THE DEVELOPMENT OF A BE-7 RADIOACTIVE BEAM : FROM NUCLEAR PHYSICS TO APPLICATIONS FOR INDUSTRY

M. Loiselet, M. Gaelens, G. Ryckewaert,
Université catholique de Louvain, Louvain-la-Neuve, Belgium

Abstract

An intense beam of Be-7 (T1/2 = 53 days) has been developed at the CYCLONE radioactive beam facility in Louvain-la-Neuve. Because of the Be-7 properties (long half-life, metallic nature) novel methods have been used for the production, ionisation and post-acceleration of this element. A dedicated ECR source has been developed to inject the minute quantities of radioactive atoms in a controlled manner and to recycle the Be-7 atoms lost on the plasma chamber walls. This Be-7 beam was initially requested for nuclear astrophysics experiments but is now also used for industry. The implantation of Be-7 is indeed a powerful tool to measure the wear properties of materials like ceramics or amorphous carbon layers which are difficult to activate with protons. This application will be illustrated with a few examples.

INTRODUCTION

The increased interest in Be-7 during recent years was mainly related to the solar neutrino problem as the calculated flux of the high energy solar neutrinos is influenced by the $^{7}Be(p,\nu)^{8}B$ reaction. The possibility to measure this reaction by inverse kinematics was at the origin of the development of the Be-7 beam at the Louvain-la-Neuve facility.

Beside its interest for the nuclear physics community, the half-life (T1/2=53 d) and the energy of the emitted ν-ray (478 keV) make Be-7 beams a useful tool for wear measurements in low Z material like organic material, ceramics and hard coatings.

The different steps involved in the off-line production of a post-accelerated Be-7 beam are reported. The technology developed for the ionisation and the recycling of the Be-7 atoms in a dedicated plasma chamber is presented in the first part of the paper. The application of the Be-7 beam for wear measurements is discussed and illustrated in the second part.

ACCELERATION OF THE BE-7 BEAM

The development time spent for the Be-7 beam has been considerably longer than for the previously accelerated beams like He-6 or Ne-19 for example [1]. This is mainly due to chemistry: the on-line extraction methods used for these noble gases are obviously not relevant for the extraction of beryllium and the ionisation efficiency of the ECR source for this non-volatile element is lower than for a noble gas. Last but not least, the long lifetime of Be-7 and the activities involved in the process (typically several GBq) make the safety issues an important aspect of this development. For all these reasons, and because of the minute quantities of available material (<1μg), dedicated techniques had to be developed to inject the radioactive atoms in a controlled manner in the ECR source and to recycle the atoms lost on the plasma chamber walls [2].

Production

The Be-7 atoms are produced via the $^{7}Li(p,n)^{7}Be$ reaction by bombarding a lithium target with 27.5 MeV protons accelerated by the CYCLONE30 cyclotron. The measured yield, obtained by observing the 478 keV ν line from ^{7}Be directly from the irradiated target, is $3.6 \cdot 10^{-3}$. The target consists of a water cooled crucible filled with 1.5 g of lithium in which the beam is stopped. Because of the high reactivity of molten lithium (melting temperature 180°C), the beam intensity was limited to about 30 μA, meaning that approximately 900 W is dissipated in the target. Due to the large amount of required activity (from 4 to 16 GBq or ~100-400 mCi), the target is provided with an integrated shielding/transporting device.

Chemical separation

After irradiation, the crucible is removed from the target holder, and the lithium is dissolved in distilled water. The separation of the Be-7 from the lithium is achieved by passing this solution on a fiberglass filter. The Be-7 is adsorbed at slightly basic pH values while the lithium passes through [3]. The whole process is performed in a hot-cell, with an extraction efficiency of 90%.

Ionisation

The ionisation of the ^{7}Be atoms is performed with a 6 GHz ECR ion source. Because of the small amount of material available, we opted for the sputtering method to inject the Be-7 atoms into the source. The sputtering rate was controlled by the electrode bias voltage (from -200V to -1200V). Stable sputtering rates in the range of 100 μg/h down to 0.5 ng/h were obtained.

Because the ionisation efficiency of ECR sources for metallic elements is limited by the condensation on the cold walls of the plasma chamber, a method of "on-line source chemistry" has been developed to recycle the Be-7 atoms lost this way. It is based on the fact that, although the vapour pressure of Be is low (below 10^{-9} Torr at 600°C), it reaches 760 Torr at 481 °C for molecular compounds like $BeCl_2$. Therefore, an externally heated

quartz liner (fig 1) has been installed inside the plasma chamber and chlorine is continuously injected in the source to transform the Be atoms into $BeCl_2$. The liner is thermally insulated from the water cooled plasma chamber by an intermediate stainless steel reflector. The assembly allows to reach 600°C on the liner while keeping the temperature of the chamber at 40°C. The ionisation efficiency for $^{7}Be^{1+}$ ions has been measured in a dedicated experiment and was estimated to be 3.1 %.

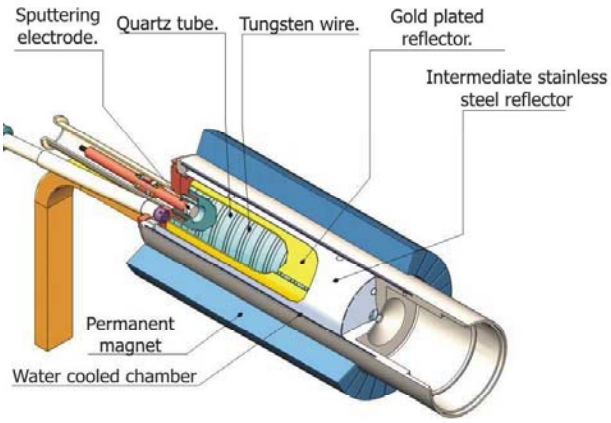

Figure 1: The ECR plasma chamber with the heated liner

Acceleration and isobaric separation

Depending on the requested final energy for the post-accelerated beam, $^{7}Be^{1+}$ ions (energy range : 5.3 – 12.9 MeV) or $^{7}Be^{2+}$ ions (25 - 62 MeV) have been injected in the CYCLONE110 cyclotron. However, since the chemical separation of Be-7 from the target always leaves traces of lithium, the Li-7 intensity after the ion source is typically about a thousand times higher than the Be-7 intensity. This ratio is due to the very small percentage of Be-7 in the production target (at most 1µg of Be-7 in 1.5 g of Li) and to the higher vapour pressure of Li (10^{-1} mbar at 600°C) which leads to a more efficient recycling of Li in the source. To remove this isobaric contamination in the post-accelerated beam ($\div m/m=1.3\cdot10^{-4}$), the stripper foil technique has been combined with the high resolving power of the cyclotron. Both the lithium and the beryllium beams were stripped by a thin carbon foil (30 µg/cm²) located at the exit of the cyclotron. The subsequent switching magnet and beam transport elements to the experimental area were tuned on m/q = 7/4 to select the $^{7}Be^{4+}$ ions. Although the attenuation factor for the lithium beam was high (~10^{5}), some Li-7 was still leaking through into the $^{7}Be^{4+}$ beam due to scattering. Therefore, the cyclotron was tuned as an isobaric separator to reduce the intensity of the Li-7 contaminant by another factor of 10^{5} during acceleration, giving a total rejection factor of 10^{10}. Since the initial Be-7 beam intensity may be as low as a few fA (near the detection limit of our Faraday cups), it is very important that the residual amount of Li-7 in the beam is at least below that limit.

At low energies, part of the beam intensity is lost due to the charge state distribution after stripping. At the lowest energy possible at CYCLONE110 (0.56 MeV/amu) about 45% of the Be ions are found in the 4+ state. At 1 MeV/amu however this fraction increases to 75 % and at a few MeV/amu it is 100%. The typical global transmission from the analysing magnet of the source to the experimental area is of the order of 4% at 1 MeV/amu. With an initial amount of 10^{16} Be-7 atoms (1.5 GBq) on the sputtering electrode, the typical beam intensity for a $^{7}Be^{1+}$ beam at 7.0 MeV is of the order of 2 10^{7} pps.

USE OF THE BE-7 BEAM

Initially, the Be-7 beam has been used for experiments in nuclear physics and astrophysics [4] but it is now also used for industry. As it has already been presented at previous cyclotron conferences [5,6,7,8,9] the presence of a radioactive tracer in the surface layer of a sample allows to measure the wear properties of this layer by following the evolution of the activity during the wear tests.

Up to now, the thin layer activation technique (TLA) is the most commonly used for such measurements. The long-lived radioactive tracer is produced by activation of the surface to be studied with light ion beams. However the TLA technique has some limitations:

-only materials containing elements with Z>20 like iron can be activated;

- the radiation damage caused by the primary beam in the material to be studied is a limitation specially for non metallic materials.

These limitations are overcome by the direct implantation of Be-7 ions. Low Z material like organic material, ceramics, and hard coatings made of amorphous graphite can be implanted with Be-7. Even materials which are sensitive to radiation damage, like polymers, can be implanted as only the radioactive atoms are penetrating the sample. Moreover, the penetration depth can be limited to a few microns by choosing the energy of the Be-7 beam, a feature which can not be achieved by the TLA method [10].

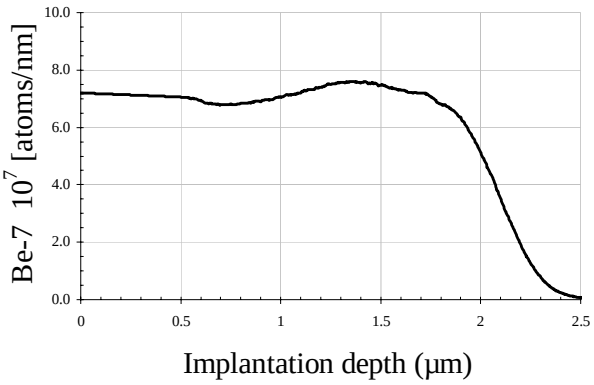

Figure 2: Typical Be-7 implantation profile

Several samples have been implanted with Be-7 ions accelerated at 7.0 MeV by CYCLONE110: hip-joints made of ceramic, engine parts covered by an amorphous carbon layer for Formula-1 racing car. The typical thickness of this layer is of the order of 3 to 5 µm. To obtain a uniform implantation profile along the depth, the energy of the beam is modulated by a combination of a fixed and a tilted foil, whose angle is controlled by a stepper-motor (fig 2 and 3). The intensity of the beam being of the order of 2 10^7 pps (12 epA), it takes 3 hours to implant 2 10^{11} Be-7 atoms (30 kBq) in an 8 mm diameter surface.

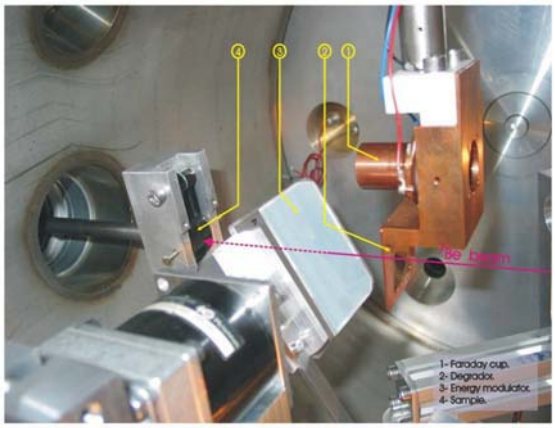

Figure 3: the Be-7 implantation chamber

This work has been done for a private company (DSI) [11] which provides the analysis of the measurements at the customer's site.

The technique would certainly benefit from an increase of the Be-7 beam intensity. The most direct way to achieve this is to increase of the initial Be-7 activity on the sputtering electrode. An other way would be to accelerate the beam in CYCLONE44 [12]. This would allow a better acceleration efficiency and higher availability of the accelerator than presently at CYCLONE110.

ACKNOWLEGEMENTS

This paper presents results of research funded by the Belgian Programme on Interuniversity Attraction Poles initiated by the Federal Policy Office, Brussels and by the Institut Interuniversitaire des Sciences Nucléaires.

REFERENCES

[1] http://www.cyc.ucl.ac.be
[2] M. Gaelens et al., NIMB 204 (2003) 48-52
[3] A. Zyuzin et al., NIMB 187 (2002) 264-274
[4] C. Angulo et al. , Nucl. Phys. A176 (2003) 211-229
[5] A.Gervé and G.Shatz, Proc. of the 7th Int. Conf. on Cycl. and their Appl., Zurich (1975) 496-502
[6] V. Bechtold et al., Proc. of the 11th Int. Conf. on Cycl. and their Appl., Tokyo (1986) 593-596
[7] P. Fehsenfeld et al, Proc. of the 12th Int. Conf. on Cycl. and their Appl., Berlin (1989) 577-581
[8] M. L. Mallory et al, Proc. of the 12th Int. Conf. on Cycl. and their Appl., Berlin (1989) 582-586.
[9] P. Fehsenfeld et al., Proc. of the 13th Int. Conf. on Cycl. and their Appl., Vancouver (1992) 171-174
[10] P. Fehsenfeld, C. Eifrig, R. Kubat, Nucl. Phys. A.701 (2002) 235-238.
[11] http://www.deltabeam.net
[12] G. Ryckewaert et al., this conference