FIRST RADIOACTIVE BEAM WITH EXCYT: ROLE OF THE K800 SUPERCONDUCTING CYCLOTRON

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Abstract

The aim of the EXCYT (EXotics with CYclotron and Tandem) facility is the production and acceleration of radioactive ion beams (RIBs). It is based on the two-accelerator method (ISOL technique): a primary beam accelerated by the K-800 Superconducting Cyclotron produces, in a target-ion source complex (TIS), the required nuclear species, which will be accelerated by a 15 MV Tandem. The nuclear research programme started in July 2006 with the experiments BIG BANG and RCS using the post-accelerated ^{8}Li ions. In the near future ^{9}Li, ^{21}Na and ^{15}O beams are planned to be developed according to the experimental proposals, with beam intensities ranging between 10^4 and 10^6 pps, at the typical energies of our tandem.

INTRODUCTION

The commissioning of the EXCYT facility started in the first months of 2005 and a detailed description of the facility and of the commissioning phases are extensively reported in [1].

The nuclear research programme started in July 2006 with the experiments BIG BANG and RCS using post-accelerated ^{8}Li ions.

Production of the radioactive ions was accomlished by sending a 45 AMeV $^{13}C^{4+}$ primary beam on a graphite target up to a beam power of 150 W, while ionisation was achieved by a tungsten positive surface ioniser. For such a kind of ion beam, the highest extraction efficiency from the TIS is obtained by positive ionisation. Then the post-acceleration with the Tandem is possible only after a charge exchange in a dedicated cell (CEC) to obtain negative ions.

Li^{+} ions were produced at different energies to cross-check the transmission efficiency together with the charge exchange efficiency. The CEC consists of a cell containing Cs vapours which interact with the Li beam converting its charge from +1 to –1 by a two step reaction; it had been characterised off-line and the results obtained at the EXCYT facility confirm our previous observations and expectations such as the efficiency at different extraction energies and the isotopic shift effect. The maximum ^{13}C primary beam intensity was 1 eμA which corresponds to a beam power of 147 W leading to a production yield of 9×10^6 pps of ^{8}Li. Table 1 summarizes the ^{8}Li, ^{9}Li and ^{21}Na production yields at the entrance of the first stage of the isobaric separation. The yields of ^{9}Li and ^{21}Na have been measured in not optimized conditions and the extrapolation to 147 W is also reported.

Table 1: ^{8}Li, ^{9}Li and ^{21}Na production yields (***** yields measured in not optimized conditions).

Beam	**Power**	**Intensity measured**	**Expected at 147 W**
^{8}Li	147 W	**$9.0\ 10^6$ pps**	**$9.0\ 10^6$ pps**
^{9}Li	82 W	**$5.3\ 10^4$ pps***	**$3.4\ 10^5$ pps**
^{21}Na	82 W	**$5.8\ 10^5$ pps***	**$3.7\ 10^6$ pps**

TARGET ION SOURCE

Due to our beam line configuration the primary beam is impinging vertically to the Target Ion Source assembly (TIS), as described in the figure 1. The target is graphite made, it is supported in a Ta container and it is heated by a surrounding electrical heater.

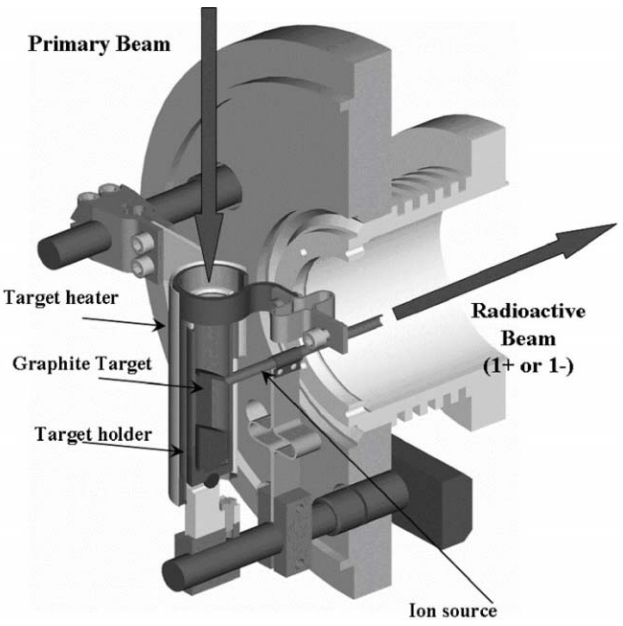

Figure 1 : Target ion Source Assembly

The $^{8;\ 9}$Li particles collected from the target will effuse through the transfer tube to the ioniser, where they are ionised by a Positive Ion Source (PIS) and then extracted by an acceleration voltage of 10 kV, this voltage was chosen as a compromise between the ion extraction efficiency from the TIS and the Charge Exchange Cell (CEC) efficiency strongly dependent on the ion extraction energy (see Figure 6). The beam is injected at 100 keV into the Tandem after the isobaric mass separation. Off-line measurements of the ion source efficiency have been

performed at LNS both for Positive Ion Source (PIS) and Negative Ion Source (NIS). The former is particularly suitable for alkaline ions for which it is highly selective and efficient, while the latter is indicated for halogens with exception of fluorine. Other available ion-sources are the Hot Plasma Ion Source (HPIS), which is suitable to ionize positively many elements, included noble gases, with an efficiency of about 1%, and the Kinetic Ejection Negative Ion Source (KENIS), especially designed for fluorine ions for which an efficiency of about 5% is expected. PIS off-line measurements indicate that Li^+ can be obtained with high ionisation efficiency (>70%) by means of a tungsten ionisation tubular cavity [2]. For a PIS the ionisation efficiency primarily depends on the work function of the ioniser material (4.5 eV for W) [3]. Rhenium and iridium exhibit a higher work function (4.8 eV and 5.4 eV respectively), therefore they are good candidate to replace the W ionisation tube.

Since oxidized tungsten exhibits a very high work function (about 6.0 eV), the natural tungsten oxide on the ionisation tube is not removed, moreover an oxygen flow into the ioniser could be an excellent solution to improve the efficiency. A new ion-source prototype is ready for a test, where the tantalum ionisation tube is internally lined with a W, Re or Ir foil. We expect from these tests a higher ionisation efficiency.

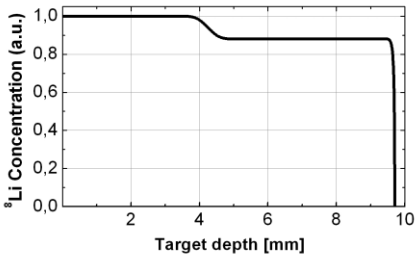

Figure 2 : ^{8}Li concentration distribution versus target depth

The production yield of the radioactive nuclear beam (RNB) depends on many factors such as: primary beam parameters (element, energy, intensity), target material (nuclear cross-section, operating temperature), target structure (diffusion mechanism), container geometry (effusion to the ioniser), ioniser type (ionisation mechanism and efficiency), charge exchange efficiency, transport efficiency, isobaric separation and post-acceleration efficiency. The selection of our target material among the available ones has been done following the criteria of high porosity, small grain size, high thermal conductivity, high chemical purity, high melting point and low vapour pressure. Experimental results indicate the UTR146 graphite from XY-Carb as the best target material for our facility [4]. Taking into account the Superconducting Cyclotron (CS) operational diagram, the ^{8}Li demand and the target material, we selected $^{13}C^{4+}$, 45 AMeV ion as a primary beam. In this energy range $^{8;\,9}$Li are essentially produced both by target and projectile fragmentation: EPAX code simulations indicate the nuclear cross-section for ^{8}Li production as 3.41 mb and 4.25 mb respectively [5]. The range of the primary beam in graphite target, calculated by SRIM, is about 4.01 mm. ^{8}Li produced by target fragmentation will recoil with a negligible energy remaining located in the production volume, while the ^{8}Li produced by projectile fragmentation will save most of the projectile speed penetrating in the target up to a depth of about 9.69 mm.

The resulting ^{8}Li concentration distribution is reported in Figure 2, where the step in the profile concentration is a consequence of the two production mechanisms. The first target prototype used for the preliminary test at SPIRAL in Ganil [6] and at LNS during March 2006 is shown in figure 3. It consists of two parts: the upper tablet and the lower part which acts also as a mechanical support. The transfer tube to the ionizer is located in between these two parts. Sizes were chosen to maximize the Li collection.

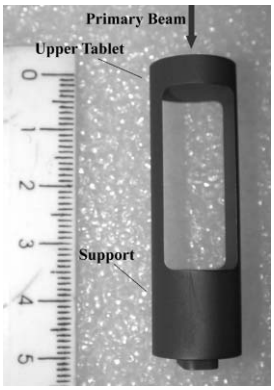

Figure 3 : First UTR146 graphite target

The production efficiency is the ratio between the number of the radioactive ions extracted from the TIS and the number of produced nuclei foreseen by the EPAX code. The production efficiency for different target temperatures indicates [7] that the ^{8}Li production is a diffusion limited mechanism which is a thermally activated process. At the operating temperature of 2600 K, many diffusion mechanisms are active inside the target: Li particles will mainly diffuse by interstitial in graphite. Once the particle reaches the grain boundary it can diffuse in a neighbour grains or effuse in the target porosity (19% of the volume for UTR146). Moreover at this temperature, after the effusion process through the porosity, the probability of re-diffusion inside a grain is quite high. For this reason a simple model like "single grain diffusion and pure porosity effusion" is not appropriate. As a first step, and in order to estimate the diffusion length before a nuclear decay, we performed some computer simulations using a very simple, mono-dimensional modified version of the Fick's law, (equation 1), that takes into account also the particles decay rate

during the diffusion path $C(x,t)/\tau$ and the concentration of the production rate $R(x)$, where t is time, x is the mono-dimensional coordinate, $C(x,t)$ is the particle concentration, and τ is the decay constant.

$$\frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(c,t)}{\partial x^2} + R(x) - \frac{C(x,t)}{\tau} \quad (1)$$

From this simulation we used the diffusion coefficient D as parameter to reproduce the ^{8}Li production efficiency measured during the test of march 2006 at LNS. It turned out that D has a large value, in the range from 10^{-6} cm^2/s to 10^{-5} cm^2/s, thus confirming the good features of this target.

By this simulation we estimated a phenomenological value of the diffusion coefficient. Nevertheless this range of values is suitable to estimate the ^{8}Li path length inside the target. Figure 4 shows the ^{8}Li concentration near the target surface for a diffusion coefficient of 10^{-5} cm^2/s, at different times starting from target irradiation by the primary beam. The secular equilibrium is reached after about 5 seconds when the ^{8}Li concentration becomes stable. In Figure 4 the dashed line indicates the equilibrium concentration without diffusion (D=0 cm^2/s), the grey area is the ^{8}Li depletion volume due to the ^{8}Li released out of the target.

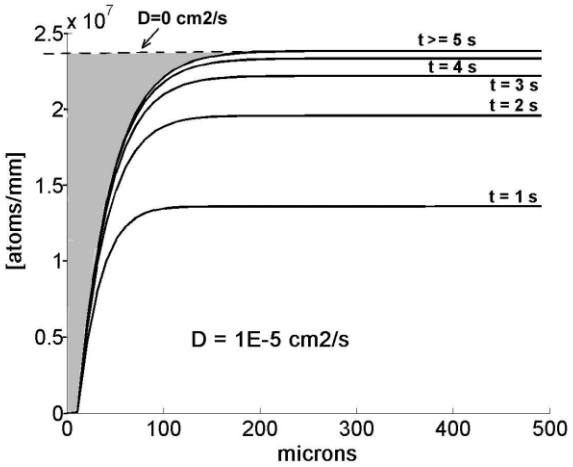

Figure 4: Simulation result of the ^{8}Li concentration near the target surface at different times starting from the primary beam irradiation

This simulation suggests that only the ^{8}Li particles produced within the first hundreds of microns are able to reach the target surface before their decay, ^{8}Li atoms produced at bigger depth will decay during their path inside the target never being collected. These considerations have triggered the decision to modify the target design by employing ten, uniformly spaced, 1 mm thick, graphite disks (see Fig. 5). An increase of a factor 6 on the ^{8}Li production yield was then expected.

An increment of a factor 3.6 has been found, which is not far from the foreseen factor 6, this reduction being probably due to a different temperature distribution in the new target. These values are very promising for the future when the beam power will be increased up to 500 W.

Further investigations are planned to better understand the Li release mechanism from the target. Other target candidate materials such as fibres, felts and nano-structured materials are taken into consideration.

Figure 5: New target design. Left: picture. Right: CAD design

CHARGE EXCHANGE CELL

The charge exchange cell (CEC) consists of a vacuum chamber containing Cesium vapours at a variable temperature, in which Li^+ ions, extracted from the ion source, are transformed into negative ones by interaction with the Cs atoms. The CEC device and the efficiency measurement procedure have already been described [8]. The charge exchange consists of a two step process, the first of which is energetically supported (exothermic) while the second is not (endothermic), as described by the following formulae, where $Ei(X)$ is the ionization energy and $Ea(X)$ is the electron affinity of the X element.

$$Li^+ + Cs \rightarrow Li + Cs^+$$
$$\Delta E = E_i(Cs) - E_i(Li) = 3.89\ eV - 5.39\ eV = -1.5\ eV$$
$$Li + Cs \rightarrow Li^- + Cs^+$$
$$\Delta E = E_i(Cs) - E_a(Li) = 3.89\ eV - 0.62\ eV = 3.27\ eV$$

Cesium was chosen because of its low ionization energy, other elements, even alkalines, exhibit bigger values reducing the CEC efficiency. The CEC efficiency strongly depends on the energy of the Li^+ extracted from the TIS: the lower the Li energy the higher the CEC efficiency. It is foreseen a maximum by the adiabatic mass criterion [9] that in this case lies at about 5 keV. The beam optics elements have been originally designed to operate at a minimum extraction energy of 15-20 keV. The first beam transmission tests were performed at 25 keV, at this energy the CEC efficiency for ^{7}Li was very low: 0.72%. Strong effort was dedicated to improve the beam transmission at the lowest suitable RNB extraction energy. This value was fixed at 10 keV as a good compromise between a good transmission and the CEC efficiency.

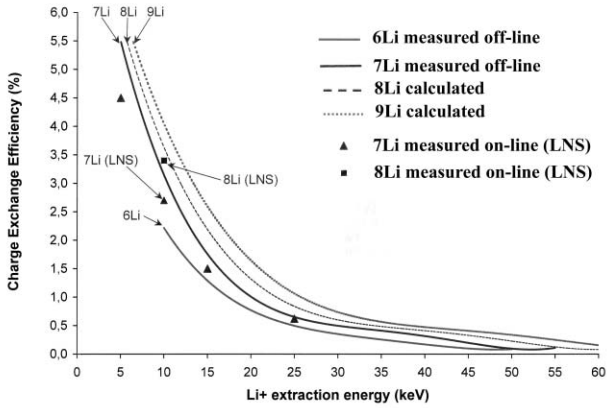

Figure 6: CEC efficiency versus Li^+ extraction energy

The measurements of the CEC efficiencies versus different $^{6;7}$Li energies are reported in Figure 6. Measurements were performed on-line at the HRBIF of the Oak Ridge National Laboratory [8]. Since the CEC efficiency depends on the ion velocity rather than on the ion energy, in this figure an isotopic shift effect is observable. From these data it is possible to estimate the CEC efficiency for ^{8,9}Li ions. On-line measurements, during July 2006, confirm the expectations. The CEC efficiency for ^{8}Li at 10 keV is 3.4%, very close to the expected value of 3.6%.

DEVELOPMENTS

Given the successful production and post-acceleration of ^{8}Li, the commissioning of the EXCYT facility is concluded. Further tests will be carried out to optimize the transport efficiencies in the pre-separator and in the tandem coupling line, nevertheless the experimental program already approved by the LNS PAC with ^{8}Li has started.

Intensity is not a limiting factor for this first experiments, however an R&D program on the TIS is under way at LNS, to enhance the production yields for Lithium, Oxygen, Chlorine and Fluorine. The increase of the primary beam power up to 500 watt will also permit a further increase of the secondary beam.

Figure 7: View of the Cyclotron median plane

THE SUPERCONDUCTING CYCLOTRON AS A PRIMARY MACHINE

The primary accelerator of EXCYT is the LNS Superconducting Cyclotron [10], a three sectors compact machine (Figure 7) with a typical extraction efficiency of 30-50%, to which a beam power of 500 watt is requested.

The need for high beam power has forced to make a totally new design of the first electrostatic deflector, where most of the lost beam is dissipated. The first modification, introduced several years ago to the deflector, was the installation of a cooling circuit, Figure 8, assembled in the rear part of the housing , which provided indirect cooling of the septum, the ground element where a big part of the accelerated beam is lost.

Figure 8: Water cooling circuit assembled in the rear part of the deflector housing

At the same time, it was necessary to upgrade also the main probe, so as to have a diagnostic device able to measure intense beams. The original probe, designed for not intense beams, was replaced by a water cooled one, able to span only a reduced radial range (170 mm) close to the extraction radius: the cooling circuit does not allow the probe to move along the spiral path in the hill, as the original probe did (Figure 9).

Figure 9: Water cooled main probe

With this equipment, it was possible to extract a $^{13}C^{4+}$ 45 AMeV beam with a power of 100 watt.

To go beyond 100 watt, it was decided to introduce further modifications to the electrostatic deflector in order to improve its reliability: a new housing was realized with a new cooling circuit, allowing the septum to be directly

cooled, as shown in Figure 10. Moreover the septum material was changed from tantalum to tungsten, which ensures a better thermal exchange. Finally, the septum thickness was increased from 0.15 to 0.3 mm, which ensures a better mechanical stability under thermal stresses. With these modifications, an extraction efficiency of 63% was obtained and a 150 watt beam was extracted in a quite reliable way.

Figure 10: New deflector provided with direct cooling of the septum

In order to reach the objective set by EXCYT, namely a beam power of 500 watt, it is wise to search for an increased extraction efficiency. To do that, a possible way can be to shape the magnetic field so as to have a certain phase-radius correlation [11] in the inner part of the cyclotron, where phase slits are installed. Phase selection might help to increase the extraction efficiency by intercepting at low energy particles that would be stopped in the electrostatic deflectors.

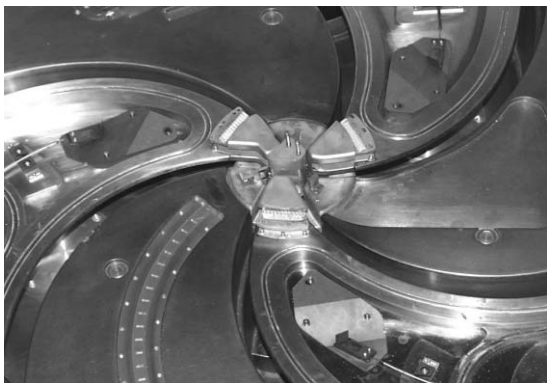

Figure 11: Phase slits assembled inside the dees

Optimization of the beam transport along the injection line is also planned: the transmission factor from the ECR source to the Cyclotron is presently of the order of 15%, while 30-40% is theoretically expected. Beam tests are planned to be performed to investigate on the beam behavior by using an emittance meter. Using phase slits (Figure 11) as previously described is possible if the amount of accelerated beam is so high to permit phase selection.

CONCLUSION

The EXCYT project has been completed with the commissioning of the facility: a ^{8}Li radioactive beam has recently been delivered to one of the experiments approved by the LNS Scientific Committee. This is indeed a quite important achievement, considering that the facility is installed in the accelerator area, most of the time not accessible during the routine operation of the accelerators, the Tandem and the Superconducting Cyclotron, with stable beams.

Of course, some improvements are necessary to make the facility more reliable and more performing. The Superconducting Cyclotron is requested to provide a primary beam of 500 watt, implying an increase of a factor 3. The transmission along the mass separator needs to be optimised. The remote handling system for the target ion source complex is being modified to be more reliable. Finally a test bench is necessary to improve the performance of the target ion source and to test new source types.

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