Introduction

Acceleration of ions heavier than hydrogen has been contemplated by the Bevatron staff for many years. Two reports on the subject were written in 1965 showing the feasibility of deuteron acceleration. Heavy-ion work was finally scheduled this year, after several developments in control and extraction techniques had taken place and after the interesting possibility arose that nitrogen ions could also be accelerated.

Performance

As indicated in Table I, we accelerated and extracted deuterons, alphas, and nitrogen ions at three different energies: 280 MeV/nucleon, 1 GeV/nucleon, and 2.1 GeV/nucleon. Also accelerated but not extracted were nitrogen ions to an energy of 36 GeV, or about 2.37 GeV/nucleon. During one month of heavy-ion work, most of the time was devoted to an exploratory experimental program to obtain the first results at these energies for fragmentation of nitrogen. Emulsions were exposed, biomedical investigations were conducted, and data were obtained on the feasibility of producing a monochromatic neutron beam by stripping high-energy deuterons. For biomedical applications, a nitrogen beam 100 times as intense as the first one is desired; however, we anticipate that within a few months we will be able to demonstrate at least $10^{11}$ nitrogen ions per pulse on target.

Acceleration Proper

A companion paper to this has described the apparatus and techniques for obtaining ions heavier than protons at an energy of 5 MeV/nucleon from our 20-MeV proton linac. Ions are stripped prior to passing through the achromatic inflection system into the Bevatron. Figure 1 is a diagrammatic representation of our acceleration system and the particle path with changes in charge-state through this system. One of the basic engineering tasks to accomplish heavy-ion acceleration was the modification of the frequency of the accelerating voltage as a function of the magnetic guide field. The guide field rises approximately linearly with time, for a period of about 1-1/2 seconds for maximum energy.

Figure 2 is a plot of acceleration frequency as a function of guide field for protons (charge-to-mass ratio = 1) and for ions with charge-to-mass ratios of 1/2 and 2/3. Indicated on the figure is a technique, employed at the Synchrophasotron in Dubna, of accelerating particles with $e/m = 1/2$; the beam is picked up on twice the normal RF frequency and later switched back to the normal frequency. At the Bevatron we planned to employ this scheme and start on the second harmonic (rotational frequency $\omega_0 = 250$ kHz) until the second-harmonic function of frequency vs. guide field departed markedly from the proton curve, then hold the magnetic field constant for a short time, during which the RF would be turned off and its frequency shifted to that frequency. The RF would then be reamplified to the particular frequency. The guide field was allowed to continue to increase. This was tried with deuterons and worked, although there were some losses following frequency-shifting. A careful examination of operating capabilities of the RF system indicated that first-harmonic operation of the RF system for particles with $e/m = 1/2$ seemed feasible. A subsequent test with deuterons using first-harmonic operation showed that it was practical, and no unusual beam losses occurred. The frequency of our accelerating voltage is matched at first approximation to that of the particles by having an inductance in the oscillator portion of the accelerating system, which is varied in step with the guide field by means of a saturable core whose characteristics were chosen to produce the requisite frequencies. Figure 3 is a plot of relative amperes turns in this saturable core to produce the frequency sweeps, shown in Fig. 2, required for particles with $e/m = 1$ and $e/m = 1/2$. The respective slopes vary directly as the charge-to-mass ratio, which means that our job of tracking particles with $e/m = 1/2$ was relatively easy. (Figure 4 is a block diagram of our acceleration system, showing the major frequency-control devices.)

Work performed under the auspices of the U. S. Atomic Energy Commission.

*Distribution of this document is unlimited.
fully accelerated nitrogen ions without having been able to monitor them during the acceleration cycle. Figure 5 illustrates the nature of the signals we were dealing with. The upper trace shows nitrogen losses as compared with estimated proton losses, and the lower trace is the actual photograph of a beam-induced signal with ~10^-5 nitrogen ions. Nitrogen losses are accounted for by recombination during the early part of the acceleration cycle, whereas the protons do not suffer from such a mechanism.

Consistent acceleration of 1^H, 2^H, 3^He, 12^C, 14^N, and 16^O, day-to-day and week-to-week, has been made possible by application of digital processor techniques to both the magnetic field power-supply system and the acceleration system, both systems having been made operational in the early part of this year. As a passing point of interest, it might be noted that the Bevatron is now capable of delivering to a target area, consistently, as few as 50 particles per pulse or as many as 10^12 particles per pulse.

**Extraction**

Extraction of the heavy ions, namely deuterons, alphas, and nitrogen, was done with the resonant-extraction system as developed at the Bevatron in the last few years. For the nitrogen ions, it was essential that we go to the resonant system rather than the energy-loss system because of possible particle fragmentation.

One should note that only magnetic fields are employed in the extraction scheme. The extraction parameters vary with the guide field only and are independent of the particles to be accelerated. The resonant extraction operates at an initial betatron frequency of 2/3 f_b, with f_b about 0.02. A local perturbation is used, which constitutes a delta function in azimuth. The radial dependence of the perturbation is described in Ref. 6. The particle trajectories in the radial phase plane are adjusted by shaping the perturbation in time.

The normal instrumentation for detecting the resonant process is scintillation screens located at the face of the two extraction magnets M1 and M2 viewed with TV cameras. Figure 7 shows a diagram of the Bevatron and the location of the extraction magnets. Both magnets M1 and M2 are plunged into the Bevatron gap prior to extraction. The M1 scintillation screen is used to observe the growth per turn of a particle, and the M2 screen is used to determine the correct extraction trajectory. These screens are effective for 10^8 to 10^12 particles per second.

The deuteron and alpha beams were intense enough so that normal means of detection could be used for extraction. For the nitrogen beam, however, alpha particles were used as tracers for acceleration and extraction. This means that the stability of the Bevatron acceleration and extraction system was relied upon. Since there is only 0.5% difference in the charge-to-mass ratio between alphas and fully stripped nitrogen ions, parameters obtained from our alpha operation were used for the nitrogen acceleration and extraction. This procedure proved to be so successful that nitrogen was extracted and transported to the target area with no change of the alpha parameters.

**Transport and Target Facility**

Ions which emerged from the Bevatron's resonant-extraction system were guided by means of steering and focusing elements through a "first focus" area, where a waist exists, to the "Channel II second focus" area at which the beam-spot size was brought to a minimum and where most of the experiments were done. Transport of the ions is accomplished almost entirely within a vacuum system. There is one air gap at the first focus for insertion of diagnostic devices; and the second focus, the actual experimental area, was just beyond the vacuum system. Losses occurring in the 30 to 50 cm of air path were acceptable in view of providing the utmost flexibility for the experimental program.

Equipment and techniques for some of the experiments conducted at the second focus are described in Ref. 7.

**Conclusion**

For physics studies of importance and excitement we feel we now have an operational machine that will produce deuterons and alpha particles whenever the experimental program calls for them. For nitrogen ions, which appear to be of considerable importance in physics, astrophysics, and biology, we need some improvement before the Bevatron will be an operational facility. We also must implement a technique of changing rapidly from one particle type to another.

At the present time, our goal for heavy ions is a facility capable of accelerating ions of e/m = 1/2 to 2.7 GeV/nucleon at intensities of 50 to 10^10 particles per pulse, as desired. To accomplish this goal, we intend to link together two Berkeley accelerators: the Hilac, located 200 yards to the northeast of the Bevatron, which will produce 8.5 MeV/nucleon ions, and the Bevatron, which will accept these ions and accelerate them to the energies useful and the intensities desirable for future research programs.

**Acknowledgements**

Work on this project was begun this spring with the approval and enthusiastic support of Dr. E. M. McMillan, Director of LBL, and Dr. E. J. Lofgren, physicist in charge of the Bevatron. Contributions to the success of the project came in large measure from E. Zajec and his co-workers who handled the manufacture and initial acceleration of the heavy ions. R. J. Force and D. J. Milberger of the Electrical Engineering department were responsible for the successful operation of the acceleration and extraction hardware. W. D. Hartough, in charge of Bevatron Operations, enlisted the enthusiastic and continued support from the rest of the Laboratory. Our staff of operators at the Bevatron learned quickly what we were doing and succeeded in refining some of our techniques of acceleration and delivery to the point, almost, of standardization.
References


Table I. Bevatron Heavy Ion Beams

<table>
<thead>
<tr>
<th>Extracted beam</th>
<th>Intensity (particles per pulse)</th>
<th>Extracted Beam Energy (GeV/nucleon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>deuterons</td>
<td>$10^{11}$</td>
<td>2.1</td>
</tr>
<tr>
<td>alpha particles</td>
<td>$5 \times 10^9$</td>
<td>1</td>
</tr>
<tr>
<td>nitrogen ions</td>
<td>$2 \times 10^5$</td>
<td>0.25</td>
</tr>
</tbody>
</table>

*At this energy the intensity is reduced by a factor of five.

Bevatron Acceleration Systems for Heavy Ion Work

Fig. 1: Bevatron generator with \( H_N^2 \) and \( H_N^5 \) sources.
Fig. 2. Bevatron acceleration frequency as a function of guide-field for particles with different charge-to-mass ratios. (Note: Middle curve is labeled e/m = 1/2; it should be e/m = 2/3.)

Fig. 3. Relative saturating current requirements in the saturable reactor for particles with e/m = 1 and e/m = 1/2.
Basic frequency programming system for the Bevatron

Fig. 4

Proton envelope

Nitrogen $7^+$ envelope

Pickup electrode signal for nitrogen $7^+$

Fig. 5. Upper: Relative losses during acceleration for protons and fully stripped nitrogen ions. Lower: Photograph of pickup electrode signal for fully stripped nitrogen ions.
Fig. 6. BEVATRON EXTRACTION MAGNETS
Fig. 7. Quality of the heavy-ion beams accelerated at the Bevatron is indicated by the size of the beam spots at the two focal points.