PRODUCTION AND ACCELERATION OF RADIOACTIVE BEAMS AT LOUVAIN-LA-NEUVE

M. LOISELET, G. BERGER, D. BREYNE, Th. DARAS, H. GOFFAUX, N. POSTIAU, G. RYCKEWAERT, J. RYCKEWAERT

Université Catholique de Louvain, Centre de Recherches du Cyclotron, chemin du Cyclotron 2, B-1348 Louvain-la-Neuve, Belgium

Various post-accelerated radioactive ion species, ranging from ^{6}He ($T_{1/2}$ = 0.8 s) to ^{35}Ar ($T_{1/2}$ = 1.7 s) are now available at Louvain-la-Neuve, with intensities of 10^5 particles per second (pps) for $^{35}Ar^{5+}$ and up to 2 x 10^9 pps for $^{19}Ne^{2+}$. Specific aspects related to the production, ionization and acceleration of these exotic elements are described in the first part of this contribution. The main design features of CYCLONE44, the new cyclotron dedicated to the acceleration and isobaric separation of radioactive elements at low energy (0.2 to 0.8 MeV/amu) are presented.

1 Introduction

Since the first successful acceleration of ^{13}N ($T_{1/2}$ = 10 min) in 1989, considerable progresses have been made in the field of radioactive beams in Louvain-la-Neuve, and various species, from ^{6}He ($T_{1/2}$ = 0.8 s) to ^{35}Ar ($T_{1/2}$ = 1.7 s), are now available in an energy range between 0.6 and 4.9 MeV/nucleon. In 1994, about 1000 hours were devoted to the acceleration of radioactive ions. These beams are used for cross-section measurements of important reactions involved in nuclear astrophysics, and for pilot experiments in nuclear physics.

An overview of different aspects related to the production, ionization and acceleration of these exotic elements is given in the first part of this contribution. Specific problems encountered with ^{18}F, which has been accelerated recently, will be described with more details. In the second part of this report, the main design features of CYCLONE44, the new cyclotron dedicated to the acceleration and isobaric separation of unstable species at low energy are presented.

2 Acceleration of Radioactive Ions in CYCLONE

2.1 General Description

The general layout of the Louvain-la-Neuve facility is presented in figure 1. It uses two cyclotrons, and an on-line ECR source to produce, ionize and accelerate the radioactive ions. The 30 MeV proton beam of the first machine, CYCLONE30, is used to produce large amounts of unstable elements in suitable targets. These are ionized in an ECR ion source and, after a first magnetic separation, they are injected in the second cyclotron, CYCLONE, which brings them to the required energy.

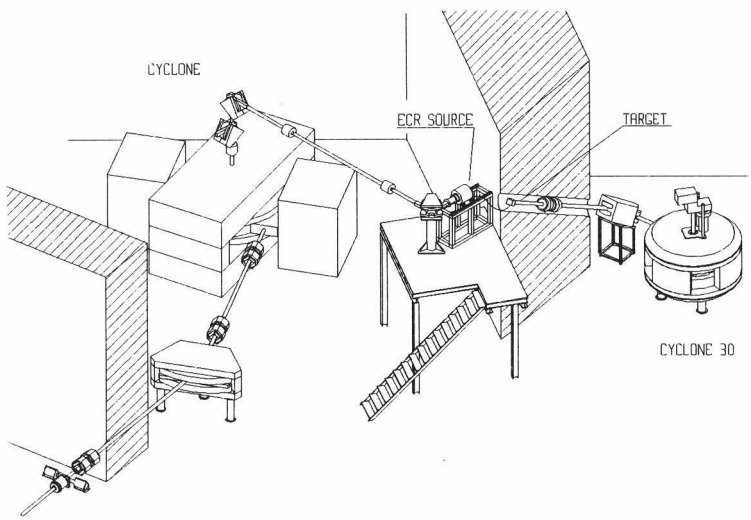

Figure 1 : Layout of the present radioactive beam facility

2.2 *Production of the Unstable Elements*

The exotic species accelerated so far in CYCLONE are given in table 1. Except for ^{18}F, they are noble gases, like ^{6}He, ^{18}Ne, ^{19}Ne, ^{35}Ar, or other elements like ^{13}N or ^{11}C which are extracted on-line from the production target in a gaseous form like ^{13}N-N or $^{11}CO_{(2)}$ molecules. They are produced in specific targets (table 1), with a beam intensity between 125 μA and 175 μA, depending on the target material and/or the charge state required for the acceleration as it will be explained below[1,2,3].

Fluorine 18 is a particular case in the list of ions that have been accelerated so far. Due to the high chemical reactivity of this element, the on-line extraction of fluorine from the production target with a high efficiency is difficult. However, the long half-life of ^{18}F ($T_{1/2}$ = 109.7 min), allows to dissociate the production process from the chemical separation. In the first step, fluorine 18 is produced using $^{18}O(p,n)^{18}F$ reaction on a ^{18}O enriched water target. After two hours of irradiation with 12.5 μA of protons at 15.5 MeV, the liquid is transferred to a hot cell where, after various chemical steps, the ^{18}F is extracted and ^{18}F fluoromethane ($CH_3\ ^{18}F$) is synthesised. After this fully automatic procedure, which takes about 40 minutes, and was developed by our colleagues from the Positron Camera Centre, $CH_3\ ^{18}F$ is transferred in a gaseous form to the ECR source, and an other ^{18}F production is started[4].

Table 1 : Reaction used to produce the exotic elements presently available at Louvain-la-Neuve. The relative mass over charge difference with a possible contaminant, coming either from the target or from the residual gas in the source, is also given.

Element	$T_{1/2}$	Production reaction	Target material	Possible contaminant	$\Delta(m/q)$ m/q
^{6}He	0.8 s	$^{7}Li(p,2p)$	LiF	^{6}Li, ^{12}C	6×10^{-4}
^{11}C	20 min	$^{11}B(p,n)$	BN	^{11}B	2×10^{-4}
		$^{14}N(p,\alpha)$			
^{13}N	10 min	$^{13}C(p,n)$	^{13}C*	^{13}C	2×10^{-4}
^{18}F	109.7 min	$^{18}O(p,n)$	$H_2\ ^{18}O$	^{18}O	9.9×10^{-5}
^{18}Ne	1.7 s	$^{19}F(p,2n)$	LiF	^{18}O	4×10^{-4}
^{19}Ne	17 s	$^{19}F(p,n)$	LiF	^{19}F	2×10^{-4}
^{35}Ar	1.8 s	$^{35}Cl(p,n)$	NaCl	^{35}Cl	2×10^{-4}

* enriched ^{13}C powder

2.3 *Ionization*

The ion source is a single stage ECR source working at 6.4 GHz and originally designed to produce single charged ions with a high efficiency : ionization efficiencies of the order of 15 % for N^{1+} and 40 % for Ne^{1+} have been measured off-line[5]. However, the ionization efficiency is a sensitive function of the pressure in the source, specially for higher charge states (2^+, 3^+). On line, this is fixed by the gas flux emanating from the target, which is function of the beam intensity. For this reason, the primary beam intensity is sometimes reduced to allow a better working pressure in the source.

For $^{18}F^{1+}$, the ionization efficiency has been estimated to be of the order of 0.3 %, a value which is rather low in comparison with N^{1+}. This is mainly attributed to the fact that, once a $CH_3\ ^{18}F$ molecule is broken, any ^{18}F which escapes from the plasma is fixed on the walls of the plasma chamber, due to the high reactivity of fluorine.

2.4 *Acceleration*

The isobaric contamination is an important factor in the acceleration of exotic elements. After a first magnetic separation in a low mass resolution dipole, the unstable ions are injected in CYCLONE together with intense (several orders of magnitude larger) beams of stable elements having almost the same mass over charge ratio (m/q) and coming either from the production target or from the residual gas in the source (see table 1). To achieve a high purity in the final beam, the cyclotron is tuned as a radiofrequency mass spectrometer, so that the intensity of the isobaric contaminants is considerably reduced after the acceleration process[2,7]. In an isochronous field, the mass resolving power $R = (q/m)/\Delta(q/m)$ is given by[2] : $R = 2\pi\ H\ N_0/\sin\phi_0$ where H is the harmonic number, N_0 the number of turns required for the acceleration of the particle with mass m and charge q to the full energy, and ϕ_0 the initial phase. It shows that the resolution is proportional to the number of turns, so that it increases if the dee voltage decreases.

A particular example of this is given by ^{18}F. For this beam, the isobaric contaminant is ^{18}O, which is always

present in the residual gas of the source (^{18}O natural abundance : 0.2 %). The relative mass difference between these two particles is 9.9 x 10^{-5}. Figure 2 illustrates the mass resolution that can be obtained with CYCLONE if a reduction of the acceleration efficiency is tolerated. It shows the intensities of ^{18}O and ^{18}F versus the magnetic field of the cyclotron, after the acceleration process. Note that the intensity scale is different for the left part of the picture (nA) and for the right part (fA). To achieve this mass resolution, the accelerator is tuned on ^{18}O with a dee voltage of 19 kV, instead of 36 kV as required for a standard tuning, and the ^{18}O contamination at the magnetic field where ^{18}F will be accelerated, is measured carefully down to a femtoampere level before any ^{18}F injection in the source. For this purpose, a current amplifier, specially developed in our laboratory, is mounted directly on a shielded Faraday cup[6]. As illustrated by the figure, the ^{18}O attenuation is larger than 10^5 at the place of the ^{18}F maximum. With this tuning, the acceleration efficiency (intensities after the analyzing magnet of the ECR source and after the cyclotron), has been measured to be 0.5 %. For the other beams, where the relative mass difference with the isobaric contaminant is 2 x 10^{-4}, like between ^{13}N and ^{13}C or ^{19}Ne and ^{19}F, the same suppression factor is obtained with an acceleration efficiency of the order of 3 to 5 %[7].

The maximum intensities presently available for the various elements are given in table 2.

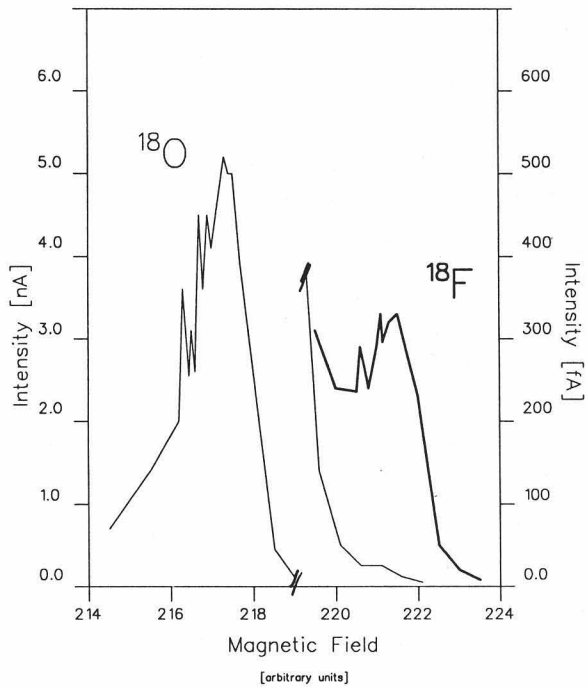

Figure 2 : Isobaric separation of ^{18}O and ^{18}F : intensity of the extracted beam versus the magnetic field of the cyclotron. Note that the intensity scale is different for ^{18}O (left scale, nA) and for ^{18}F (right scale, fA)

Table 2 : Maximum intensities obtained for the various radioactive ions accelerated by CYCLONE, together with the maximum energy available for each charge state

Element	$T_{1/2}$	Q	Intensity (pps)	Maximum energy (MeV)
^{6}He	0.8 s	1^+	1.2 x 10^6	18
^{11}C	20 min	1^+	1.0 x 10^7	10
^{13}N	10 min	1^+	4.0 x 10^8	8.5
		2^+	3.0 x 10^8	34
		3^+	3.0 x 10^7	70
^{18}Ne	1.7 s	3^+	4.2 x 10^5	55
^{19}Ne	17 s	2^+	1.9 x 10^9	23
		3^+	1.5 x 10^9	50
		4^+	5.0 x 10^8	93
^{35}Ar	1.8 s	5^+	10^5	79
^{18}F	110 min	2^+	1 x 10^6	24

3. CYCLONE44

As it appears in table 2, the present facility is quite flexible and can provide beams up to a few MeV/nucleon when multiply charged ions are available. ($^{19}Ne^{4+}$ has been accelerated to 4 MeV/nucleon for example).

However, in the energy range of nuclear astrophysics (from 0.1 to 1 MeV/nucleon), for which the radioactive species provided in Louvain-la-Neuve are of particular

interest, the present facility has some major limitations : the lowest energy of CYCLONE is 0.56 MeV/nucleon and the acceleration efficiency at this energy is limited to about 3 %. For these reasons, a new cyclotron, CYCLONE44, is presently under construction.

It will cover the energy range between 0.2 and 0.8 MeV/nucleon, and is designed to combine a high acceleration efficiency (one order of magnitude larger than it is in CYCLONE), with a high mass resolving power, in order to provide pure radioactive beam of low intensity in the presence of intense isobaric contaminant. The main challenge in the design of CYCLONE44 lies in the combination of these two requirements. As shown, the resolving power of a cyclotron is proportional to the number of turns times the acceleration harmonic mode number, thus asking for low dee voltage and high harmonic modes. On the other hand, a large acceleration efficiency can only be obtained if the axially injected low energy beam is perfectly matched to the cyclotron central region acceptance, in six dimensional phase space. This requirement calls in turn for low harmonic modes, high injection voltage and high Dee voltage. More details and the present status of CYCLONE44 are reported in an other paper of this conference (G. Ryckewaert et al.). The main characteristics of this new postaccelerator are given in table 3.

Table 3 : Main characteristics of CYCLONE44

Energy Constant K	MeV	44
Energy Range	MeV/amu	0.2 - 0.8
M/Q Range		4 - 14
Max. Average Field	T	1.54
Extraction Radius	m	0.633
RF System	2 Variable Angle Dees	
Frequency Range	MHz	13.3 - 18.7
Max. Dee Voltage	kV	20
Harmonic Modes		6 - 8

The layout of the future Louvain-la-Neuve facility, showing CYCLONE44 and the new injection line coming from the present target ion source station is presented in figure 3.

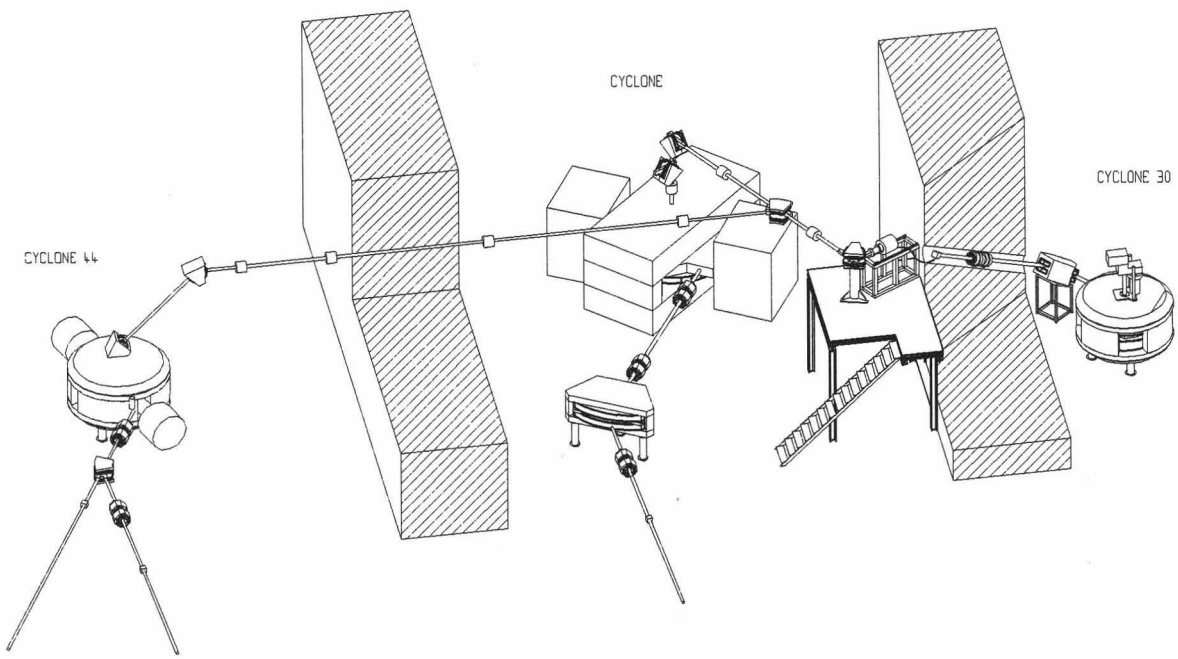

Figure 3 : Layout of the future radioactive beam facility

4. Conclusion

Various radioactive beams of light species from ^{6}He to ^{35}Ar are accelerated at Louvain-la-Neuve with intensities ranging from 10^5 pps for $^{35}Ar^{5+}$ up to 10^9 pps for $^{19}Ne^{2+}$. These are now intensively used for pilot experiments in nuclear astrophysics and nuclear physics. The Louvain-la-Neuve facility has shown that the problem of the beam contamination with isobaric elements, which is of particular importance for any radioactive beam facility, can be solved by the specific characteristics of the cyclotron which combines a good acceleration efficiency and a high mass resolving power.

The performances of CYCLONE44 the new accelerator specially design for the acceleration and isobaric separation should give an additional knowledge on the possibilities and the limits of cyclotrons in this new field of the physics of accelerators.

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