# Acceleration and mass-separation of radioactive ion beams in an isochronous cyclotron

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*Abstract*

The paper reports on first operational results obtained with the two-cyclotron concept for the production and acceleration of a $^{13}N$ radioactive beam ($T_{1/2}$ = 10 min.). A pure beam of 70 particle pA of $^{13}N$ at 0.63 MeV/amu has been accelerated and used for cross-section measurements of the $^{1}H(^{13}N,\gamma)^{14}O$ reaction which is involved in astrophysical processes. Although the $^{13}N$ beam is accelerated with a $^{13}C$ beam at least $10^3$ times more intense, the specific characteristics of a cyclotron allow to separate clearly these two species whose relative mass difference is only 1.8 $10^{-4}$, without loss of intensity for the $^{13}N$ beam. The $^{13}C$ contamination on the final target is less than 1 particle pA. The advantages of a cyclotron over a linac as a post-accelerator for low energy radioactive beams are discussed.

## I. INTRODUCTION

The Radioactive Ion Beam project at Louvain-la-Neuve aims at the acceleration of radioactive nuclei in the energy range between 0.2 and 1.0 MeV/amu which is of interest in the so-called nuclear astrophysics. It opens the way to direct measurements of nuclear cross-sections involved in astrophysical processes.

The general layout of the facility is presented in figure 1 and has been described in detail in earlier papers [1,2]. The high intensity (up to 500 μA), 30 MeV proton beam of a first cyclotron, CYCLONE 30, is used to produce a large amount of radioactive atoms in a suitable target. These are ionized in an on-line ECR source and injected in a second cyclotron (CYCLONE) which brings them to the desired energy.

With this scheme, up to 70 pA (4 $10^8$ particles per sec.) of $^{13}N^{1+}$ has been accelerated at 0.63 MeV/amu. Although the $^{13}N^{1+}$ beam is injected in the cyclotron with a $^{13}C^{1+}$ $10^3$ times more intense, this contamination is reduced to less than 1 pA after acceleration. It turns out that the high resolving power of a cyclotron is crucial in order to eliminate the isobaric contamination in a very efficient way.

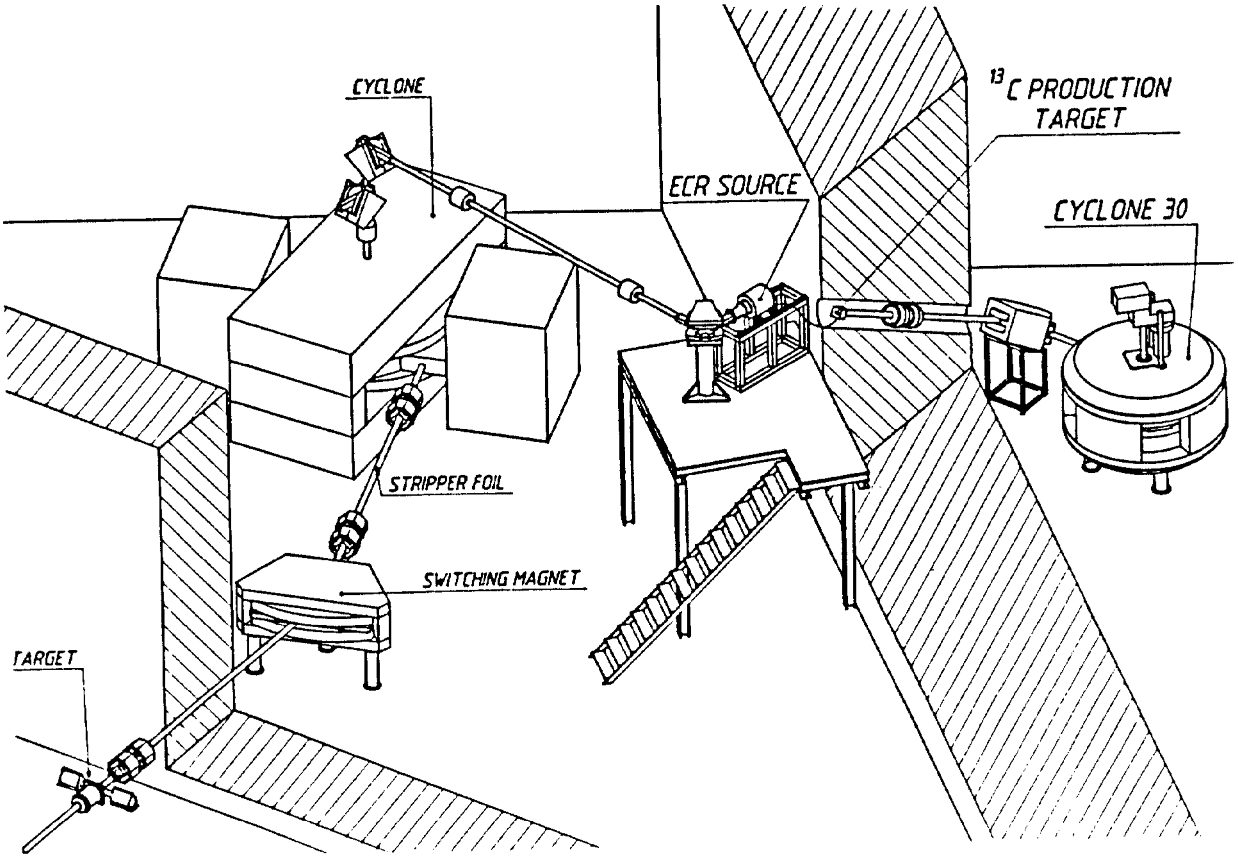

Figure 1 : Schematic layout of the RIB facility.

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## II. PRODUCTION AND ACCELERATION OF A PURE $^{13}$N BEAM

### *Production of $^{13}$N*

The $^{13}$N atoms are produced by the $^{13}C(p,n)^{13}N$ reaction which has a total yield of 1.6 $10^{-3}$ for 30 MeV protons [3]. The graphite target consists of a 10 mm thick disk with a diameter of 35 mm. It contains 50 % of $^{13}$C and is able to dissipate the 6 kW of the 200 µA proton beam. A 50 Hz sweeping magnet, located 1 m in front of the target, is used to limit the maximum power density to about 800 W/cm$^2$.

### *Extraction of the radioactive gas*

The $^{13}$N activity is extracted from the target as $^{13}N\text{-}^{14}N$ molecules by a small nitrogen gas flow. It is pumped out of the target through the 10 mm extraction hole of the ECR source only. The extraction efficiency is a sensitive function of the target temperature and of the gas flow. An extraction efficiency of 20 % is routinely achieved.

### *Ionization*

It has been shown that the ionization efficiency of the ECR source strongly decreases as the pressure in the source increases [4]. As the gas coming out of the production target not only contains nitrogen but also molecules like $H_2O$, $CO_2$ and hydrocarbons, a liquid nitrogen trap is used in front of the source in order to lower the gas load. After outgassing of the target, the ionization efficiency of the source connected to the target is about 8 % for nitrogen $1^+$.

### *Acceleration and purification*

After ionization, the ions with a mass over charge ratio equal to 13 are injected in the cyclotron. The beam not only contains $^{13}N^+$, but also $^{13}C^+$ and $^{12}CH^+$. Due to the small mass differences between these species ($\Delta m/m \cong 2\ 10^{-4}$), the beam cannot be purified magnetically at low energy without loosing too much in the transmission efficiency between the source and the cyclotron.

Different systems were tried to selectively trap carbon composites without trapping nitrogen molecules, before injection of the gas in the ECR source. Nor chemical traps nor a cryogenic trap were able to reduce the $^{13}$C contained in the beam to a level acceptable for the experiment. It appears that the most effective way to purify the beam is to use the high resolving power of the cyclotron. In first approximation, it is proportional to the harmonic mode and to the number of turns inside the accelerator. Taking advantage of the 6th harmonic mode which is required to accelerate $^{13}$N at 0.6 MeV/amu and lowering the dee voltage in order to increase the number of turns, $^{13}$C and $^{13}$N were clearly separated [fig. 2]. The $^{12}CH^+$ contamination, which still remains after acceleration, is removed from the $^{13}$N beam by a stripper foil located in front of the switching magnet. The $5^+$ charge state being the most abundant for nitrogen at this energy is transported to the final target. The overall transmission from the ECR source to the final target is about 3 %. Table 1 summarizes the efficiency of the different steps involved from the production to the experimental area.

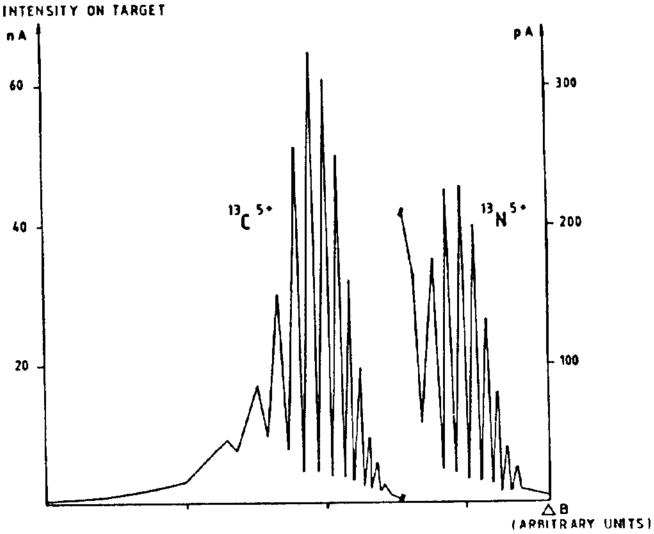

Figure 2 : Resolving power of the cyclotron : intensity versus the cyclotron magnetic field.

Table 1
Efficiency of the different steps involved in the acceleration

| | | |
|---|---|---|
| proton intensity | | 170 µA |
| $^{13}C(p,n)^{13}N$ yield | 1.6 $10^{-3}$ | |
| $^{13}$N/s produced in the target (50 % $^{13}$C) | | 8 $10^{11}$ |
| extraction efficiency | 20 % | |
| $^{13}$N/s extracted from the target | | 1.6 $10^{11}$ |
| ionization efficiency | 8 % | |
| $^{13}N^{1+}$/s extracted from the source | | 1.3 $10^{10}$ |
| acceleration efficiency | 6 % | |
| $^{13}N^{1+}$/s extracted from the cyclotron | | 7.5 $10^8$ |
| stripping efficiency $^{13}N^{5+}$ | 56 % | |
| $^{13}$N/s beam | | 4.2 $10^8$ ≅ 70 ppA |

## III. DEVELOPMENT OF OTHER RADIOACTIVE BEAMS

Besides $^{13}$N, other radioactive species like $^{11}$C, $^{15}$O, $^{19}$Ne have already been produced and extracted in large amounts from a suitable production target. They will be accelerated in a near future and the intensities after acceleration are expected to be of the same order of magnitude as for $^{13}$N.

## IV. A DEDICATED POST-ACCELERATOR FOR RADIOACTIVE BEAMS

Although the present facility is quite flexible, nuclear astrophysicists are requesting radioactive beams in the energy range from 0.1 to 1.0 MeV/amu with larger intensities. It seems difficult to go to lower energies than 0.56 MeV/amu with CYCLONE so that a dedicated low energy post-accelerator is now under study.

The generally proposed solution for the acceleration of radioactive beams is the combination of a c.w. radiofrequency quadrupole accelerator (R.F.Q.) and a superconducting linac [6,7]. With this scheme, it is theoretically possible to have an acceleration efficiency close to 100 %. However, in many cases, it is necessary to have a high resolution separator in front of the RFQ in order to eliminate isobaric contamination in the beam.

It is feasible to have a resolving power larger than $10^4$ and an acceleration efficiency larger than 25 % in a specially designed cyclotron. In this case a cyclotron should be favorably compared to the linac scheme if the transmission of the high resolution mass separator in front of the RFQ is taken into account.

The preliminary characteristics of this cyclotron dedicated to the acceleration and isobaric separation of radioactive ions are presented in table 2.

Table 2
Proposed characteristics of the cyclotron dedicated to the acceleration and isobaric separation of radioactive ions.

| | |
|---|---|
| K value | 73 MeV |
| Bav (max) | 1.52 T |
| energy range | 0.07 to 1.3 MeV/amu |
| frequency range | 8-18 MHz |
| number of dees | 2 |
| dee angle | 20° |
| harmonic modes | 6-8-10-12 |
| M/Q max | 31 |
| resolving power M/ΔM | $10^4$ |
| acceleration efficiency | > 25 % |

## V. REFERENCES

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