RADIOACTIVE ION BEAM PRODUCTION USING THE LOUVAIN-LA-NEUVE CYCLOTRONS : PRESENT STATUS AND FUTURE DEVELOPMENTS

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ABSTRACT

CYCLONE 30, the high intensity 30 MeV H^- cyclotron, is used to produce large quantities of short lived radioactive isotopes. These are extracted on-line from the target, ionized in an ECR-source and accelerated with CYCLONE. Isobaric contamination is eliminated in the acceleration and ejection process without loss of intensity. Pure radioactive beams of $^{13}N^{+1}$ and 2^+, $^{19}Ne^{+2}$, 3^+ and 4^+ are now accelerated routinely in the energy range between 0.56 and 4.5 MeV/AMU with intensities reaching 2 10^9 pps. They are used for nuclear astrophysics and nuclear physics experiments. To overcome a number of limitations due to CYCLONE the design of a dedicated postaccelerator cyclotron has been started. In this paper, recent developments of the present system and design features of the new cyclotron are described.

1. GENERAL DESCRIPTION

The installation for the production of intermediate energy RIB has been described earlier.[1] In this paragraph we summarize the main features of the subsystems and their recent developments.

1.1. The production of radioactive elements

The radioisotopes of interest are produced selectively on specific targets. In this way, only small quantities of unwanted (eventually long lived) activity are formed, allowing still relatively simple ways to manipulate the production targets.

A special beamline transports the proton beam from CYCLONE 30 to the target, located in the shielding wall between the two cyclotrons. It consists of a 90° doubly focusing magnet, tilted up 32°, a quadrupole doublet, steering magnets and a 50 Hz wobbling magnet. Table 1 lists a number of radioactive elements of interest that could be produced with CYCLONE 30 and the respective production reactions. The first target developed, for the production of ^{13}N, consisted of a solid disk made of enriched ^{13}C, fixed on a watercooled target holder. The target assembly is isolated from the beamline vacuum by a thin carbon window. However, other target materials such as LiF, B_2O_3, BN, could not be used this way. Therefore we developed closed graphite containers, filled with the respective materials, and which are outgassed before being placed on the watercooled target holder. Even the operating ^{13}C-target for ^{13}N-production is now made this way.

Several sweeping gases are being tried out for the different elements. ^{19}Ne production is special in two aspects : it does not require any sweeping gas and since it is not cryopumped itself, an additional purification is achieved by passing the target gas flow through a cryopump. In this way very low pressures are obtained in the ECR-source yielding high ionization efficiencies even for relatively high (4^+, 5^+) charge states. It should be noted that in the LiF-target the ^7Be activity ($T_{1/2}$ = 53 d) builds up slowly.

1.2 Ionization

A single stage ECR-source working at 6.4 GHz was built and its ionization efficiency for the light elements was carefully optimized. To obtain the maximum beam current for a given isotope at a given charge state, it is important that all accessible source parameters, such as axial field, microwave power, source-to-puller gap be carefully adjusted. The pressure in the source is crucial : it must be as low as possible. In the case a carrier gas is to be used with the production target, an optimum flow rate has to be found since the extraction efficiency from the target usually requires increased flow whereas the ionization efficiency requires the lowest possible flow. Using a source aperture of 10 mm this optimum lies around 0.1 cc/min.

Element	$T_{1/2}$	Production reaction	Target material	Contaminant/ analogous beam	$\frac{\Delta Q/M}{Q/M}$	Reaction	Energy MeV/AMU
^{6}He	0.8 s	$^{7}Li(p,2p)$	Li	^{6}Li, ^{12}C	6.10^{-4}	$^{6}He(\alpha,n)^{9}Be$	0.4
^{7}Be	53d	$^{7}Li(p,n)$	LiF	^{7}Li, ^{14}N	$1.3.10^{-4}$	$^{7}Be(\alpha,\gamma)^{11}C$	0.4
^{8}Li	0.8 s	$^{9}Be(p,2p)$		^{16}O	3.10^{-3}	$^{8}Li(\alpha,n)^{11}B$	0.4
						$^{8}Li(d,n)^{9}Be$	0.6
^{11}C	20 min	$^{11}B(p,n)$	B_2O_3	^{11}B, ^{22}Ne	2.10^{-4}	$^{11}C(p,\gamma)^{12}N$	0.6
		$^{14}N(p,\alpha)$	BN				
^{13}N	10 min	$^{13}C(p,n)$	enriched ^{13}C	^{13}C	2.10^{-4}	$^{13}N(p,\gamma)^{14}O$	0.6
^{14}O	70 s	$^{14}N(p,n)$	BN	^{14}N	4.10^{-4}	$^{14}O(\alpha,p)^{17}F$	0.6
^{15}O	2 min	$^{19}F(p,\alpha n)$	LiF	^{15}N	2.10^{-4}	$^{15}O(\alpha,\gamma)^{17}F$	0.3
^{19}Ne	17 s	$^{19}F(p,n)$	LiF	^{19}F	2.10^{-4}	$^{19}Ne(p,\gamma)^{20}Na$	0.5

Table 1 : Some radioactive beams, their production reactions, contaminants and nuclear reactions of interest for astrophysics.

1.3. Acceleration and isobaric separation

The low energy beam is injected axially in CYCLONE and accelerated on 6th harmonic mode. The limited resolution in M/Q (40) of the low energy analyzing system eliminates neighbouring charge states and contaminants but not those particles that have nominally the same M/Q (see table 1).

To achieve the required purity of the final beam, various physical and chemical methods have been tried out, all rather unsuccessfully.

Finally it was tried to use the cyclotron as a high resolution mass spectrometer. Let us recall here briefly how this could work.[2)]

Consider an isochronous field in which a particle with a given Q/M is accelerated to full energy in N_0 turns with an accelerating voltage working at the H^{th} harmonic of the particle revolution frequency. Consider another particle whose charge to mass ratio differs slightly from the first by an amount $\Delta(Q/M)$. The change in phase, ϕ, during acceleration between the two particles will be given by :

$$\Delta\sin\phi = 2\pi H N_0 \Delta(Q/M)/(Q/M) \qquad (1)$$

When the absolute phase of the particle with respect to the RF reaches 90° the acceleration will stop. The condition to eliminate the wrong particle from the beam, is that this should happen before the extraction radius is reached. Remember that $\Delta\sin\phi$ means $(\sin\phi e - \sin\phi b)$ where e means end of acceleration and b means beginning of acceleration. Depending on the starting phases of the particles, $\Delta\sin\phi$ will be somewhere between 0 and 2. Defining the resolution $R = (Q/M)/\Delta(Q/M)$ gives then :

$$R = 2\pi H N_0 / \Delta\sin\phi \qquad (2)$$

This relation shows that the mass resolution of a cyclotron is not an unambiguous quantity. It depends for example strongly on the starting conditions in the central region. If starting phases around 0° are considered then the resolution R_0 becomes :

$$R_0 = 2\pi H N_0 \qquad (3)$$

If for some reason (axial focusing e.g.) starting phases far from 0° have to be adopted then the resolution for wrong particles with larger or smaller Q/M values will be totally different. As an example let us take a starting phase of 30°. In the case of a slightly heavier particle $\Delta\sin\phi$ equals 1.5, in the opposite case 0.5 or a factor of 3 difference in the resolution for a given cyclotronsetting. This situation was experimentally verified with CYCLONE and illustrated in Fig. 1.

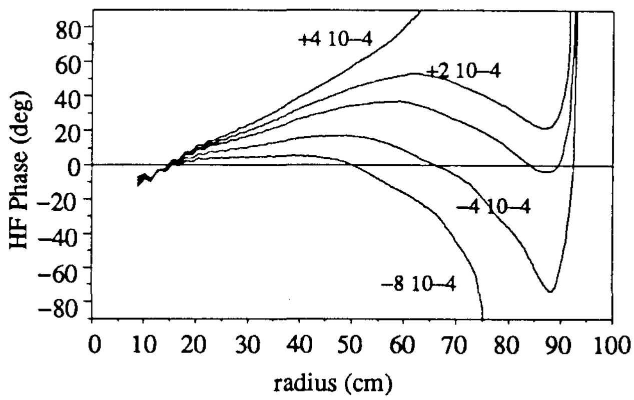

Figure 1 : Phase histories for a given particle in the reference field and fields with $\Delta B/B = +2, +4, -4$ and $-8\ 10^{-4}$.

Another effect is illustrated in Fig. 2 : even when some of the wrong particles reach the extraction radius and start their way through the deflector, they never reach the cyclotron exit because they do not fall into the extraction system's acceptance.

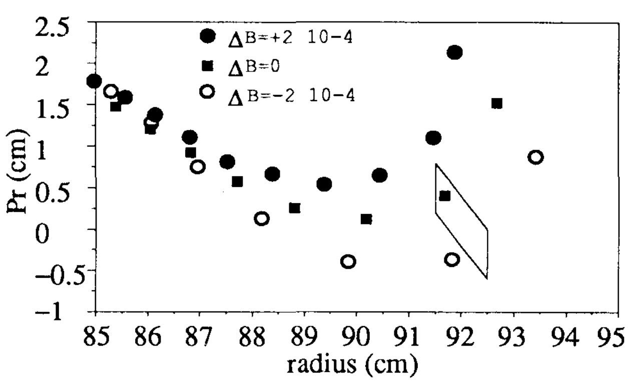

Figure 2 : Acceptance of the extraction system and trajectories of a particle in the reference field and fields with $\Delta B/B = +2$ and $-2\ 10^{-4}$.

Using systematically these effects we have been able to suppress contaminant beams by factors of 10^5 or more without loss of the radioactive beam intensity although their respective Q/M ratios differ only by less than 2 parts in 10^4.

2. OPERATIONAL ASPECTS

Arrangements have been made so that production, transport and acceleration can be optimized independantly. In a first step,the gas flow from the production target can be pumped to a counting station outside the cyclotron vault. This way, the initial outgassing does not have to go through the source and the extraction efficiency can be checked. New targets can be tested.

When the target conditions have been optimized, the gas flow is directed to the source. To optimize the source conditions and to check the ionization efficiency, the low energy beam is stopped and focused on a plate at some distance behind the first Glaser lens. The beam current measured at this point represents essentially the intensity of the contaminant beams. To get an idea of the radioactive beam intensity this beam stop has also been equipped with a β^+ detector. This detector is well shielded from the background generated by the proton beam. At this point the overall efficiency (production + ionization) can be optimized. This works particularly well with the short lived elements (^{19}Ne e.g.).

Transport from the source to the cyclotron, axial injection, acceleration and transport to the experimenter's target are adjusted using a stable beam having the almost identical Q/M value (see Table 1). If the natural contamination in the source is not sufficient, gas is fed to the source. Finally, before switching to the radioactive beam, the mass resolution is checked carefully and the cyclotron is eventually retuned to make sure that a pure radioactive beam is obtained. Table 2 lists the intensities of radioactive beams obtained until now.

Element	Charge State	Intensity [pps]	Maximum Energy [MeV]
^{13}N	1+	4×10^8	8.5
($T_{1/2}$ = 10 min)	2+	3×10^8	34
^{19}Ne	2+	1.9×10^9	23
($T_{1/2}$ = 17 s)	3+	$(10^9)^*$	52
	4+	5×10^8	93

* expected

Table 2 : Intensities and energies of the radioactive beams which are presently available at the Louvain-la-Neuve facility.

Figure 3 shows the operating diagram of CYCLONE in the area of interest.

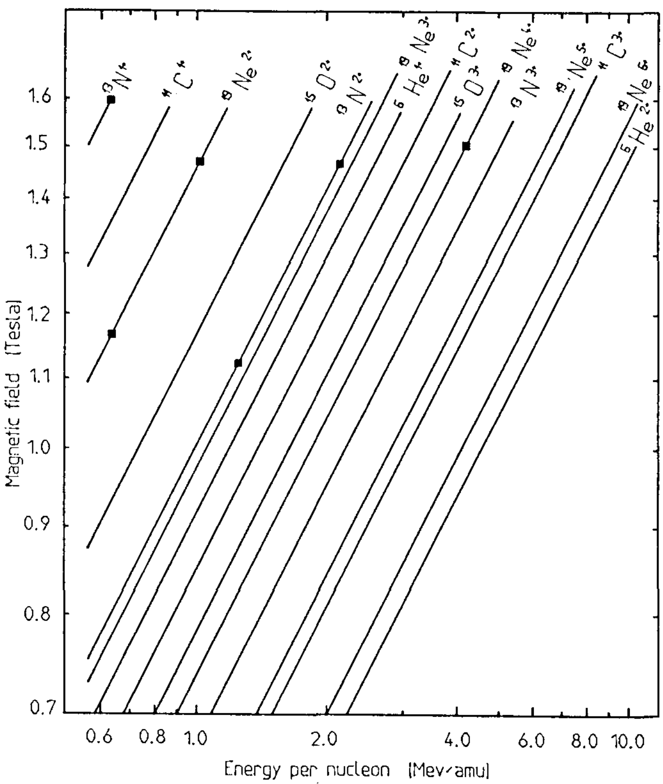

Figure 3 : Operating diagramme for RIB acceleration with CYCLONE.

3. A DEDICATED POSTACCELERATOR FOR RADIOACTIVE ION BEAMS

The actual system suffers two major drawbacks with respect to the requirements for nuclear astrophysics experiments. First, the lower energy limit in H = 6 mode is 0.56 MeV/AMU. Higher harmonic modes seem out of the question. However, as Table 1 shows, there are a number of reactions to be measured at lower energies. Secondly, some of the cross sections to be measured are extremely low so that a minimal intensity is required to make the experiments feasible. This intensity will not be reached: the losses (50 to 80%) due to insufficient vacuum are too high and the matching in the central region is poor. It is very difficult to improve these parameters significantly because of the basic design and operational modalities of CYCLONE.

We have proposed to build a dedicated postaccelerator for radioactive beams. Earlier proposals by other groups comprise a combination of an RFQ and a linac or a tandem for the postacceleration of Isotope Separator On Line (ISOL) beams. In this case very high resolution separators together with ion sources of very high optical qualities are needed at the low energy side to eliminate any isobaric contamination.[3] In our case we want to use an ECR-source because of its high ionization efficiency and high charge state yield for the light elements : higher charge states imply a reduced size for the accelerator. For the metal and alkali elements however, a solution has still to be developed to transfer the activity from the production target to the ECR-source. The emittance of ECR-sources is also larger by a factor of 10 to 100, compared with the classical ISOL-sources.

A cyclotron which combines a large acceptance with a high Q/M resolving power has been chosen. In order to achieve a high acceleration efficiency, special attention has to be paid to the vacuum in the cyclotron and to the matching of the cyclotron acceptance with the source emittance. Harmonic modes 4 and 6 have been chosen: this allows a reasonable size for the RF-resonators, a low effective number of turns which reduces the losses due to stripping whilst assuring a large Q/M resolution. The cyclotron parameters have been redefined as shown in Table 3. Design and construction are planned for the period 1992-1996.

Energy constant	33 MeV
Energy range	0.2 - 0.8 MeV/AMU
M/Q (max)	13
Resolution in Q/M	10 000
Magnet structure	4-sector
Average Field (max)	1.6 T
(min)	0.7 T
Extraction radius	0.52 m
RF-system	2 DEES, 30° wide
Frequency range	11 - 15 MHz
Max DEE voltage	20 kV
Harmonic modes	4,6

Table 3 : Characteristics of the new postaccelerator cyclotron.

4. REFERENCES

1) Berger, G. et al., "Acceleration and mass-separation of radioactive ion beams in an isochronous cyclotron", 1991 IEEE PAC, San Francisco 1991, pp. 2610-2612.
2) Clark, D.J., "Cyclotrons as mass spectrometers", Proc. of the 10th Int. Conf. on Cyclotrons and their Applications, (IEEE, New York, 1984) pp. 534-539.
3) Wollnik, H., et al., "The proposed JHP-ISOL and its expected performance," Proc. of the 1st Int. Conf. on RIB (World Scientific, Singapore,1990) pp. 603-609.