HEAVY ION ACCELERATION AT THE BEVATRON *

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(presented by H. A. Grunder)

Abstract

Deuteron, alpha and nitrogen beams have been accelerated in the Bevatron and extracted, at beam energies between 280 MeV/nucleon to 2.1 GeV/nucleon. Nitrogen ions have also been accelerated to 36 GeV total energy. Completion of the resonant extraction system and recent extension of digital control to the acceleration cycle made this program feasible. Changing from proton operation to deuterons or alphas requires retuning which is within capability of the computer control. Deuteron and alpha beam intensities are well within the range of the feedback-loops. A special technique was developed using alpha particles as a tracer for nitrogen ion acceleration. Several exploratory experiments in physics, biology and nuclear chemistry using these beams have been performed.

Introduction

An exploratory program directed at the production of high energy heavy ion beams at the Bevatron has been undertaken and completed in August 1971. The heavy ion program is supplementary to the present proton physics program and its purpose is to further increase the research capability of the Bevatron facility. Deuterons, alpha particles and nitrogen ions have been accelerated and extracted. Exploratory experiments have been performed in the external beam channel. The performance of the Bevatron for extracted heavy ions is summarized in Table I at energies of 0.28, 1.0 and 2.1 GeV/nucleon. For comparison, the proton external beam is usually 10^{12} per pulse in each of three channels and may be up to 3×10^{12} ppp in one channel. Nitrogen ions have also been accelerated, but not extracted to 2.57 GeV/nucleon or 36 GeV total energy.

Table I: Extracted intensities (particles/pulse) for various extracted beam energies E(GeV/nucleon)

Particle	E=2.1	E = 1	E=0.28
Deuterons	10^{11}	not done	$2x10^{10}$
Alphas	$5x10^{9}$	$5x10^{9}$	10^{9}
Nitrogen ions	$7x10^{5}$	not done	$1.4x10^{5}$

Not included in Table I are small amounts of carbon and oxygen ions accelerated, extracted and identified at 2.1 GeV/nucleon. These ions originated from background gas and were obtained by tuning the injection system for the respective charge to mass ratios.

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Ion Sources

The duoplasmatron ion source normally used for proton operation was readily adaptable for the production of deuteron and alpha particle beams. A change of the exit orifice from 0.020" diameter to 0.030" doubled the ion-output for alphas. However, no measurable quantities of high charge states of nitrogen were observed. Because the presently obtainable gradient in the linac restricts operation to a charge to mass ratio $e/m < 1/3$, it was necessary to provide a source that would produce acceptable intensities of $^{14}N^{+5}$. Hence it was decided to adapt the PIG source developed at the Berkeley Heavy Ion Accelerator (Hilac) for use in the Bevatron Cockcroft-Walton preaccelerator. Fig. 1 shows a cross-section of this pulsed cold cathode PIG source. Forty µA of $^{14}N^{+5}$ have been extracted from this source, bunched and injected into the 20 MeV proton linac. The lifetime of the PIG source for nitrogen is several days, which we consider satisfactory considering that we run 2 - 8 A of arc current with up to 2 kV across the arc.

Linac

Deuteron and alpha acceleration ($e/m = \frac{1}{2}$) is accomplished through the linac on the $2\beta\lambda$-mode with approximately the same electric gradient in the tank as for protons and the identical quadrupole magnet settings. The charge to mass ratio of quintuply charged nitrogen, e/m = 5/14, requires a 40% increase in linac gradient and the quadrupole magnet field. Fortunately these values could be reached with minor modifications. In fact, a test run revealed that we could nearly reach 1.75 times the gradient needed for deuteron acceleration and hence we might be able to accelerate $^{14}N^{+4}$ in the future. Our 20 MeV proton linac will accelerate particles to 5 MeV/nucleon in the $2\beta\lambda$-mode with an overall transmission of 5%. This is a factor of ten less than the transmission in the $1\beta\lambda$-mode used for protons.

Stripping

Acceleration of particles in the Bevatron is limited to fully stripped ions. The stripping cross-section for partially stripped ions is unacceptably high at the Bevatron vacuum of 10^{-6} Torr and with the rate of rise of the Bevatron guidefield of 7.8 kG/s. Thus a stripping foil, 40 µg/cm^2 of aluminium, is used to completely strip the nitrogen ions before injection. The efficiency of stripping is 50%. For measuring ion intensity and contamination a 1 mg/cm^2 foil is used to completely stop all particles which drift unaccelerated through the linac. A 20 mg/cm^2 foil may also be used to stop the nitrogen ions but pass deuterons and alphas of 5 MeV/nucleon in the unlikely event that they should be a contaminant of the beam. Using these foils in conjunction with the dispersion of the magnets in the injection line, we measured 1 μA of fully stripped nitrogen ions at the electrostatic inflector. Fig. 2 shows schematically the acceleration scheme for nitrogen.

Acceleration in the Bevatron proper

For the heavy ions, having one-half the velocity of protons, acceleration either has to start on the second harmonic of the RF or the frequency-swing of the RF system has to be lowered by a factor of two. Since the required extended frequency-swing was essentially already built into the RF system, we chose first harmonic operation. The trapping in the Bevatron is somewhat above 10% for first harmonic operation.

Deuteron and alpha beams are intense enough that normal phase and radius feedback can be used. The nitrogen beam, however, only was detectable on the induction electrode system at injection (2×10^7 particles) for a well tuned machine (Fig.3). Thus the feed-back systems could not be used. The strong dependence of the recombination-cross section on particle energy accounts for losses which occur at the beginning of the acceleration cycle. Ninety per cent of the fully stripped ions trapped in the Bevatron recombine with electrons in the residual gas and are lost, ten per cent survive and are accelerated to high energy.

In order to avoid extensive new instrumentation for nitrogen acceleration, the Bevatron was tuned carefully with the abundant alpha-particle beam. As alphas differ in charge to mass ratio by only 0.04% from fully stripped nitrogen ions, the resulting frequency error is within tolerance. The stability of the Bevatron acceleration and extraction systems were relied upon after the injected particle was changed to nitrogen. The frequency program was recorded on computer tape. The source gas, the linac gradient and the drift tube currents were then changed for nitrogen, and operation restored under computer control. It should be pointed out that all our low level RF, with exception of the feedback-loops, has been converted to digital control.

The resonant extraction, which has been used for heavy ions,and the high-energy beam transport were handled similarly to the RF programming. This scheme worked very well. Indeed the controls were so stable that we could detune the linac and accelerate reliably 5-10 particles per pulse for eye-flash experiments on humans.

It should be noted here that the resonant extraction system, employing magnetic-field perturbation, is dependent only on the rigidity of the particles. The efficiency of extraction for beams of kinetic energy greater than 1 GeV/nucleon is 50 to 70%.

As expected, the beam quality is nearly the same for heavy ions and for protons. The emittance at 2.1 GeV/nucleon has been measured to be 6π mm mrad in the radial plane and 30π mm mrad in the vertical plane. This results in a beam spot of 2x5 mm on the target.

We have unambiguously identified the nitrogen ions by using a solid-state counter telescope. The quantity measured by this particle identifier is the profile of the energy loss along the particle's path through the detector system. We found the beam to have some contamination ($<5\%$) of singly and doubly charged ions resulting from breakup of nitrogen ions by restrictive apertures.

Exploratory Experiments

Various exploratory experiments in physics, biology and nuclear chemistry were performed during August. Only two shall be mentioned here. Heckmann et al have measured the fragmentation of 2.1 GeV/nucleon nitrogen ions in passing through a polyethylene target. A beam transport system following the target was used as a spectrometer to analyse the fragments.

A striking observation in the present experiment was the fact that virtually all of the fragments heavier than helium (Z=2) and emitted in the forward direction have velocities that differ very little from the velocity of the ^{14}N beam. Qualitatively, the fragmented ^{14}N nucleus appears to simply "fall apart" with the resultant nuclear products proceeding on with little or no change in velocity. The consequence of this fact is that as one varies the rigidity R of the particles transmitted by the magnetic spectrometer, the intensity of a fragment of mass M and atomic number Z exhibit a sharp maximum when $R=\frac{M}{Ze}\beta\gamma$, where $\beta\gamma=\beta(1-\beta^2)^{-\frac{1}{2}} \equiv (\beta\gamma)_{beam}$. The atomic number of the fragment is measured by the ion's rate of energy loss in traversing the counter telescope. The rigidity R has units GV when the mass M is expressed in GeV.

We illustrate this in Fig. 4ab, where we show the spectra of elements produced in a carbon target at 0° when the rigidity R of the fragments transmitted by the spectrometer was set at 5.0 GV and 6.2 GV (the rigidity of the 2.1 GeV/nucleon ^{14}N beam is 5.8 GV). In Fig. 4a, the prominent feature is the Z=4, or Be, peak. Assuming that it is due to ^7Be, we find that the $\beta\gamma$ of this nuclide is 3.06, which is only slightly less than $(\beta\gamma)_{beam} = 3.10$. By "tuning" the spectrometer to accept particles with R=6.2 GV, figure 4b, we observe that the intensity of Be vanishes and that carbon, Z=6, now dominates. Because 6.2 GV is greater than the rigidity of the beam, no ^{14}N ions are observed. It follows, therefore, that no ^{12}C can be present, since these ions have the same rigidity as ^{14}N at equal velocities. The Z=6 peak at R = 6.2 GV is therefore ^{13}C, which has, at this rigidity, a $\beta\gamma = 3.07$ -- again equal to that of the incident ^{14}N beam.

These, and subsequent measurements, can be interpreted in terms of Fig. 5, where we have plotted the values of rigidity R for several isotopes of the elements Z=1 through 8 under the assumption that their velocities, hence $\beta\gamma$'s, are equal to $(\beta\gamma)_{beam} = 3.1$. For orientation purposes we indicate by arrows the points R = 5.0 and 6.2 GV, appropriate for Fig. 4ab.

The Donner Laboratory-Group, headed by Dr. C. Tobias was kind enough to let us use prior to publication the Bragg curve (Fig. 6) which Tobias et al have measured at 278 MeV/nucleon nitrogen ions. Heavy ion acceleration at a few hundred MeV/nucleon has given the opportunity for the investigation of the use of heavy ions for biological and biomedical research. These particles are particularly well suited because of their depth-dose characteristics and because of a high linear energy transfer of the individual particles. Experiments to study the biological effects of nitrogen ions, employing animals and mamalian tissue are in progress.

Future plans

The present intensities of deuteron and alpha beams is adequate for a substantial experimental program. Intensity increase by factors of two to four, if required, can readily be obtained.

For counter experiments and some biological studies, the present intensity of the nitrogen beam is sufficient. For biomedical experiments and radiotherapy 10^7 particles per pulse are desired. By increasing the linac gradient for acceleration of $^{14}N^{+4}$ and by improving the Bevatron vacuum with cryogenic pumping, we can reach this intensity. With the improved vacuum we also can accelerate a usable beam of heavier ions up to neon.

For the longer range we are making a study of possible means to improve our high-energy heavy-ion facility. One possibility is to use the Hilac (Berkeley's heavy-ion linear accelerator) as an injector for the Bevatron. The Hilac, which soon will be capable of accelerating any ion species up to an energy of 8.5 MeV/nucleon, could provide fluxes of up to 10^{14} particles/s. With this arrangement, we could produce beams of $^{20}Ne^{+10}$ of 10^{10} ions per pulse, $^{40}Ar^{+20}$ of 10^9 ions per pulse, and possibly beams of higher atomic mass numbers.

Acknowledgements

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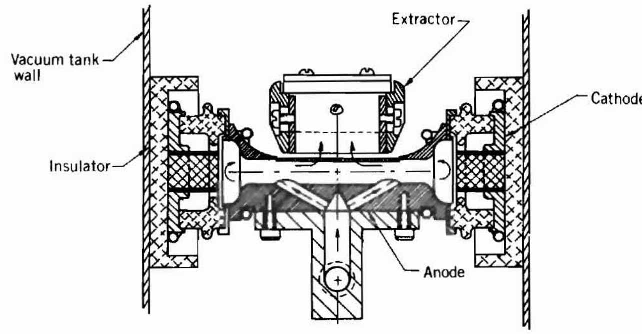

Fig. 1

Side-extracted, cold cathode PIG-source.

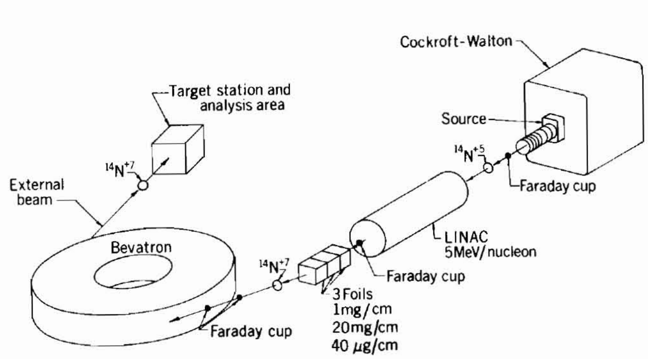

Fig. 2

Schematic layout of the acceleration scheme for nitrogen.

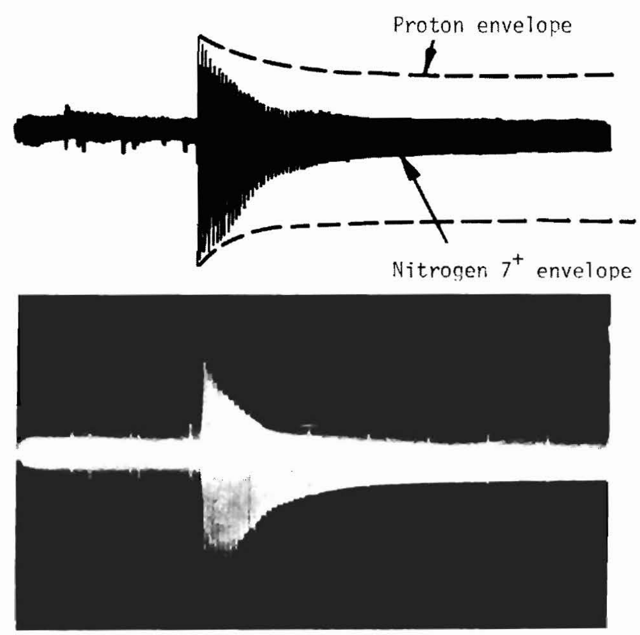

Fig. 3

Pickup electrode signal for fully stripped nitrogen. Sweep speed 5 ms cm^{-1}.

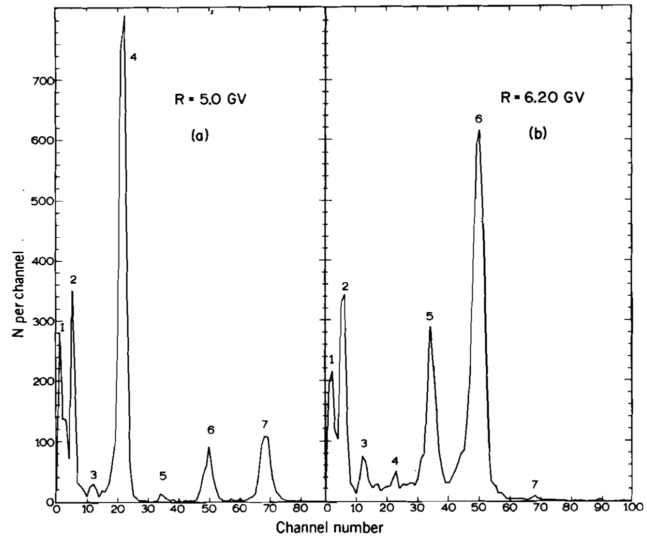

Fig. 4 ab

Spectra of the rates of energy loss (1 channel = 6.8 MeV), of the fragmentation products of 2.1 GeV/nucleon ^{14}N ions. Rigidities (momentum per unit charge) are (a) 5.0 GV and (b) 6.2 GV. The elements hydrogen (Z=1) through nitrogen (Z=7) are indicated by their atomic numbers Z. These data are the direct read-outs of the particle identifier, and are unprocessed. The target material was carbon.

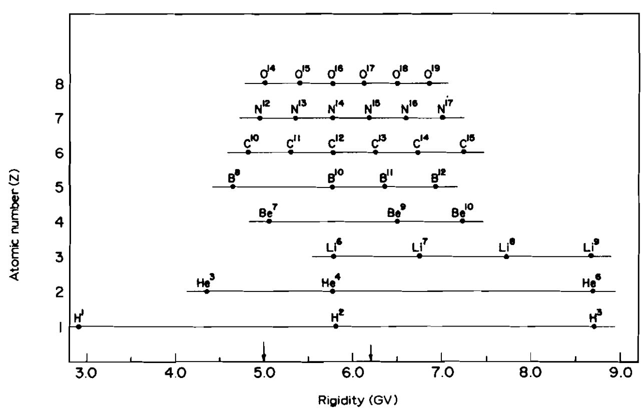

Fig. 5

Diagram of the rigidities R at which various isotopes of hydrogen through oxygen will be observed when their velocities are equal to that of the 2.1 GeV/nucleon ^{14}N beam. At this energy, ^{14}N ions have a rigidity R = 5.78 GV. The arrows indicate the rigidities at which the data shown in Fig. 1 ab were taken.

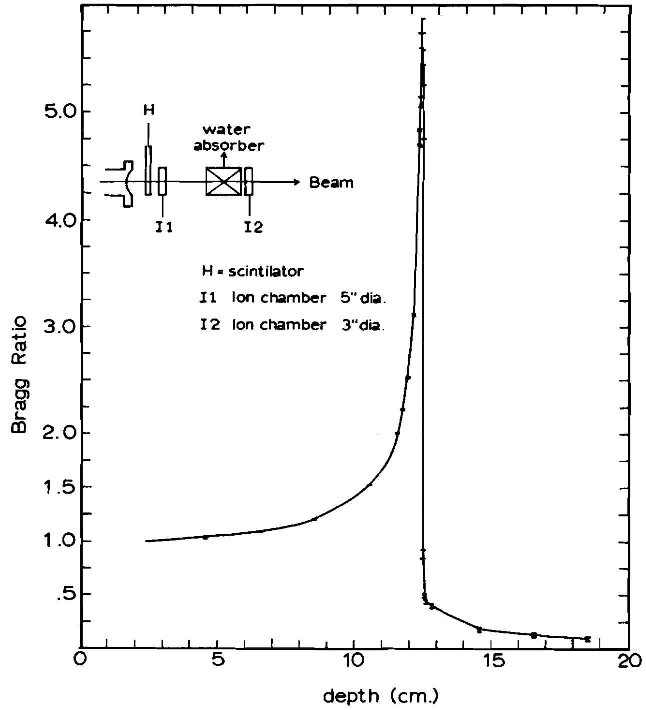

Fig. 6

This sketch shows the apparatus used to obtain the Bragg ionization curve. It also presents the Bragg ionization curve for the 278 MeV/nucleon N^{7+} beam in water.

DISCUSSION

V. P. DZHELEPOV: What intensity of heavy ions, such as Xenon, could you achieve at your accelerator?

H. A. GRUNDER: One must distinguish between modest fluxes of high-energy Xenon ions for counter experiments ($\sim 10^3$/s) and high fluxes for nuclear chemistry. Both aspects need development effort. But ion sources of an ERA type, or with "linear" collective effects in which the "residence-time" of the ions in the electron cloud is long, might well be developed soon for modest fluxes of very heavy ions.