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β-beams: R&D challenges in FP7

P. Delahaye[1]
CERN
1211 Geneva 23, Switzerland
E-mail: pierre.delahaye@cern.ch

U. Köster
Institut Laue-Langevin
6 rue Jules Horowitz, 38000 Grenoble Cedex 9, France
E-mail: koester@ill.fr

As a quite novel concept for producing pure flavour neutrino beams, the beta-beam project presents several R&D challenges requiring careful studies. In the centre of these, the production of radioactive ion beams of beta-decaying nuclides of intensities orders of magnitudes higher than achieved so far has triggered various investigations. This article focuses on the production and beam preparation issues of such intense radioactive ion beams for beta-beams.

Among the different scenarios for next generation neutrino beam facilities, beta-beams make use of intense post-accelerated radioactive ion beams for producing pure electron neutrino and antineutrino beams [1]. For such a project to meet the sensitivity requirements for the θ_{13} mixing angle and CP violating phase determination, fluxes of 1.10^{18} ν and 3.10^{18} were generally assumed [2], in first approximation independant of the isotopes that are considered. The isotopes that were proposed so far are ^{6}He and ^{18}Ne [1,3], and more recently ^{8}Li and ^{8}B with an original production method making use of ionization cooling mechanism in a ring [4,5]. For each of these isotopes, general considerations will be made concerning the production, transport, ionization methods and efficiencies. Issues concerning the collimation of such intense ion beams in the storage ring used for neutrino beam generation were introduced during the time of the conference and will be reported in a future paper [6]. Other R&D challenges related to the acceleration techniques, radioprotection and multi-ionization are presented in separated contributions to this conference [7,8] as well as a possible alternative production technique for ^{6}He and ^{8}Li [9].

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1. Production of ^{6}He and ^{18}Ne beams

Originally, ^{6}He and ^{18}Ne respectively as antineutrino and neutrino emitters were selected by using the figure of merit given in [1] among the rather short-lived isotopes that are efficiently and cleanly produced using quite standard ISOL (isotope separation on-line) methods [3]. The ionization of such radioactive noble gases is very efficient in standard ECR (electron cyclotron resonance) ion sources used in continuous mode. A prototype of 60GHz ECR source is being developed for the production of intense and short bunches of such ions for beta-beams [8].

In the frame of EURISOL, the scenario investigated so far for the production of ^{6}He was the use of a neutron converter bombarded by a 1-2 GeV p beam surrounded by a BeO target . The large cross section of the ^{9}Be(n,α)^{6}He reaction (100 mb at 3MeV and above 30 mb until 10 MeV) and the expected intensities for EURISOL primary drivers ($\geq$100 μA) give a favourable projection for the beta-beams requirements [10]. About 10^{14} ^{6}He isotopes could be produced per s with an optimized target and converter assembly. This is consistent with a few 10^{13} atoms transported to the ECR source as given in the top-down approach of the beta-beam facility [11].

For ^{18}Ne though, the production rate as predicted in EURISOL 100kW targets is at least one order of magnitude below the requirements [3,12]: 10^{12} atoms per second at maximum could be obtained by spallation reactions in 1 m long targets of MgO or Al_2O_3 bombarded directly by the proton beam. Thus, again a direct reaction at lower energy is preferred to spallation or fragmentation reactions. Recently, cross sections for the reactions ^{19}F(p,2n)^{18}Ne and ^{16}O(^{3}He,n)^{18}Ne at low energy (<~65MeV and ~15MeV respectively) were measured at LLN [13]. The latter reaction could be promising for beta-beams as it was estimated that a 2MW beam of 130mA of ^{3}He at 14.8MeV impinging on a 60 cm diameter MgO target could produce of the order of 10^{13} atoms/s, maintaining a reasonable deposited power per unit surface. Other oxide targets could be considered, BeO for instance which would provide less stopping for the primary beam through the lower Z of Be and a better heat conductivity than MgO.

2. Production of ^{8}Li and ^{8}B beams

Recently ^{8}Li and ^{8}B were proposed as candidates for beta-beams using an original production method developed by Rubbia et al. [4]. The choice of these mirror nuclides is mainly motivated by their higher beta-decay Q-value which yields higher energy neutrino spectra at a given Lorentz gamma of the decay ring [5]. Again ion beam intensities of the order of 10^{13}/s are necessary to reach the physics objectives, and could be achievable using the ionization cooling technique in a production ring [4]. There reactions such as ^{7}Li(d,p)^{8}Li and ^{6}Li(^{3}He,n)^{8}B could be used in inverse kinematics on an internal gas target. The Li beams are circulating in the production ring with typical energies of 25MeV and their energy loss in the internal target is compensated by means of an RF cavity. Rather than discussing the production principle itself, we will give here general ideas on the collection device as proposed as a first attempt by Rubbia et al. and relying on existing ISOL techniques. In ref. [4], it is assumed that thin Ta rings collect the reaction products at a typical angle of 10° compared to the closed orbit axis. The Ta foils are heated for accelerating diffusion and effusion processes towards the ion source.

2.1 Collection, transport and (multi-)ionization of ^{8}Li beams

We recall that an ISOL target and ion source system consists of a heated target or catcher respectively from which the stopped reaction products are released by thermal diffusion. This target or catcher is placed in a volume that is closed, except for the way communicating with the ion source, such that more or less all released atoms are forced to effuse eventually to the ion source. To avoid excessive delays through adsorption, all surfaces that might be encountered by the effusing atoms have to be kept at a temperature where the adsorption time of the wanted species does not exceed much the flight time between two surface collisions during the random walk effusion (order of milliseconds).

Whereas the ionization of gases is extremely efficient in ECR ion sources (almost 100% summing all charge states for He and Ne), the ionization of condensable elements has always been considerably more complicated. The plasma chamber of a typical ECR ion source is usually cooled for protecting the permanent magnets of the hexapole (or other multipole) which is used for radial confinement. In the case of the beta-beam 60GHz ECR ion source, the hexapolar field could be produced by special radiation-hard copper coils [8]. In this case a “hot” plasma chamber could be envisaged within acceptable temperature limits that will be defined by the plasma chamber material itself, the coils and surrounding materials. Mostly steel and aluminum, known for its good properties as electron donor for the plasma are presently used as material for the plasma chamber. Other materials need therefore to be investigated. In any case a too low temperature would inevitably yield significant losses because of too long sticking times on the wall of the ECR ion source before the atoms are ionized and captured within the plasma. Efficiencies obtainable in such scenario can be orders of magnitude lower than for noble gases. To circumvent this problem, ^{8}Li isotopes could instead be extracted after surface ionization to 1+ and transported as 1+ ions from the collection device to the ECR ion source.

In any case the Ta catcher foils as described in ref. [4] have to be heated to the right temperature. Ta foil targets at ISOLDE have to be kept at temperatures well above 2000 °C to assure an efficient release of ^{8}Li [14]. This is achieved by placing the target foils in an Ohmicly heated Ta target container with 0.5 mm wall thickness. A direct adaptation of such a solution to the production method discussed here is obviously impossible due to the short range of few 10 μm for the product nuclei [4]. Hence the catcher foil cannot be placed in a separate vacuum vessel, but must be placed in a common enclosure with the internal gas target. Consequently the released radioactive atoms or ions would not effuse under vacuum to the ion source, but would be swept away by the gas flow of the gas target. However, a good fraction of the Li atoms will be surface ionized when leaving the hot Ta foil. Hence they could in principle be separated from the neutral gas jet by a skimmer with appropriate electric fields. A similar technique is known as the IGISOL method, in use e.g. at JYFL [15]. In this case the reaction products would be stopped in a ^{4}He gas cell (instead of a solid catcher), guided as 1+ or 2+ ions within a gas flow to the extraction region where they would be skimmed from the neutral gas by electric fields. Efficiencies of the order of 1 to 10% are quoted in [15] for light-ion induced fusion reactions and have been recently further optimized by improving the differential pumping of the IGISOL cell [16]. We can conclude that a possible solution points towards the use of a gas stopper

instead of a heated solid stopper. The latter would introduce a significant technical complication without evident advantage.

Once a 1+ ion beam could be created, an extraction potential of several tens of kV could be used for injecting the 1+ ions into the plasma of a separate ECR ion source. This so-called 1+-n+ method has been tested at Grenoble, ISOLDE and TRIUMF for the post-acceleration of radioactive ion beams [17-19]. Efficiencies of about 30% in continuous mode summing all charge states have been obtained for masses above 40 amu. For light masses though, the injection efficiency is significantly lower (<10% for Na) and specific injection methods need to be developed. These include the possible use of ion coolers as proposed in ref. [18].

2.2 Collection, transport and ionization of ^{8}B

As boron reacts with many elements usually present in ISOL target and ion source units (C, N, O, various metals), and has high melting and boiling points, no boron beams have been produced so far at an ISOL facility. The nearly impossible desorption of elemental boron from the surface of a catcher foil calls for a chemical evaporation method. The introduction of CF_4 gas in order to form in-situ volatile $^{8}BF_3$ molecules has been proposed in [20]. It is not evident to find a suitable catcher material that simultaneously provides a rapid out-diffusion of boron, allows for an efficient formation BF_3 on its surface and is itself resistant against massive attack by CF_4. The choice of an ISOL catcher material offers more freedom than an ISOL target material that moreover has to provide favorable cross-sections for the production reaction. Still, even when the problem of desorption could be solved, the $^{8}BF_3$ molecules would be carried away by the stream of target gas. Being neutral, the elegant electric separation is no longer possible in this case. Therefore even more than in the case of ^{8}Li, a direct use of a gas stopper in an IGISOL scheme is preferable. The yield of ^{12}B ions obtained by such a scheme in ref. [16] allows to estimate an overall efficiency of about 5% for the stopping, release and ionization efficiency. Combined with the likely lower charge breeding efficiency compared to the ^{18}Ne case this leads to a massive reduction of the finally available radioactive ion beam intensity.

Without an innovative solution to this fundamental problem the ^{8}Li/^{8}B beta beam scenario is not as competitive to the ^{6}He/^{18}Ne beta beam baseline scenario as it may have first appeared.

3. Conclusion

The production of neutrino and antineutrino beams from the decay of ^{6}He and ^{18}Ne has been studied in the frame of EURISOL. Whereas ^{6}He required intensities are probably within reach, the case of ^{18}Ne still needs to be studied carefully. A promising reaction channel ^{16}O(^{3}He,n)^{18}Ne has been studied at Louvain La Neuve which could give compatible production rates. It would require the developement of a primary driver providing an intense beam of ^{3}He sent onto a large oxide target. Diffusion and effusion delays for such a geometry still need to be investigated.

In the frame of EURO-ν, the production of ^{8}Li and ^{8}B will be investigated as the first focus. As condensable elements these isotopes are more difficult to release, transport and ionize. Imaginative solutions will have to be found, some of them have been presented here. On-line

tests will be performed at Louvain La Neuve and GANIL [7]. The ionization and bunching of ^{8}Li, ^{8}B in atomic, ionic or molecular form will be undertaken by the LPSC Grenoble [8].

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