RADIOACTIVE BEAM INJECTOR FOR SHORT-LIVED HEAVY IONS

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Proposed is a project of an efficient system that is to allow the nuclear reaction products (NRP) produced at the FLNR JINR cyclotron U-400 to be extracted from the target, ionized and quickly transported to the ECR source located at the input of the U-400M axial injection system. The NRP extracted from the target are ionized by an ion source located near the target to produce singly-charged ions. The source is based on the principle of surface ionization. To ensure a wide range of the elements to be ionized, provision is made for producing both positive ions and negative ions.

1. Introduction

At the last conference in Cape Town the FLNR project to produce radioactive ion beams (RIB) with the U400M - U400 cyclotrons was presented [1,2]. In this complex RIB will be produced in an ISOLDE-type target-ECR ion source assembly using the light and heavy ion beams from U400M with energies up to 100 MeV/n, transported via the exciting 120 m long transfer between two accelerators and injected into the U400 cyclotron accelerated to energies of (25-0,5) MeV/n.

However, in spite of its attraction, this project needs the considerable alterations of the existing accelerator infrastructure (first of all, of the U400M), which, in turn, needs a lot of investment and time.

At the same time the preliminary consideration shows, that the project cost could be essentialy less if the combunation U400 - U400M will be used (U400 as a production machine and U400M as a post accelerator).

To give grounds for this project, it is necessary to provide a brief explanation concerning the physics of the production of RIB.

One of the important questions in the production of RIB is the question of isotope yields and the most probable fragment mass as a function of the target, projectile mass and energy. The investigations that were performed at the FLNR and GANIL showed that the isotope production cross sections rise for energies up to about 15-20 MeV/u (contribution from deep inelastic trancfer reactions), after which they remaining more or less flatten for energy regions where fragmentation is expected to prevail (~75 MeV/n) [2].

In our case, taking into accout that for the U400 cyclotron the intensity of the ions at energies of 15-20 MeV/n will be high enough (up to 10^{13} pps), one can expect high yields of isotopes of various masses from the stability line.

Nuclear Reaction Products (NRP) are produced in a target located in the first accelerator (U400), then extracted from the target and pre-ionized, where upon they are transported along a channel to a multiply-charged ion source (of an ECR type) connected to the axial injection system of the second accelerator U400M (see Fig. 1).

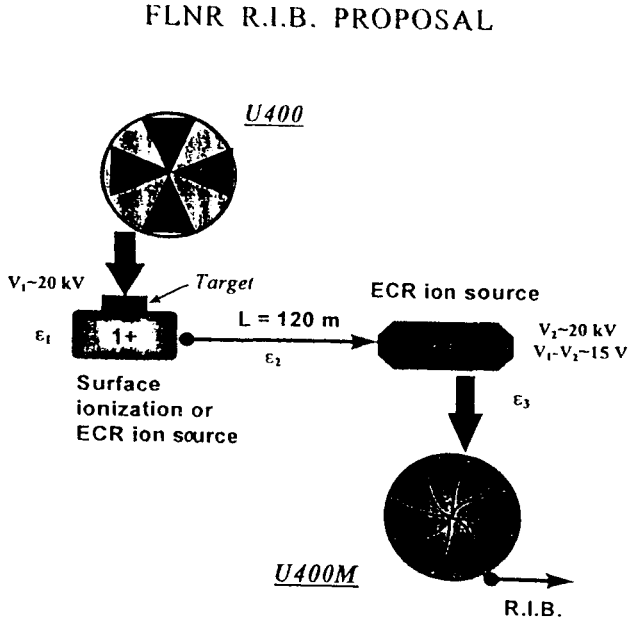

Fig. 1. A lay-out of the system under consideration involving the heavy ion accelerators U-400, U-400M and sources of single-charged and multiple-charged ions of radioactive atoms.

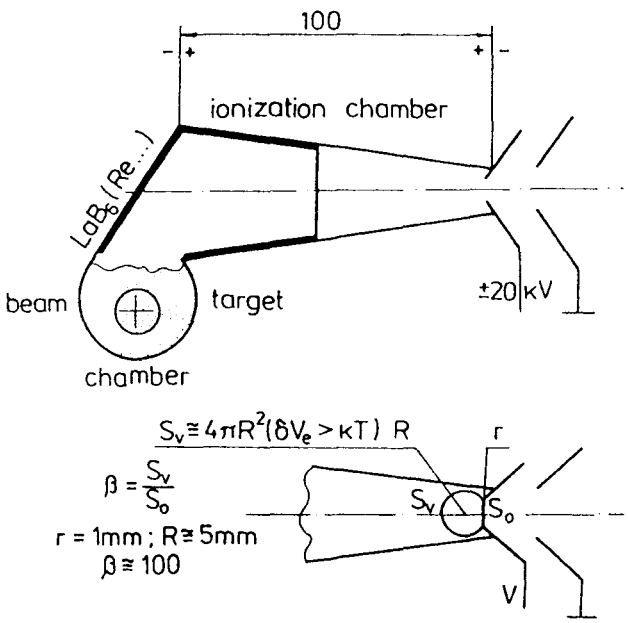

Fig. 2. An ISOL-type ion source of single-charged ions of radioactive atoms.

2. The target

As the target is used a fine-grained powder (grains of ~1 μkm) or melt of materials that afford the fast diffusion of NRP, a special-purpose chemical compound with similar properties can be used as well (for example stearats for inert gases). The target is placed in a chamber made of W (WRe, Ta) foil, the chamber being heated with a direct current up to T < 2000 K.

The target thickness along the direction of the incident heavy-ion beam depends on the pathlength of the light nuclei at the beam energy < 50 MeV/n and, for example, is 40÷50 mm for the ^{6}He produced in the reaction $Be^{9}(Li^{6}, He)$.

3. The single-charged ion source

The single-charged ions of NRP are produced in an ion source of the simplest type (hot cavity) by the surface ionization technique [3].

Its ionization chamber, made of W (WRe, Ta, Ir...) foil as well (Fig. 2), is 30 mm in length and 20 mm in diameter. It is connected to the target chamber. The walls of the ionization chamber are heated up to T < 2500 K with a direct current of such polarity as for its electric field induced inside the source to guide and accelerate the ions towards the extraction outlet. The outlet is 1-2 mm in diameter. The penetration of the external extraction field through that outlet into the source cavity permits the ion extaction efficiency (β) to be increased. The depth of the penetration, r_V, determines the equipotential sphere from whose surface (S_V) the ions to be extracted can acquire energy $Z\delta V > kT$ and be extracted from the source.

The yield of neutrals given by the source is directly proportional to the geometrical area, S_0, of the outlet, whereas the yield of charged particles is directly proportional to the area S_V of the sphere (Fig. 2). Therefore the ion extraction efficiency of such a source is increased by the factor β:

$$\beta = \frac{S_V}{S_0}; \quad \text{for } r_V = 5\text{mm}, r_0 = 1\text{mm} \quad \beta \approx 100.$$

To extend the range of the ions to be ionized, provision is made to produce both positive ions and (or) negative ions. For this purpose, used are two kinds of surface material: one of a high work function (for example Re < φ ≈ 5÷5.7 eV) and the other of a low work function (for example LaB_6, φ ≈ 2.7÷2.27 eV), or use is made of a specially created composite material of a high thermal shock resistence whose work function φ is < 1.2 eV. This allows an ionization efficiency of 10÷80% to be achived for most of the elements of the Periodic Table, with the exception of inert gases, B, Be, N, Zn, Cd, Hg and, probably, some others.

4. The duration of stay of NRP atoms in the source hot cavity

The duration of stay of NRP atoms in the source hot cavity, τ_i, consists of the time it takes an atom to move from wall to wall, τ_f, multiplied by the number of the collisions with the walls before leaving the source, n, the duration of stay on the wall, τ_s, also multiplied by the number of the collisions with the walls and the time it takes to diffuse from the target, τ_d:

$$\tau_i = \tau_d + n(\tau_f + \tau_s).$$

The time of diffusion τ_d for targets of a molten material, fine-grained powder or a solid-state absorbent was measured both in special-purpose investigation [4, 5] and in on-line experiments using mass-separators [6, 7]. It was found to depend strongly on the experimental conditions, the phisical and chemical properties of the target material and the kind of the atoms produced. The minimum time of diffusion observed in on-line experiments with mass-separators, as a rule, was from $\tau_d \approx 0.1$ s.

The time of a single wall-to-wall flight of an atom being negligibly small ($\tau_f \sim 1*10^{-4}$ s), the duration of stay of NRP in the source is governed by the time of sorbtion τ_s, the number of the collisions n and the time of diffusion τ_d: $\tau_i \approx \tau_d + n\,\tau_s$. The time τ_i can be reduced considerably first by decreasing the number of the collisions of the atoms with the source walls n, which has an estimated value of about 100 [5, 6]. This is done by the electric field inside the source, which prevents the atoms just ionized from sorbing onto the walls, guides and accelerates the iones towards the extracting outlet.

The electric field inside the source is induced by a direct current ($I_w \approx 500 \div 800$ A) of appropriate polarity, the current simultaneously heating the source walls ($T_w \approx$ 2500 K), which are made, as previously indicated, of thin W (Re, WRe, ...) foil < 0.1 mm thick.

Thus, the duration of stay of radioactive atoms (NRP) in the ion source will be determined as follows: $\tau_i = \tau_d + \tau_s$ and be several tenth parts of a second. The time it takes 20 keV single-charged ions to be transported along the 120 m channel is less than 1 millisecond.

5. Transporting and injecting the single-charged ions into the ECR-source

The source of the positive single-charged ions of NRP is at potential of +20 kV, whereas the electrode extracting the ions, along with the transportation channel equipped with a system of lenses and magnets focusing the beam, is at ground potential (Fig. 1). The investigation of the technique of injecting single-charged ions directly into the discharge chamber of an ECR ion source showed that the optimal energy of the ions is to be of order of 15 eV [15]. Therefore the potential of the ECR source, which is at the input of the axial injection system of the U-400 cyclotron, is to be +(2000 V - 15 V). The ion-accelerating voltage must be stabilized within $\sim 1*10^{-4}$, because the efficiency of such a technique of injecting single-charged ions into the discharge chamber of an ECR source, which is determined as the ratio of the single-charged ion fluence at the input of the ECR source to the current of the beam extracted from the multiple-charged ion source, is characterized by a sharp resonance, the peak half-width being of order of several volts [8]. The efficiency of such a technique is ~ 2%. Therefore provision is made for a tungsten (titanium ...) absorber of single-charged ions to be used, which is to be placed inside the discharge chamber at the input of the ECR source. The more so as it is highly difficult to perform the resonance injection of the negatively charged ions from the surface ionization source, which is at potential of - 20 kV in the transportation design chosen (Fig. 1), to the ECR source, which is at potential of +20 kV. The duration of stay of the atoms retarded by a hot absorbent (T > 2000 K) will be determined by their desorbtion from its surface τ_S, because the depth to which electrons of an energy < 40 kV (the more so of ~ 15 V) can penetrate into the obsorbent material is negligibly small.

6. Spherical grid electrodes for the ECR source

To increase the efficiency of extracting ions from the plasma source (and the intensity of the extracted ions in specific cases), which, apart from the other parameters, is directly proportional to the outlet area S, it is intended that the fixed boundary of the plasma at the output of the ECR source will be formed with the help of spherical grid electrodes of high transparency, which will also allow the given mode of focusing to be ensured [9, 10].

Fig. 3 schematically depicts how spherical grid electrodes are to be placed at the output of the discharge chamber of the ECR source. The plasma electrode is made of a tangsten grid of transparency of ~ 0.9, the grid cells measure 130 by 130 μkm, which corresponds to Debai's radius of screening in the source plasma. The plasma electrode radius of curvature, R, is about 650 mm. The centre of curvature (point O) is at the input of the first beam-focusing lense-solenoid. The extracting electrode is also made of a tangsten grid of transparency of ~ 90%, the cells measuring 500 X 500 μ. It is placed coaxially relative to the first one, the electrode spacing, d, being remotely adjustable in the range from 10 to 40 mm. This allows the beam to be focused before being injected into the solenoid. The necessity for the ion beam extracted from the ECR source to be focused geometrically before being enjected into the first focusing lense-solenoid results from the fact that only in such a way is it possible to make the real cross section (perturbed by the thermal motion of the ions) of the beam to be injected to the solenoid, less than the acceptance of the lense. For the source with spherical grid electrodes to produce a beam of an emittance that would be less than or equal to the emittance of the DECRIS-14 source [11] with an outlet diameter of 6÷8 mm, its outlet diameter, in view of the given configuration (Fig. 2), can be less than or equal to 25 mm. Because, all other factors being equal, the outlet cross section, S_g , of the source with a grid is 10-17 times as big as that of the source without a grid, it is to be expected that, in spite of the density of the plasma in the cross section of the discharge chamber of the ECR source showing some nonuniformity, the ion extraction efficiency and beam intensity will increase significantly.

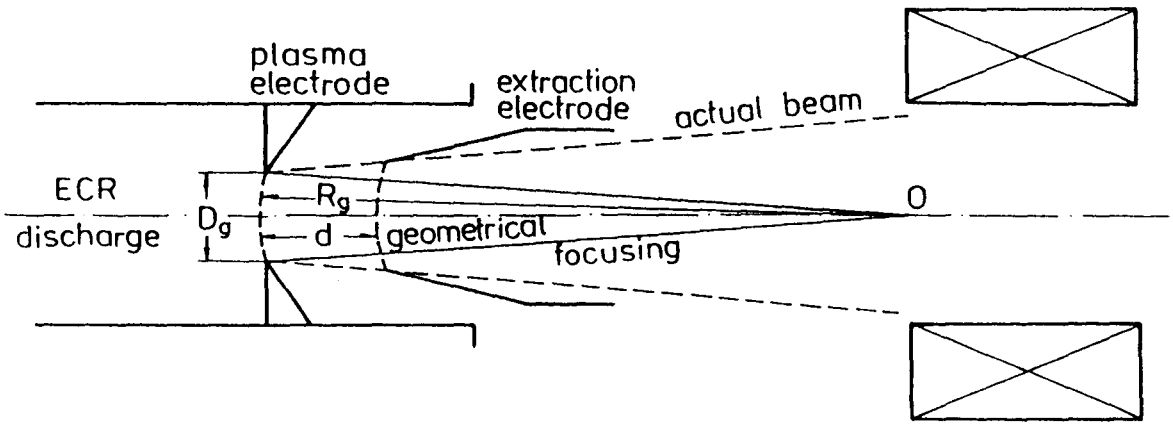

Fig. 3. A lay-out of a set of spherical grid electrodes placed at the outlet of the discharge chamber of the ECR source.

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