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Production of intense radioactive ion beams using two accelerators

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An intense beam (1.5×10^8 particles/sec) of radioactive $^{13}N^{1+}$ ions (half-life: $T_{1/2}=10$ min) has been produced and accelerated to 0.65 MeV/nucleon, by coupling two cyclotrons with an electron cyclotron resonance ion source. This is the first time a short-lived radioactive ion beam has been produced by this method, at such an energy and with such a high intensity, a result which opens up a wide field in many applications. The first experiment along these lines will be the measurement of the cross section for the nuclear reaction $^1H(^{13}N,\gamma)^{14}O$ which is the crucial reaction for the operation of the so-called hot CNO cycle in nuclear astrophysics.

The production, acceleration, and use of radioactive ion beams is a topic of great current interest.[1-3] Possible applications for such beams can be found in nuclear astrophysics,[1] nuclear structure physics, solid state physics, biomedical research, and cancer therapy.[2,3] Until now, radioactive ion beams have been produced by bombarding suitable targets with primary beams from a *single* accelerator; the kinematics of the recoil products is then used to separate the primary stable beam from the secondary radioactive ones. Using this method, beams of ^8Li have been produced in the energy range suitable for astrophysical applications, i.e., below 2 MeV/nucleon, with intensities between 2 and 5×10^4 particles/sec.[4] Radioactive ion beams of much higher energies, i.e., above 10 MeV/nucleon, have been obtained by fragmentation of primary beams in the energy range between 10 and 44 MeV/nucleon (Ref. 5) and above 100 MeV/nucleon.[6] The approach followed in the Louvain-la-Neuve project[7] is radically different from the previous ones: it uses *two* accelerators coupled on line by an intermediate ion source, in our case two cyclotrons with an electron cyclotron resonance (ECR) ion source as shown in Fig. 1. The first accelerator, the cyclotron CYCLONE 30, is used to produce large amounts of the radioactive atoms of interest by a suitable nuclear reaction. The radioactive species are ionized in the ECR source, transported to and injected in the second accelerator, the cyclotron CYCLONE. The latter brings them to the desired energy, and the resulting beam is directed to the user's station. This two-accelerator method has several advantages: radioactive ions of different types can be obtained, a wide range of energies can be reached, in particular in the astrophysically interesting region, i.e., between 0.2 and 2 MeV/nucleon, and high intensities can be achieved. We have shown the feasibility of this method by producing, for the first time, a radioactive $^{13}N^{1+}$ beam with an energy of 0.65 MeV/nucleon and an intensity of 1.5×10^8 particles/sec. Other projects to produce and accelerate radioactive ion beams with energies and intensities similar to ours have been proposed.[8-12]

The $^{13}N^{1+}$ radioactive ion beam has been obtained under the conditions summarized in Table I and illustrated in Fig. 1. A 30-MeV, 100-μA proton beam produced by the cyclotron CYCLONE 30 (Ref. 13) was directed towards a target located in the concrete wall separating the

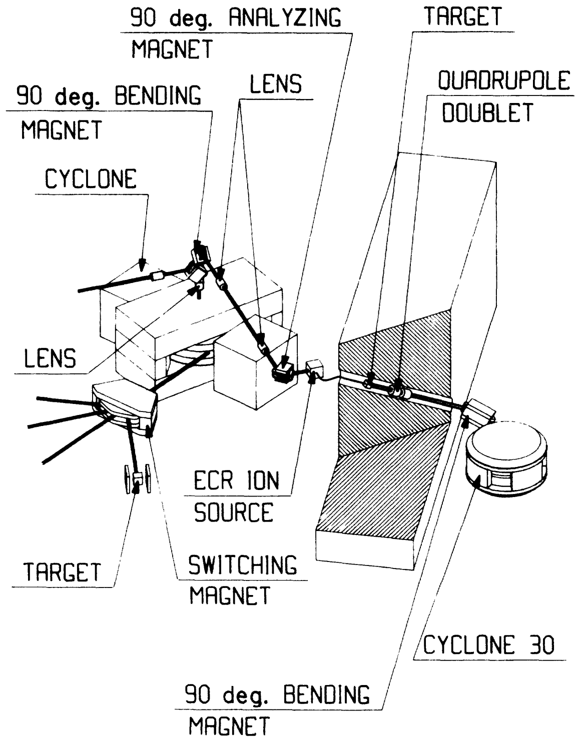

FIG. 1. General layout of the radioactive ion beam facility.

TABLE I. Performances of the elements involved in the production of a $^{13}\mathrm{N}^{1+}$ radioactive ion beam, achieved during the most recent on-line run of the whole system and during previous off-line separate tests. I_p is the proton beam intensity. N(p) is the number of protons, N(^{13}N), the number of ^{13}N nuclei produced by the $^{13}\mathrm{C}(p,n)^{13}\mathrm{N}$ reaction. $\epsilon_{\rm extraction}$ is the extraction efficiency of the ^{13}N activity from the target, $\epsilon_{\rm ionization}$ the ionization efficiency of the ECR source, and $\epsilon_{\rm acceleration}$ the acceleration efficiency of CYCLONE, all quantities quoted in percents (%). N($^{13}\mathrm{N}^{1+}$) is the number of $^{13}\mathrm{N}^{1+}$ ions extracted from CYCLONE, in particles/sec (pps). The number between parentheses represents the expected performance.

Quantity	One-line run	Off-line tests
I_p	100 μA	500 μA
N(^{13}N)/N(p)	1.6×10^{-3}	1.6×10^{-3}
$\epsilon_{\rm extraction}$	9%	80%
$\epsilon_{\rm ionization}$	4%	15%
$\epsilon_{\rm acceleration}$	4%	10%
N($^{13}\mathrm{N}^{1+}$)	1.5×10^{8} pps	(6×10^{10} pps)

vaults of the two cyclotrons. This target was made of ^{13}C pellets, obtained by graphitizing 99% enriched ^{13}C powder under high temperatures and pressures, and embedded into a natural graphite rod in good thermal contact with a water-cooled copper cylinder.[14] Large amounts of ^{13}N nuclei were thereby produced through the $^{13}\mathrm{C}(p,n)^{13}\mathrm{N}$ reaction, whose cross section has been measured up to 30-MeV proton energy.[15] The ^{13}N activity was extracted from the ^{13}C target as $^{13}\mathrm{N}^{14}\mathrm{N}$ molecules using a small nitrogen support gas flow ($\sim$0.1 standard cm^3/h). These N_2 molecules were transferred to a single-stage ECR ion source, especially designed to optimize the yield of 1^+ atomic ions with respect to the injected molecules.[16] The $^{13}\mathrm{N}^{1+}$ ions were extracted out of the ECR source (extraction voltage ≤ 7 kV), mass analyzed by a 90° magnet, transported to the cyclotron CYCLONE using two lenses and axially injected into the machine through a 90° bending magnet. The central region of CYCLONE has been modified to allow its use for acceleration in the sixth harmonic mode,[17] necessary to obtain the low energies ($\sim$0.65 MeV/nucleon) required for nuclear astrophysics experiments. The $^{13}\mathrm{N}^{1+}$ beam extracted from CYCLONE was directed through a switching magnet towards a thick stopper plate, and the β^+ activity deposited on the latter was measured with two NaI(TI) scintillators in coincidence, whose efficiency, for the detection of the annihilation radiations from the positrons, was determined with a ^{22}Na calibrated source. The observed activity was checked to be due to ^{13}N through its half-life, and its saturation value corresponded to 1.5×10^{8} $^{13}\mathrm{N}^{1+}$ particles/sec. The performances of the various elements involved in the production of this beam are summarized in the second column of Table I.

Previous off-line separate tests of these elements, whose results are given in the third column of Table I, allow one to expect the following improvements on the above-mentioned achievement. The yield of the $^{13}\mathrm{C}(p,n)^{13}\mathrm{N}$ reaction, for 30-MeV protons impinging on a thick ^{13}C target, is 1.6×10^{-3} ^{13}N nuclei/incident proton, and is the highest one for producing ^{13}N with proton beams whose energies are limited to 30 MeV (Ref. 15). The number of ^{13}N nuclei obtained with CYCLONE 30 can be increased by raising the intensity of its proton beam to 500 μA, as was already achieved,[13] provided a suitable ^{13}C target, able to handle the corresponding 15-kW beam power, can be designed. Tests with natural graphite targets bombarded with a 30-MeV proton beam of about 100 μA have shown that extraction efficiencies for the ^{13}N activity larger than 80% can be achieved at a suitable target temperature of about 2000 K.[14] The best overall ionization efficiency of the ECR source, measured with an enriched $^{15}\mathrm{N}_2$ gas inlet, is currently about 15% of N^{1+} atomic ions/injected N atom for a pressure in the source of 1.5×10^{-5} mbar. The operation of CYCLONE in the sixth harmonic mode has been tested with a $^{13}\mathrm{C}^{1+}$ beam, and its optimum efficiency, in terms of the fraction of $^{13}\mathrm{C}^{1+}$ ions injected into CYCLONE which are extracted from it after acceleration, is currently about 10% (Ref. 17). If all the above-mentioned optimal performances can be simultaneously achieved, an intensity in the range of several 10^{10} particles/sec will be obtained for the $^{13}\mathrm{N}^{1+}$ beam, as shown in Table I.

Another improvement on the current result will be the lowering of the only contamination present in the $^{13}\mathrm{N}^{1+}$ beam, i.e., $^{13}\mathrm{C}^{1+}$, from the current $^{13}\mathrm{C}/^{13}\mathrm{N}$ ratio of about 1000 to a value lower than one. This will be achieved by trapping the useless gas flow between the target and the ECR source, which is mainly composed of H_2, $\mathrm{H}_2\mathrm{O}$, CO, CO_2, and hydrocarbons as determined with a quadrupole mass analyzer; this should, at the same time, improve the performances of the ECR source whose ionization efficiency is a very sensitive function of the source pressure.[16]

The first experiment which will be carried out with our ^{13}N beam will be the measurement of the cross section for the nuclear reaction $^{1}\mathrm{H}(^{13}\mathrm{N},\gamma)^{14}\mathrm{O}$. This reaction is crucial to the operation of the so-called hot CNO cycle which is expected to occur in supermassive stars, novae, and supernovae outbursts, and accreting neutron stars.[1,18] It is dominated, at the temperatures which prevail in these objects or events, by a resonance at 0.545 MeV center-of-mass energy. The planned experiment will aim at the determination of the γ width Γ_γ of this resonance; the present theoretical estimates of Γ_γ (Ref. 19), and the available experimental indications on its value resulting from indirect methods[20] both fall in the 1-10-eV range.

The availability of radioactive ion beams with such energies and high intensities opens the way to many experiments in widely different fields: study of nuclear reactions of astrophysical interest other than $^{1}\mathrm{H}(^{13}\mathrm{N},\gamma)^{14}\mathrm{O}$,[1] investigation of the properties of exotic nuclei in nuclear structure physics,[3,10] implantation, at large depths, of radioactive nuclei, possibly polarized, in different kinds of solids,[2,10] and application in the biological sciences and medicine.[3] There are thus wide areas in different sciences which are opened by the acceleration of short-lived radioactive ion beams whose energies are below 2 MeV/nucleon and whose intensities are in excess of 10^{8} particles/sec, as reported for the first time in this paper.

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