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High intensity ion guides and purification techniques for low energy radioactive ion beams

S. Grévy

Centre d'Études Nucléaires de Bordeaux Gradignan, CNRS/IN2P3-Université de Bordeaux, BP 120, F-33175 Gradignan Cedex, France

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ABSTRACT

This report gives an overview of the different devices which can be used for the purification of high intensity low energy radioactive ion beams: high resolution magnetic separators (HRS), multi-reflection time-of-flight mass separators (MR-TOF-MS) and Penning traps (PT). An overview of HRS, existing or in development, and the methods to increase the resolving power are presented. The MR-TOF-MS of ISOLTRAP and other projects having been presented during this conference, only the main characteristics of such devices are discussed. Concerning the PT, intensively used to measure masses with high precisions, we will present the PIPERADE project which aims to provide pure beams of exotic nuclei with unprecedent intensities at the future DESIR/SPIRAL2 facility.

1. Introduction

A large number of low energy radioactive ion beam facilities are currently operating, constructed, or planned all around the world [1]. These facilities aim at providing high intensity and high purity beams for experiments so as to make sensitive measurements possible. In this context, the development of high intensity ion guides and powerful purification devices is important for the nuclear physics community. The production of intense beams of exotic nuclei can be accompanied by a strong contamination of nuclides closer to stability. Therefore, it is possible that the nuclei of interest represent only a very small fraction of all the produced nuclei. The ions are extracted at low energy (typically in the range of 30–60 keV). These are mostly singly charged and the beams have relatively poor optical qualities with emittances in the range of few tens of $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$. However, the experiments require more intense beams in order to reach more and more exotic nuclei as well as beams with high purities and good optical properties. To meet these requirements, powerful purification devices with high transmission are necessary. These devices are characterized by two important criteria: (1) the selectivity, which is the capability to separate the ions of interest from the contaminants and (2) the rapidity, which is the time needed to separate the ions of interest from the contaminants. These two aspects are usually difficult to be satisfied simultaneously, especially that the efficiency in providing the ions of interest has to be maximized.

An example of radioactive beam production is given on Fig. 1 with the extracted fission product yield from a ^{252}Cf source such as the one used at Argonne National Laboratory [2]. If a selection based on the chemical element (i.e. on the proton number Z) is made, for example using resonant laser ionization, a mass (A) selection able to separate different isotopes is sufficient. The needed resolving power in this case is of the order of $M/\Delta M \simeq 400$, see Section 2.1, and can be achieved for example using a dipole magnet (M and ΔM are the atomic mass and their difference, respectively). Such an elemental selection using laser-ionization sources is widely used in many laboratories [3]. Despite their continuous development and improvements [3,4], laser-ionization sources are not available for all elements. Moreover, surface-ionizable contaminants may still be extracted as contaminates. Therefore, a mass selection (A) able to separate the nuclei at the level of isobars is often needed. For example, without an initial Z selection, the required mass resolving power to separate ^{132}Sn and ^{132}Sb is $\simeq$40,000, a factor 100 larger than what is typically achievable with standard dipole magnets. To illustrate the importance of the resolving power, the left part of Fig. 2 displays the number of neighboring isobars as a function of the resolving power required for separation. We clearly see that while a resolving power of 10^4 allows to separate most of the isobars, an additional factor 10 is clearly needed to separate almost all of them. Moreover, it should be noted that the most demanding resolving power in isobaric separation may not necessarily be due to the neighboring isobar but due to an isobar located on the other side of the mass parabola. The right panel of Fig. 2 shows the distribution of the required resolving powers to separate neighboring isobars as a

E-mail address: grevy@in2p3.fr

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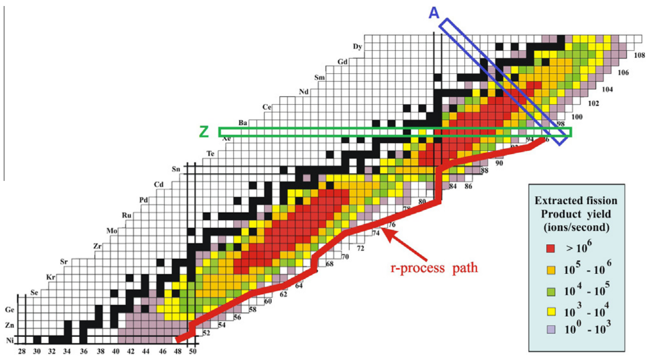

Fig. 1. Extracted fission fragment yield from a ^{252}Cf source (activity of 1 Ci) illustrating the non-selective production method. Less exotic nuclei are produced with orders of magnitude larger intensities. The selection of a given nucleus requires high selectivity which can be achieved, for example, by element (Z) and mass (A) selection with a limited resolving power on both parameters or by using only a mass (A) selection but with a selectivity at the level of the isobar. Adapted from [2].

function of ΔZ from stability (ΔZ indicates the number of protons away from stability when considering an isobaric chain). We notice that higher resolving powers are needed for the isobars closer to the stability (at the center of the mass parabola) whereas more exotic isobars require smaller resolving powers. Nevertheless, other issues have to be considered for more exotic nuclei such as the time available for separation (due to the lifetimes limits) or the overwhelming ratio of contaminant to ion of interest. We can also notice that, if isobars are the most common contaminants, other species like molecules may also be produced in very large quantities and therefore a high resolving power will always be useful. Finally, very high resolving powers may also allow for isomeric separation in order to produce isomerically clean beams.

In the following sections, we are going to discuss the possibilities offered by three different types of devices which can be used to obtain high resolving powers: high resolution magnetic separators (HRS), multi reflection time-of-fligh mass separators (MR-TOF-MS) and Penning traps (PT).

2. High Resolution Magnetic Separators

2.1. From a magnetic separator to a HRS

Most separators are based on the use of magnetic fields. A particle of mass M, charge Q and velocity v is deviated by a magnetic field B with a curvature radius ρ according to the relation:

$$B\rho = M.v/Q \tag{1}$$

In the first order, neglecting aberrations, the mass resolving power of such a separator is given by

$$R = \frac{D_M}{2x_0|M_x|} \tag{2}$$

where D_M is the mass dispersion of the system, x_0 is half of the width of the initial object in the dispersive direction and M_x is the magnification (see Fig. 3). The resolving power depends thus on the magnetic dispersion and inversely on the beam emittance. Considering standard values of 2 m (2 cm/%) for the dispersion (at the first order, the dispersion of a magnet is given by its curvature), 5.10^{-3} m (5 mm) for the beam width and a magnification of 1, the typical resolving power is 400, as stated in the introduction. In order to increase the resolving power, the size of the initial object has to be reduced and/or the mass dispersion increased. To decrease x_0, slits can be used but the transmission will also get reduced, the beam can be better focused but there are limitations in terms of angular acceptance for a given emittance. Alternatively, the incoming beam can be cooled using a radio-frequency quadrupole (RFQ) to reduce the emittance [6]. In this case the ions are injected into a linear trap located on a high-voltage platform and filled with a neutral buffer-gas. The slowed-down incoming ions collide with the buffer-gas particles which cools the ion beam. At the same time, the ions are confined on the beam axis by the RF field and transported towards the end of the RFQ by a continuously decreasing DC potential to be finally re-accelerated by the HV platform. For example, the device SHIRaC [7] that will be installed in front of the DESIR-HRS provides low-emittance beams with $x_0 = 0.5$ mm. The mass dispersion of the system (D_M) depends mainly on the magnet curvature (ρ_M), the dispersion angle (θ_M) and the *used-area* of the magnet (A_M). In order to increase the resolving power, these three parameters need to be maximized, as illustrated on Fig. 3. Using a dedicated optical system between the initial object and the entrance of the magnet to produce an elongated beam in the dispersive plane, the *used-area* of the magnet can be increased. The curvature can also be increased using a bigger magnet and finally a larger deviation angle can be used. For the HRS being constructed in the framework of SPIRAL2, optimizing these parameters allowed to reach a magnetic dispersion of ≈ 31 cm/% and therefore a calculated resolving power of 31,000 [8]. With such a large value, the aberrations cannot be neglected anymore. In particular, the increase in beam width due to the energy dispersion has to be limited and an RFQ is used to keep this value below 1 eV.

In the next section, we present the status of the development and the planned upgrades of the HRS devices of the main low

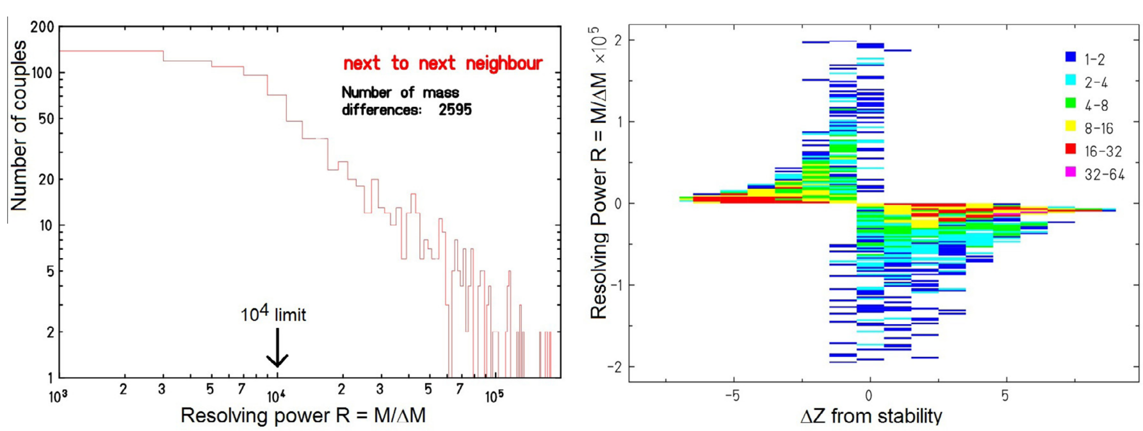

Fig. 2. Left: number of neighboring isobars as a function of the resolving power needed to separate them. Right: resolving power distribution as a function of the ΔZ from the stability (see text); the color code indicates the number of neighboring isobars. Data taken from Ref. [5]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)