Heavy Ion Acceleration

The highest energy available in the laboratory for ions heavier than helium has been approximately 10 million electron volts per atomic mass unit. These low energies were sufficient to permit synthesis of transuranic elements and to study the structure of the nucleus. The only source of high-energy ions was the very weak flux of heavy cosmic rays at high altitude. Only recently has it been realized that the proton synchrotron at Princeton (Princeton Particle Accelerator) and the bevatron at Lawrence Berkeley Laboratory could be used to reach energies of hundreds of million electron volts per nucleon. Nitrogen ions have now been accelerated to 36 billion electron volts. The impact of this new research is sure to be powerful in nuclear chemistry, nuclear and solid state physics, and astrophysics. There are numerous biomedical applications, including cancer therapy. Research in most of these areas has been underway at Princeton since July. Similar work began at Berkeley a short time later. Studies have been done on the behavior of nitrogen ions as they pass through matter. Cell destruction can be concentrated at the end of the ion range. Experiments have verified the prediction that heavy ions can produce the bright visual flashes observed by the astronauts in outer space.

Acceleration of Nitrogen Ions to 7.4 Gev in the Princeton Particle Accelerator

Abstract. *Nitrogen ions in charge states N^{5+} and N^{6+} have been accelerated in the Princeton Particle Accelerator to 4 and 7.4 billion electron volts (Gev), respectively. An external N^{5+} beam of 1×10^6 particles per second has been obtained and focused to a 6-millimeter-diameter spot. The N^{6+} beam was about 2×10^5 particles per second. The total charge-changing collision cross section of N^{5+} in water vapor was determined as a function of ion energy. The improvement in vacuum necessary to increase the N^{5+} beam at least tenfold was calculated. The N^{6+} total cross section is probably smaller than that of N^{5+} at the higher energies.*

The Princeton Particle Accelerator, formerly known as the Princeton-Pennsylvania Accelerator (PPA), became operational in 1963 as a 3-Gev proton synchrotron. In 1970 the ability to accelerate deuterons to 2.4 Gev and α-particles to 4.8 Gev was added. In this form the PPA served as a major high-energy research facility for some 20 universities and government research laboratories. Construction and operating funds came largely from the Atomic Energy Commission, which decided in 1970 that for economic reasons it would cease funding the PPA as of 30 June 1971. Teter (*1*) has described the early history and recent financial tribulations of the PPA.

A grant of $230,000 from the Fannie E. Rippel Foundation was sufficient to operate the laboratory until 15 September 1971. Subsequent funds from Princeton and the Rippel Foundation and from purchasers of beam time will maintain operation until 1 January 1972. Contracts are being sought to continue the work described in these reports.

Figure 1 is a pictorial representation of the PPA as an accelerator and heavy ion facility for research. Ions in a low charge state are accelerated by the Van de Graaff, stripped to a high charge state, and injected into the synchrotron. After acceleration to the desired energy they are extracted, focused, and directed into the experimental "caves" as shown. A synchrotron is capable of accelerating any particle in any charge state provided the radio-frequency acceleration system can cover the requisite frequency band and provided steps are taken to minimize charge-changing collisions with the background gas during the acceleration process. The magnitude of the latter problem is connected with the vacuum attained, the injection velocity, the time spent accelerating to full energy, and the charge state of the ion to be accelerated. The unique features of the PPA that make it readily adaptable to heavy ion acceleration are its high pulse rate of 20 cycle/sec, the large radio-frequency swing already made available for α-particle acceleration and the small vacuum chamber cross section, which simplifies the problem of attaining a very good vacuum.

Beam loss during acceleration, after the particles are captured in phase-stable radio-frequency "buckets," is almost entirely due to charge-changing collisions with the residual gas in the acceleration chamber. An exact calculation of the residual gas pressure that would allow a certain beam transmission requires a detailed knowledge of the charge-changing collision cross sections as a function of velocity. As there are no empirical data above 30-Mev total energy, it is necessary to rely heavily on theoretical prediction (*2*) and bold extrapolation. Table 1 gives the required pressures for 37 percent beam

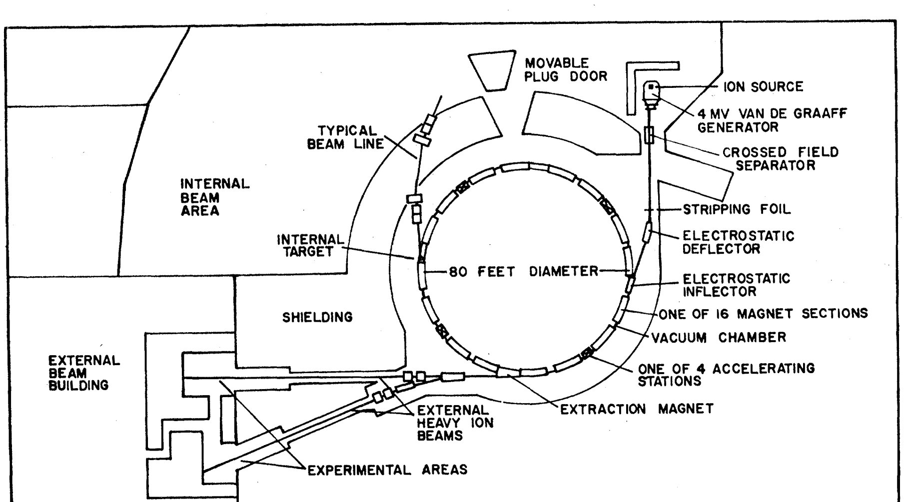

Fig. 1. Diagram of the Princeton Particle Accelerator.

transmission in the PPA. The calculations assume that a 4-Mv Van de Graaff injector is employed to accelerate ions in the initial charge state (as indicated in column 1 of Table 1) with subsequent foil stripping to various charge states before injection into the synchrotron. In the case of Xe^{4+}, Xe^{5+}, and U^{7+} no stripping is assumed after acceleration by 4 Mv.

From Table 1 it is evident that a vacuum in the range of 10^{-7} torr is sufficient for N^{7+} acceleration, and even for N^{5+} or N^{6+} if a more rapid attenuation than 37 percent can be tolerated. The present PPA vacuum chamber consists of two ceramic semioctants that regularly reach 2 to 3×10^{-8} torr. Of the remaining 14 semioctant chambers, which are made of fiber glass and epoxy, three reach 6×10^{-8} torr and the remainder about 2 to 4×10^{-8} torr, for an overall average pressure around the complete ring of 1.9×10^{-7} torr. The residual gas is largely water vapor in spite of the liberal use of liquid-nitrogen cold fingers.

The ion source in the Van de Graaff terminal was designed for heavy ion work and has been described elsewhere (*3*). It is of the axial Penning ion gauge (PIG) cold-cathode type equipped with a pulsed 0.4 tesla magnetic field. It is capable of delivering at the base of the Van de Graaff a pulsed current of N^{2+} (105 μa), N^{3+} (12 μa), and small amounts of higher charge states. The N^{+2} ions are selected by a crossed electric-magnetic field separator and sent through a 10-μg cm^{-2} carbon foil. The N^{5+}, N^{6+}, and N^{7+} ions emerge at pulsed currents of 16.5, 6.7, and 0.33 μa, respectively. These currents are measured at the entrance to the synchrotron electrostatic inflector, which can be adjusted to transmit only a single ion species. About 8×10^{8} N^{5+} ions are injected into each synchrotron cycle. While any one of the three charge states can be accelerated, and the attenuation of N^{7+} would be very small, as indicated by Table 1, we have thus far tried only N^{5+} and N^{6+}, since the N^{7+} current is too small to detect in the synchrotron with our present electrostatic pickup system. On the other hand, N^{5+} and N^{6+} are readily detected.

Table 1. Vacuum required for 37 percent survival of various ions. A 4-Mv injector is assumed.

Initial charge state	Charge state in synchrotron	Vacuum required (10^{-8} torr)
N^{2+}	N^{5+}	3–5
N^{2+}	N^{6+}	4–6
N^{2+}	N^{7+}	12–20
N^{3+}	N^{7+}	20–30
Xe^{4+}, Xe^{5+}, U^{7+}	Xe^{4+}, Xe^{5+}, U^{7+}	0.1–0.2

Initial success with N^{5+} was obtained on 16 July 1971, when a beam of 1×10^{6} sec^{-1} was obtained at 279 Mev/amu (3.9 Gev). Figure 2, curve (a), shows the observed attenuation of the N^{5+} beam during the acceleration cycle at a vacuum of 2.2×10^{-7} torr. Beam currents could be observed on the electrostatic pickup plates only for 10 msec, which corresponds to 500 Mev total or 35 Mev/amu. From this point on, the beam was detected for the purpose of synchrotron tuning by particle scintillation detectors placed at the inner and outer radial limits of the vacuum chamber. Counts were registered only for those ions that had lost or gained electrons by collision and therefore, having the wrong charge for acceleration, rapidly move in or out radially and are soon lost to the beam. This system proved to be very convenient for tuning the synchrotron and can be employed for much smaller currents if the need arises.

From the attenuation curve (a) in Fig. 2 one can readily derive the total charge-changing cross section, curve (c). It agrees well with the low-energy data of Macdonald and Martin (*4*) and extends their measurements to 500 Mev, at which point the total cross section is dropping rapidly. Curve (b) in Fig. 2 indicates the attenuation that should be observed for an improved vacuum of 1×10^{-7} torr. Clearly even a small improvement in vacuum would greatly enhance the N^{5+} current. A vacuum of 8×10^{-8} torr, which we expect to reach soon, should give 10 to 20 times more beam than we currently have.

We have also accelerated N^{6+} to 530 Mev/amu (7.4 Gev total) at substantially the same currents as N^{5+}. Since the injected current of N^{6+} was smaller by a factor of 2.46, this observation must mean that the total charge-changing cross section of N^{6+} is somewhat smaller than that of N^{5+}.

Beam extraction from the synchrotron is accomplished by the same resonant extraction system that we have used for several years with protons. Approximately 25 to 50 percent of the internal beam is extracted and transported 30 m where it is focused to a 6-mm-diameter spot. Peak beam currents of 2×10^{6} sec^{-1} have been produced, with a long-term average of 1×10^{6} sec^{-1}. This corresponds to a dose delivery rate of 20 rad/min for a typical 10-cm^{2} beam spot used in biomedical work. The ultimate space charge limit of the PPA is about 10^{12} sec^{-1} with a 4-Mv injector.

Our successful experience with N^{5+} and N^{6+} indicates that we can accelerate neon and even argon in our present vacuum chamber. Still heavier ions can also be accelerated, but probably in very small quantities only. Completion of our ceramic vacuum chamber would permit a 10^{-9}-torr vacuum and hence the acceleration of any ion in any charge state with very little attenuation.

While our present energy is ideal for the biomedical program, nuclear and cosmic-ray physicists could profitably

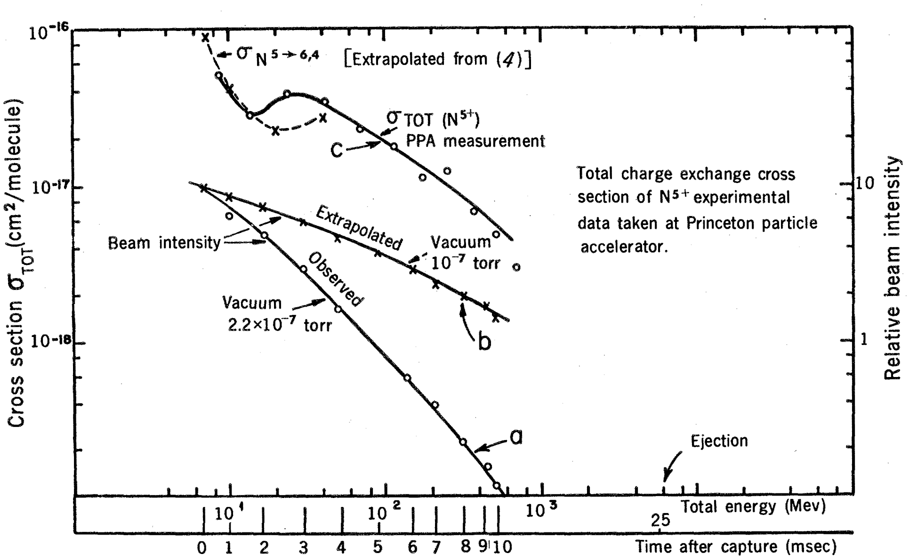

Fig. 2. Attenuation of N^{5+} beam during acceleration. Curve (a), beam intensity observed for 2.2×10^{-7} torr; curve (b), predicted beam intensity at 1.0×10^{-7} torr; curve (c), measured total cross section $\sigma_{TOT}(N^{5\rightarrow 6,4})$ as function of ion energy. The scale of relative beam intensity for curves (a) and (b) appears at the right.

use higher energies. The PPA is capable of accelerating fully stripped nitrogen, or any ion whose atomic number is half its mass number, to 1.2 Gev/amu. Still heavier ions with more neutrons than protons (for example, xenon) could be accelerated to 900 Mev/amu. To accomplish full stripping requires the development of new types of ion sources or the use of a two-step acceleration and stripping process (*5*).

M. G. WHITE, M. ISAILA
K. PRELEC, H. L. ALLEN
Princeton Particle Accelerator, Princeton University, Box 682, Princeton, New Jersey 08540

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6. We thank the Fannie E. Rippel Foundation for its timely and generous support of this work. The support of Princeton University and the cooperation of the Atomic Energy Commission are also acknowledged. Finally, we are grateful to the entire Princeton Particle Accelerator staff for their unwavering loyalty and outstanding technical performance.

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Interaction of 3.9-Gev Nitrogen Ions with Matter

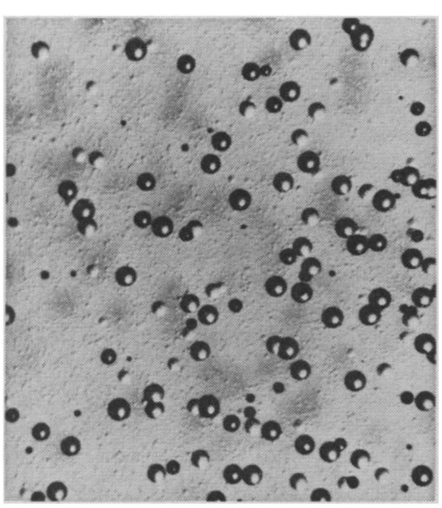
Abstract. *The interaction with matter of nitrogen ions in the 3.9-billion-electron-volt (Gev) beam of the Princeton Particle Accelerator has been studied. In polyethylene, the range of ions is 12.6 ± 0.2 grams per square centimeter and the mean free path for nuclear collisions is 15.4 ± 3.8 centimeters; the loss of energy by the ions passing through polyethylene agrees with that predicted by stopping-power theory. The production of secondary particles has been investigated. These data are useful for experiments and for evaluating the merits of nitrogen ions in biomedical applications.*

We have measured physical properties of beams of relativistic nitrogen ions made available by the Princeton Particle Accelerator (PPA) (*1*). Their interaction with matter was studied with the goal of obtaining accurate measurements that will be useful in planned experiments and in evaluating the predicted merits of nitrogen ions for cancer therapy and other biomedical applications involving localized tissue destruction (*2*).

The beam intensity was measured with an argon-filled ionization chamber (*3*) and scintillation-counter telescopes. The telescope counting rate was corrected for accidental coincidences and used for normalization in ionization chamber studies. The beam current, as measured by the ionization chamber, was found to be proportional to the corrected telescope counting rate and independent of the voltage applied to the chamber (indicating proper saturation). In the course of a test exposure of Lexan polycarbonate, consistent values for the number of particles were also obtained (*4*). Figure 1 shows the etched tracks in Lexan of stopping nitrogen ions from the beam. Particles other than nitrogen ions constituted less than 4 percent of the beam, as measured with nuclear emulsions (*5*).

The average energy needed to produce an ion pair in argon, W_{Ar}, can be calculated from the beam intensity measured by the counter telescope, the ionization chamber current, and the mass stopping power of the nitrogen ions. The last parameter was measured as described below. The preliminary result obtained for W_{Ar} is 29.2 ± 3 ev per ion pair. This is somewhat higher than but not inconsistent with the average value of 26.3 ± 0.1 reported for α-particles (*6*).

The ranges of nitrogen ions in polyethylene, aluminum, and lead were measured with the differential absorption scintillation-counter telescope shown in Fig. 2. Counters 1 and 2 detect the incident beam by registering only particles resulting in coincident signals. Counter 3 detects the beam transmitted through the variable absorber of thickness R (cm), which includes the scintillators, while counter 4 detects the beam transmitted through the incremental thickness ΔR of counter 3. The thickness of counter 3 affects the range resolution. The number of particles stopping in a depth of material between R and $R + \Delta R$ cm is defined by counter 4 in anticoincidence with counters 1, 2, and 3, designated $123\bar{4}$, and normalized to the total beam count, designated 12. This



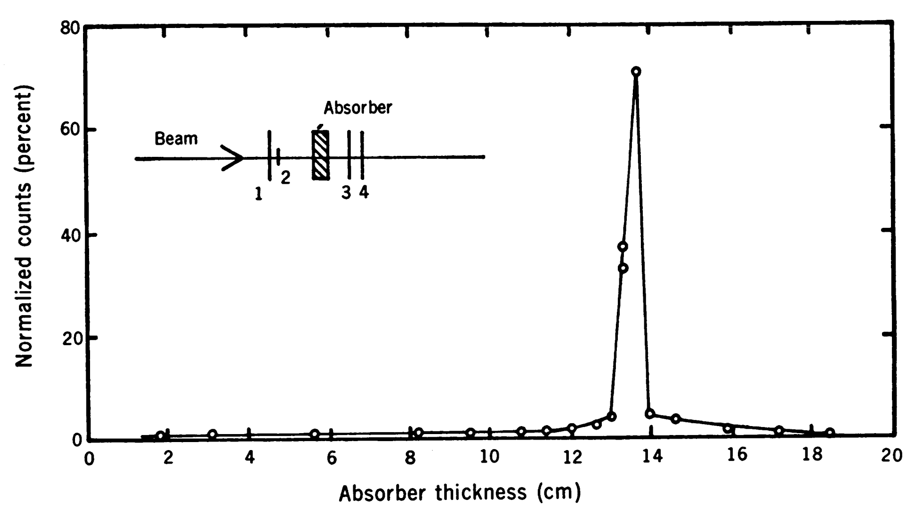


Fig. 1 (left). Nitrogen ion tracks etched in a Lexan polycarbonate sheet. Many of the nitrogen tracks in this photograph are overetched and appear as low-contrast depressions. Roughly the last 90 μm of the range of a nitrogen ion can be made visible in Lexan by etching; a suitable etchant is a mixture of equal volumes of 6.25*N* NaOH and ethanol, at 50°C. A 5-hour etch yields tracks with diameters up to 60 μm (*4*). Fig. 2 (right). Differential absorption curve for 3.9-Gev nitrogen ions in polyethlene. The mean range of the ions is given by the absorber thickness at the maximum. The inset shows the scintillation-counter telescope arrangement used for this measurement. The normalized counts refer to the ratio $123\bar{4}/12$ discussed in the text.