for the discussions concerning the feasibility of a low-energy beta-beam facility as well as for suggesting the GANIL and GSI laboratories as possible sites. Thanks also to A. Villari and H. Weick for fruitful discussions and to R. Lombard and J. Serreau for careful reading of this manuscript.

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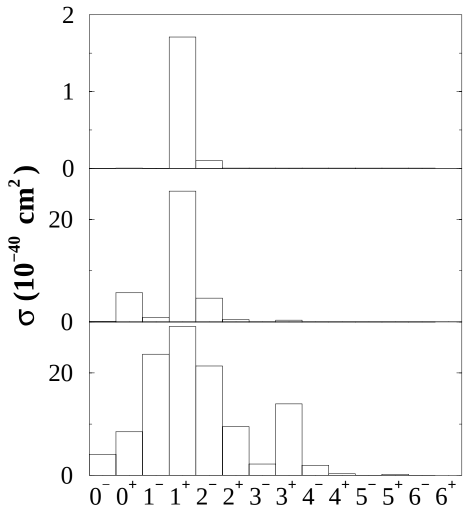

FIG. 1. Contribution of states of different multipolarities to the ^{208}Pb$(\nu_e, e^-)^{208}$Bi reaction cross section (10^{-40} cm^2) for $E_{\nu_e} = 15$ MeV (up), 30 MeV (middle), 50 MeV (bottom) [19].

	Ion intensity	γ
GANIL	10^{12} ions/s	1
EURISOL	10^{13} ions/s	1
CERN	2×10^{13}ions/s	1-150

TABLE I. The table shows the ion intensities and the gamma of the parent ion which could be available at possible sites for a low-energy beta-beam facility. The numbers refer to ^{6}He as an example. Results for CERN are from [5].