Radioactive ion beam production tests for SPIRAL

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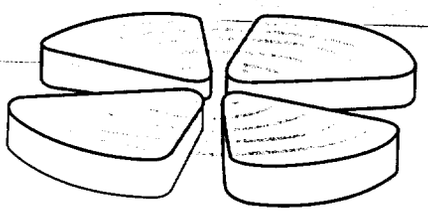

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Abstract:

The principles for the production of multicharged radioactive ion beams (RIB) for the SPIRAL project at GANIL is described. We discuss the main parameters which concern the efficiencies of the production system from the target to the exit of the low energy separator. The first results for the production of noble gases with an ECRIS and an external production target, which is similar to the system delivering the first RIB for SPIRAL in 1998, are shown. A new system consisting of an ECRIS with an internal target devoted in the future to the production of condensable elements is also presented.

1. INTRODUCTION:

The problem of producing multicharged radioactive ion beams (RIB) for the SPIRAL project [1] by the so called ISOL technique [2] at GANIL has been divided into two main axes of research. The first one is dedicated to a solution which is well adapted to the production of gases, mainly noble, and is based on an external target linked by a transfer tube to a fully permanent magnet electron cyclotron resonance ion source (ECRIS) [3]. The second one is dedicated to the production of condensable elements and is constituted of an ECRIS with an internal target. The principal difference between these two systems is the existence or not of a transfer tube between the production target and the plasma inside the ECRIS. The transfer tube is cold in the first case, avoiding for the production of any element which can stick on its walls. In the second solution there is no transfer tube, therefore any element, condensable or not, can reach the plasma zone of the ECRIS. The first solution has been already successfully tested at the test bench SIRa [4] of the GANIL and revealed good yields for the

production of He, Ne, Ar and Kr isotopes. The second solution is already in the stage of research and development.

In the following sections we discuss the main parameters involved in these production systems and the results obtained in our tests at SIRa.

2. THE ON-LINE PRODUCTION METHOD AND ITS EFFICIENCY.

The on-line production method can be schematically described with the help of fig. 1. The primary beam impinges a thick target producing radioactive species via nuclear reactions. For the case of SPIRAL, due to the large variety of beams accelerated by the GANIL cyclotrons, the primary beam can in principle vary from Deuteron [5] to Uranium. This is particularly useful and constitutes the main characteristics of the SPIRAL project when comparing to other on-line facilities based on light ion primary beams; i.e. in order to produce the radioactive species one can vary the nature of the beam instead of the target, using consequently the most chemically resilient target in all cases.

After the production in the target, the radioactive species diffuse from the crystalline structure of the target and are transfered through a tube to the ion source. Two important factors for losses play a role in these processes. The first one is the diffusion, which can be responsible to a reasonable delay between the stopping of the radioactive nucleus inside the target and its releasing. The second is the effusion, which can be even slower then the diffusion. For both cases, the high temperature of target and/or walls are crucial for having a good release efficiency.

At the ion source, the radioactive element is ionised and after, extracted. The subsequent separation is made by a spectrometer of resolution power of R = 200, in the case of SIRa. The identification and quantification of the radioactive elements produced are made downstream SIRa by a detection system based in the decay radiation of the nuclei studied.

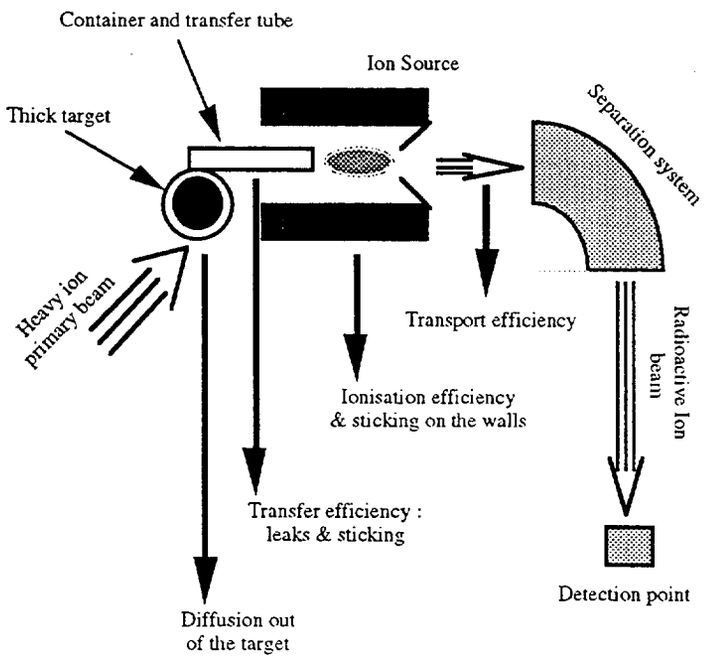

Figure 1.

Principle of on line production of radioactive elements.

2.1 Diffusion and Effusion

The diffusion of an element in a solid state material is governed by the Fick's laws, which have been solved already for several conditions [6-8]. The efficiency of diffusion, defined by the ratio between the number of radioactive atoms which are released before its decay and the number of atoms created in the target is given by the following relationship:

$$\varepsilon_\mu(\lambda) = \frac{3(\sqrt{\pi^2\lambda/\mu_0}\coth\sqrt{\pi^2\lambda/\mu_0} - 1)}{\pi^2\lambda/\mu_0} \quad (1)$$

where λ is the decay probability of the radioactive probe nucleus and

$$\mu_0 = \pi^2 D / r^2 \quad (2)$$

$$D = D_0 e^{(-E_a/kT)} \quad (3)$$

and where E_a and D_0 are the Arrhenius coefficients for diffusion, r is the grain radius of the material and k and T the universal gas constant and the temperature. The equation 2 is valid only for a material with a grain micro-structure. Other kinds of micro-structures are discussed in ref. [8].

We can see that the efficiency of diffusion is strongly dependent of the particle grain radius of the material and the working temperature of the target. The smaller is the grain size as well as the higher is the temperature, the better would be the efficiency. In the case of the first beams of SPIRAL and, in particular considering that we can use as much as possible the projectile fragmentation for the production of a radioactive beam, we have chosen Carbon of r =2μm as target. Carbon fulfils almost all target properties requirements for most of cases, being a refractory element with possible fine micro structure and low atomic number (Z), allowing a long range for the primary beam and consequently enhanced yields when comparing with heavier elements.

Considering the effusion, which takes place inside the target container and the transfer tube up to the ion source, we follow the description of R. Kirchner [6]. The efficiency for effusion is given in the following relationship:

$$\varepsilon_\nu(\lambda) = \nu/(\nu+\lambda) \quad (4)$$

where,

$$\nu = 1/\tau_\nu \quad (5)$$

Where τ_ν is the mean time spent on the transit from the target to the ion source. This is the sum between the mean time of flight from the target to the ion source and the mean total sticking time in the walls of the container and transfer tube. Considering χ as being the mean number of collisions with the surface of the container and the transfer tube, τ_a as the mean sticking time per collision and τ_f the mean time of flight between two successive collisions, we can deduce that the mean total effusion time is equal to:

$$\tau_v = \chi(\tau_a + \tau_f) \tag{6}$$

The mean sticking time can be written as a function of the enthalpy of adsorption ΔH_a in a tantalum surface of temperature T as the following relationship [9]:

$$\tau_a = 2.4 \times 10^{-15} \bullet e^{(1.16 \times 10^4 \Delta H_a / T)} \tag{7}$$

In order to understand more clearly the meaning of these equations we calculated the efficiencies for diffusion and effusion for two cases. The first one refers to the diffusion of ^{11}Be ($T_{1/2}$= 13.81 s) in a carbon target and the effusion of the same element in a tantalum container and transfer tube. The temperature dependence of the releasing efficiency is plotted in fig 2. We can see that the effusion is hardly dependent of a high temperature in the container and transfer tube. By the way, the temperatures needed for having reasonable efficiencies of, say 80%, are only of the order of 2000K, which can be attained experimentally. In the other hand, for the case of ^{12}Be ($T_{1/2}$ = 23.6 ms) the temperature needed for having a good transfer efficiency is out of the present possibilities. This is mainly due to the high enthalpy of adsorption ΔH_a = 5 eV for the Be, which produces a long sticking time τ_a = 0.5 s. For cases like Be, the best choice would be to eliminate the transfer tube completely if we would want to produce with reasonable efficiency, condensable elements with short life times. Certainly for gases, mainly noble, this problem does not exist because the sticking time τ_a in this case is negligible.

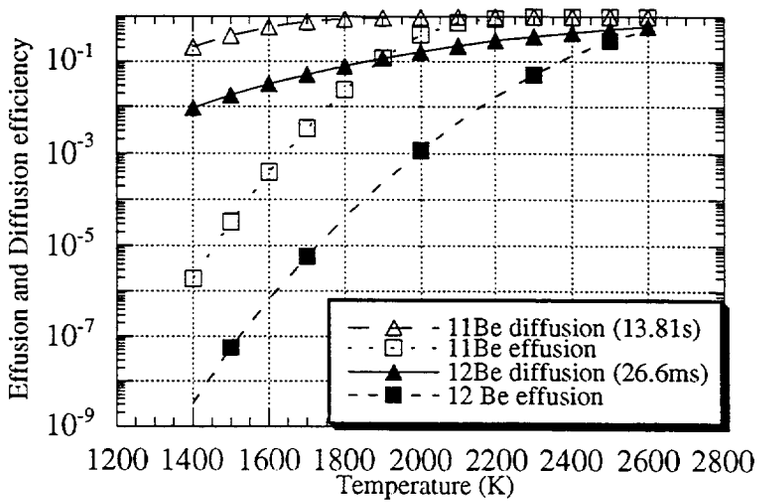

Figure 2.

Diffusion and effusion of ^{11}Be and ^{12}Be

2.2. Ionisation

The total ionisation efficiency of each ECR ion source used in the experiments at SIRa were measured. For the case of gases, this total efficiency was of the order of 80% and was measured with the help of a calibrated leak injected

directly in the RF coupling of the ECRIS. The charge state distribution can be tuned in a way that we can have between 10% and 20% of the total particles entering in the ECRIS at the optimum charge state. The optimum charge state varies with the maximum magnetic field and working frequency of the ECRIS. For the small models used in the SIRa tests, the optimum charge state efficiencies are attained up to $Q/Z \approx 0.5$.

The efficiency of a condensable element is considerably smaller. The ECRIS is a cold ion source, which means that a condensable element can stick in the walls of the source chamber, decreasing its performance. In this paper we consider the losses from the sticking in the walls of the source chamber as an efficiency default. This efficiency has been measured for the ^{52}Cr. The experiment consisted in weighting an oven placed inside the ECRIS with a ^{52}Cr charge, before and after 30 hours of continuous running of the ion source. From the difference of weight and knowing the current extracted during the experiment, we deduced an overall ionisation efficiency (all charge states) of the order of 15%. The most probable charge state (7+) has been populated with 3% of the total particles evaporated by the oven.

2.3. Transport.

The efficiency of transport in the SIRa separator varied between 30% to 100% depending on the conditions of extraction. This efficiency can be easily measured: It is the ratio between the sum of the currents of each charge state of each element after analysis by the full current passing through the extraction electrode.

3. RESULTS WITH EXTERNAL TARGET.

The results we present have been obtained using a classical target-ion source test system based on the ISOLDE type, i.e., with an external carbon target inside a tantalum tube, linked with the ion source by a 60cm *long* tantalum plus copper transfer tube. These results demonstrate the order of magnitude of the beam intensities which can be reached by SPIRAL for noble gas beams.

The carbon of the target was furnished by Carbonne Lorraine, France (grade 2318) with a grain size of 4μm and 8% open porosity. The ion source used during the tests is the Caprice-type ECR3 [10]. The entire system has been mounted at the on-line separator SIRa. The overall efficiency of the system, including SIRa, has been measured by implanting a known rate of ^{18}Ne ions produced by projectile fragmentation of a ^{20}Ne primary beam. The secondary ^{18}Ne beam was selected and purified by the α-shaped spectrometer and its rate determined by a Si detector located in front of the target of SIRa. The ^{18}Ne released by the target at high temperature (between 1500 and 2100K) effused through the ECRIS, was ionised, extracted, selected by the separator and implanted in a plastic tape located downstream of SIRa. The γ-rays emitted by the decay of ^{18}Ne were detected using a Ge detector located in close proximity to the tape. The overall efficiency measured in this case for ^{18}Ne for the charge state 5+ was 3%. Using a calibrated leak of ^{22}Ne gas which passed through the carbon target, we could unfold the efficiencies of each part of the separator. We extracted

the time dependent part of the efficiency, which is the product of the diffusion and effusion efficiencies, from the time independent part which comprises the ionisation and transport efficiencies. The ion source efficiency can be described as the product between an ionisation and a delay efficiency, where the latter represents the time spent by an atom inside the source before being extracted. For noble gases with $T_{1/2}$ > 100ms, the sticking time on the walls is negligible and the confinement time is much smaller then the life time of the radioactive element. In this case the ion source efficiency can be assumed to be the same for stable and radioactive atoms. The different efficiencies are the following:

a) Product of diffusion and effusion efficiencies at T_{target}=2000K for ^{18}Ne: 45%;
b) Efficiency of ionisation in the ECR for ^{18}Ne(5+): 20%;
c) Transport efficiency of the SIRa separator: 36%.

The performance of the ECRIS for a radioactive atom is the same as for a stable one. It has been tested on-line with an intense ^{20}Ne beam bombarding the target. The charge state distribution for ^{18}Ne, ^{19}Ne and ^{22}Ne are equivalent (see figure 3), demonstrating that the performance of the ECRIS is unaffected by the presence of the primary beam.

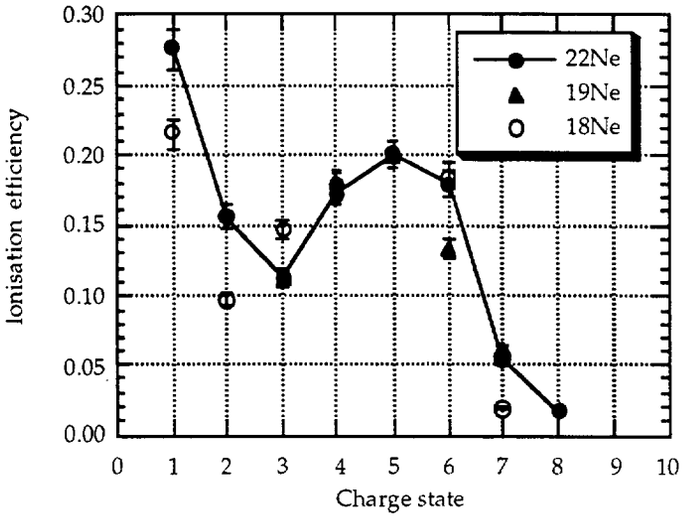

Figure 3.

Charge state distribution for Ne isotopes

The production yields of RIB have been measured for a certain number of noble gases, where we expect to have good performance of the test system considering the effusion and ionisation efficiencies. The yields at the end of the separator, i.e., after diffusion, effusion, ionisation and transport, are presented in table 1. These yields were obtained using ^{13}C, ^{20}Ne, ^{36}Ar and ^{78}Kr primary beams at the maximum energies and intensities presently available at GANIL. We present also a projection to RIB intensity supposing a total beam power of 6kW and a transmission of 50% inside the CIME cyclotron. The poor transport efficiency of the SIRa separator will be greatly improved for the separator to be incorporated in SPIRAL. This will enhance the final intensity of the beam by a factor of at least two. The full test system is being redesigned, in particular with a view to minimise the distances between target and the ion source. The latter can

significantly augment the final SPIRAL beam intensities, in particular for short lived nuclei. The first SPIRAL ion source has been inspired by the full permanent magnet NANOGAN ion source [3] which is very compact and easy to maintain. Finally, other target materials will be tested in the near future.

Table 1. Measured yields with present Ganil intensities; with projections for 1pμA of primary beam; and 6kW of maximum incident beam power supposing a transmission of 50% inside the cyclotron CIME.

RIB(charge state) and life time	primary beam	Yield (pps) with present intensities	Yield(pps) for 1pμA beam	projected SPIRAL intensities
^{77}Kr (10+) 74.4 m	^{78}Kr, 73A MeV 35pnA (2.2×10^{11}pps)	6.1×10^{6}	1.7×10^{8}	9.2×10^{7}
^{76}Kr (10+) 14.8 h		3.6×10^{6}	1.0×10^{8}	5.3×10^{7}
^{75}Kr (10+) 4.3 m		1.8×10^{5}	5.1×10^{6}	2.7×10^{6}
^{74}Kr (9+) 11.5 m		7.0×10^{4}	2.0×10^{6}	1.1×10^{6}
^{73}Kr (9+) 27.0 s		2.5×10^{3}	7.1×10^{4}	3.8×10^{4}
^{72}Kr (9+) 17.2 s		2.6×10^{2}	7.4×10^{3}	3.9×10^{3}
^{35}Ar (8+) 1.77s	^{36}Ar, 96A MeV 115pnA (7.2×10^{11}pps)	6.2×10^{7}	5.4×10^{8}	4.7×10^{8}
^{34}Ar (7+) 844.5ms		1.4×10^{6}	1.2×10^{7}	1.1×10^{7}
^{33}Ar (8+) 173ms		1.8×10^{4}	1.6×10^{5}	1.4×10^{5}
^{32}Ar (8+) 98ms		1.0×10^{2}	8.7×10^{2}	7.8×10^{2}
^{19}Ne (5+) 17.22s	^{20}Ne, 96A MeV 208pnA (1.3×10^{12}pps)	5.0×10^{7}	2.4×10^{8}	3.8×10^{8}
^{18}Ne (5+) 1.67s		3.1×10^{6}	1.5×10^{7}	2.3×10^{7}
^{17}Ne (5+) 109ms		3.1×10^{4}	1.5×10^{5}	2.3×10^{5}
^{8}He (1+) 119ms	^{13}C, 75A MeV 421pnA (2.6×10^{12}pps)	2.1×10^{5}	5.0×10^{5}	1.5×10^{6}

4. THE INTERNAL TARGET DESIGN.

In order to keep the distance between the target and the plasma zone as low as possible, we decided to place the target inside the ion source. This solution is optimum for condensable elements, reducing to a minimum the transit time and, consequently, maximising the efficiency. The solution we have taken is shown in fig. 4. This design is particularly interesting because it eliminates all permanent magnets from zero up to 90 degrees from the beam direction. This is important for avoiding radiation damage of the magnets, reasonably sensitive to the neutron radiation. The solution for this particular design was to mixt coils and permanent magnets, therefore making an hybrid ECRIS.

As shown in fig. 4, the primary beam enters from the extraction electrode of the ECRIS, crosses the plasma zone and hits the target placed in the point of maximum magnetic field B. The radioactive atoms released from the target are ionised in the plasma and extracted from the ECRIS. The low energy RIB is deviated by an electrostatic channel and follows to the direction of the SIRa separator.

The target is made of a bulk of Carbon with a grain size of 4μm and 8% open porosity, surrounded by a container made with pyrolitic Carbon. The full ensemble can be heated by a W - filament up to 2300K. A Ta reflector placed

between the filament and the ECRIS chamber assures the protection of the copper chamber.

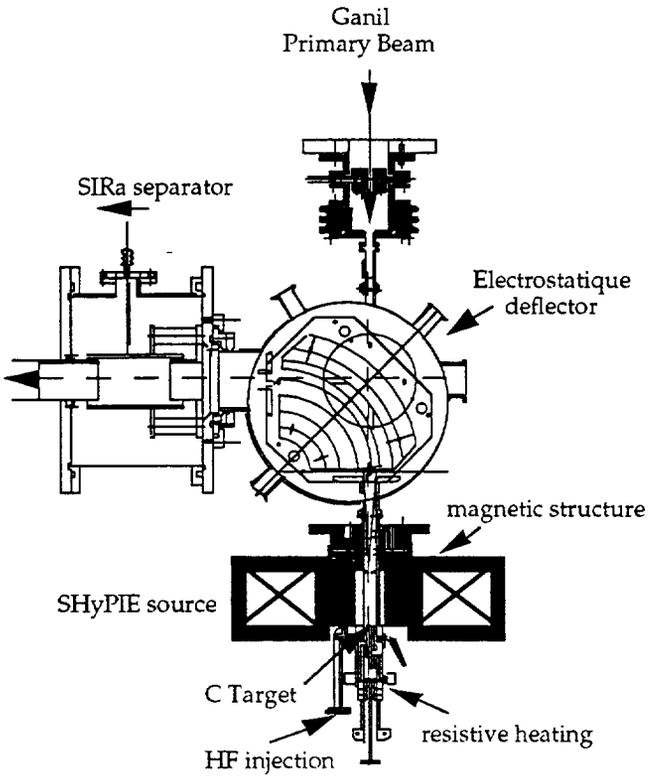

Figure 4.

Internal target ion source systeme : SHyPIE (Source Hybride pour la Production d'Ions Exotiques)

In principle, the performance of the ECRIS was supposed to be the same with and without the presence of the primary beam. Tests off-line showed a very small change of the tuning of the ECRIS when the target is hot, mainly due to the change of the nature of the supporting gas during the outgassing period. This degassing is very important and can take a long time when the ensemble is heated for the first time.

A preliminary test performed during 12 hours with ^{40}Ar (E=70.A MeV) primary beam showed a reasonable production yield of ^{35}Ar (7+), which corresponds to an overall efficiency of the order of 3 %, but an efficiency of approximately 0.01% for ^{25}Na (4+). Other condensable elements have been observed, like Mg and Al, but also with efficiencies smaller then the theoretical ones. The efficiency for ^{25}Na is, for the moment, at least one order of magnitude worse then the projected one. This bad performance should be better understood in a subsequent experiment with primary radioactive beam which will allow us to unfold all different efficiencies of the system.

5. SUMMARY.

We have presented the principles for the production of multicharged radioactive ion beams (RIB) for the SPIRAL project at GANIL and discussed the main parameters which concerns the efficiencies of the production system from the target to the exit of the low energy separator. The first results for production

of radioactive ion beams using a test production system in the new SIRa separator at GANIL, show reasonably good performances for production of RIB of noble gases. A new system consisting of an ECRIS with an internal target devoted in the future, to the production of condensable elements were also presented. The efficiencies of this new system are, for the moment, at least one order of magnitude worse than the theoretical projected efficiencies. New tests will be performed during may at GANIL.

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