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# ACCELERATION OF PARTIALLY STRIPPED IONS AT THE BEVALAC*

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## Summary

We present results of the first attempts to accelerate partially stripped heavy ions in the Bevatron. Experiments were performed for hydrogen-like argon and neon ions, and, although the survival time of these ions in the $10^{-7}$ torr Bevatron vacuum was not sufficient to achieve full energy, valuable charge-changing cross section information was obtained.

## Introduction

To design heavy ion accelerators with the greatest possible beam repertoire one must have the capability of accelerating partially stripped ions. This arises simply because of the impossibility of obtaining fully stripped heavy ions at the desired injection energies.

One must worry, then, about the survival of the partially stripped ion in the machine vacuum since an ion which undergoes a charge-changing collision with a gas atom will be quickly lost. Vacuum requirements for linear accelerators, one-pass machines, are not nearly as stringent as those for circular accelerators. At $10^{-7}$ torr the mean free path for an ion-gas collision is about 5 km, an insignificant flight distance for acceleration in a synchrotron. Fortunately, electron pickup and loss cross sections are not generally geometric, so that not all collisions involve charge-changing. It is clear, though that a good understanding of these cross sections is of the utmost importance for advanced circular heavy ion accelerator design.

At low energies (up to about 1 MeV/amu) considerable work has been done on measurements and interpretations of these electron pickup and loss cross sections. This work has been most recently reviewed by H. D. Betz[1]. Empirical formulae are presented which fit data quite well, and which are expected to retain validity over a reasonably broad range of ion velocities ($v_0 < v < Zv_0$, where $v_0 = e^2/\hbar = 2.2 \times 10^8$ cm/sec). Above this velocity range, though, no information, either experimental or theoretical has been available, and little confidence is placed in extrapolations of the above-mentioned formulae into this higher velocity region.

Initial impetus for calculating charge-changing cross sections at high energies occurred during the 1976 ERDA Summer Study of Heavy Ions for Inertial Fusion, where high energy accelerators were contemplated for $U^{1+}$ ions. At this time, G. Gillespie[2,3] developed a technique for calculating electron loss cross sections in the Born approximation using an extension of the Bethe theory.[4] The method yields the total inelastic scattering cross section for structureless particles; the energy absorbed by the ion going into either electronic excitation or ionization. Independent calculation of the excitation and ionization portions is not an easy task, so that the derived inelastic cross sections must be viewed as an upper limit on the actual ionization cross section.

In the case of $U^{1+}$ or other singly charged ions, the binding energy of the last electron is so low that the excitation portion of the cross section is considered to be negligible, leaving the calculated inelastic cross section probably quite close to the expected ionization cross section. However, for more highly stripped ions the nature of the ionization-to-excitation ratio is not so clear cut, and theoretical charge-changing cross section estimates become more uncertain. Going to the other extreme--that of one electron ions--the situation is again simplified since hydrogenic wave functions are well known, and the excitation portion of the cross section can be calculated. In fact, recently Gillespie has carried out calculations of this type, yielding predictions for cross sections of hydrogen-like carbon, neon and argon ions on residual nitrogen gas.[5]

## Experimental Techniques

Experimental testing of the full range of the above theoretical predictions is not easily carried out. Since the approach is valid only for ion velocities appreciably higher than the orbital velocity of the outermost electron, reasonably high ion energies are needed. First of all, acceleration of singly charged very heavy ions is not possible to high enough energies (at least several MeV/amu) with any present accelerators. Experiments with relatively high charge state ions at energies up to 8.5 MeV/amu can be performed at the SuperHILAC, but this energy is towards the lower end of the energy range where cross sections are wanted, and also is the region of charge states where the theory is most uncertain. Consequently, the most logical area for experimentation involves hydrogenic ions. It is this area that has been most actively pursued in our Laboratory.

The Bevalac was used to perform the experiments, producing the hydrogenic ions at the SuperHILAC Post-Stripper exit, transporting these ions down the Transfer Line, injecting them into the Bevatron, and proceeding with acceleration. The measurements were made by observing the decay of the beam intensity with time during normal acceleration, using standard Bevatron beam monitoring instrumentation. Since there are many different possible causes for beam loss, the charge-changing effects were isolated by observing the decay rate at different values of the pressure in the Bevatron vacuum tank. The charge-changing cross sections were determined by fitting the decay rate data using a semi-empirical velocity-dependent formula. A two-component velocity dependence was assumed: a $1/\beta^2$ term to correspond to the Born approximation velocity dependence at high energies, and a $1/\beta^5$ term, suggested by the trends of cross sections in lower velocity regions. These trends discussed by Betz indicate a rapid fall-off of cross section as the velocity-dependent equilibrium charge state $\bar{q}$ moves away from the actual ionic charge q.

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### Data Collection

The beam decay rate was measured using the Beam Induction Electrode (BIE) system, the instrument normally employed to observe the circulating current in the Bevatron. The BIE signal is brought into the control room, amplified, and displayed on an oscilloscope as a rapidly oscillating bipolar trace directly reflecting the voltage induced on the electrodes by the passing beam. Figure 1 shows such an oscilloscope picture for an Ar$^{17+}$ beam pulse. For these experiments the BIE signal was rectified and averaged with a high-impedance operational-amplifier filtering system (time constant less than 1 millisecond). One of the Bevatron PDP-8's was made available for data collection; the rectified BIE signal was digitized every millisecond and stored in a memory array. The full array, representing data from one single beam pulse was then stored on disc and cleared for the next pulse. Data collection and storage occurred continuously and automatically, but could be stopped at will. Then the last digitized pulse would be available for print-out, or else any individual pulse could be recalled and dumped from the disc. The overall accuracy of this system, including errors due to beam shape variations and rectification time constants was substantially better than 5%.

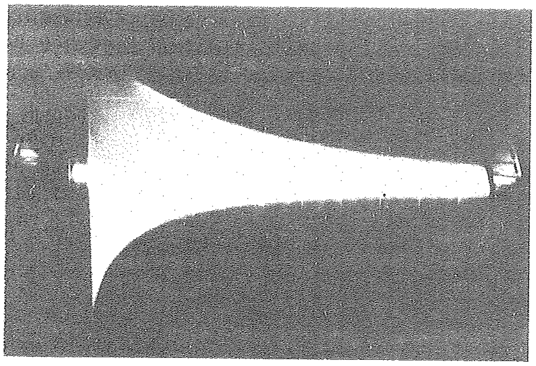

Figure 1. Ar$^{17+}$ beam pulse detected by the Beam Induction Electrode system. Time scale is 20 msec/cm.

### Vacuum Measurements

The Bevatron is divided into four 90° quadrants, where the magnet continuously encloses the vacuum tank, and four three meter long straight "tangent tanks" connecting the quadrants. Vacuum pumping consists of six 32" diffusion pumps in each of the four tangent tanks and a distributed cryopumping system in the magnet quadrant sections. Pressure readings are taken by ionization gauges located in the tangent tanks. Pressure measurements are not made in the quadrant sections because the pulsing field grossly distorts ion gauge readings. At the normal operating pressure range, low- to mid- $10^{-7}$ torr, the residual gas has been analyzed and is almost exclusively air. Thus the cryopanels, which circulate helium gas at 15°K provide a large portion of the effective pumping speed of the system.

For the present experiments the pressure was varied by closing gate valves for several or all of the diffusion pumps. The rise in pressure registered by the ion gauges in the tangent tanks was probably somewhat greater than the rise in the average pressure value, due to the continued presence of active pumping in the magnet quadrants. Best estimates place the possible error in determining average pressure values from the ion gauge readings at about 30% to 50%. This represents the largest source of error in the experiments.

### Beam Tuning

Ar$^{17+}$ After stripping at 8.5 MeV/amu, the argon beam was roughly equally divided between the 17+ and 18+ charge states. The intensity of the single-electron argon beam was thus high enough to be easily picked up with the existing beam monitors. Essentially 100% transmission of the Ar$^{17+}$ beam to the Bevatron injection point was obtained. Once injected into the Bevatron, the attenuation due to charge exchange was slow enough (some beam was still observable after 400 milliseconds) that the normal Bevatron radial and phase feedback systems were activated to trap and track the beam, thus minimizing beam losses due to mechanisms other than interactions with residual gas.

Ne$^{9+}$ The production of Ne$^{9+}$ ions at 8.5 MeV/amu required the use of very thin stripper foils, since an equilibrium thickness of carbon foil only yielded 7% of the ions in the 9+ state. An optimum carbon foil thickness of 9 μg/cm$^2$ was found to yield an almost 60% hydrogen-like neon beam.

The tuning of the Ne$^{9+}$ beam was facilitated by the equivalence of the charge-to-mass ratios of Ne$^{9+}$ and Ar$^{18+}$, allowing use of well studied tuning data for fully stripped argon to set the Transfer Line, injection and acceleration parameters. This proved extremely valuable, because the decay rate of the Ne$^{9+}$ beam was too rapid to allow use of the Bevatron feedback systems. The variation in decay rate with pressure confirmed that beam losses were primarily due to charge-changing interactions and not to tuning parameters.

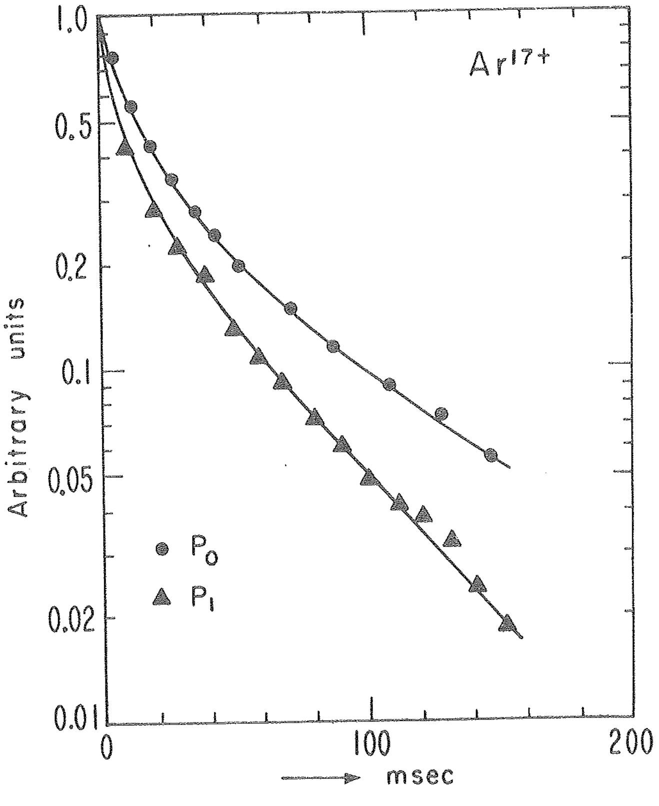

Figure 2. Decay of Ar$^{17+}$ beam at two pressures, $P_o \sim 2 \times 10^{-7}$ torr and $P_1 \sim 3 \times 10^{-7}$ torr. The change in the slope of the curves is representative of the velocity dependence of the charge-changing cross section.

Table I - Summary of Cross Section Information

$\sigma = A/\beta^5 + B/\beta^2$

(Units are $cm^2$/molecule)

| Ion | Experimental Coefficients |  | Theoretical Coefficients |  |
|---|---|---|---|---|
|  | A | B | A | B |
| $Ar^{17+}$ | $2.4(\pm 1) \times 10^{-23}$ | $7(\pm 3) \times 10^{-21}$ | (NA) | $6.83 \times 10^{-21}$ |
| $Ne^{9+}$ | $0(\pm 1) \times 10^{-23}$ | $2.4(\pm 1) \times 10^{-20}$ | (NA) | $2.55 \times 10^{-20}$ |

## Results

Figure 2 shows $Ar^{17+}$ survival data for two pressures, $P_0 \sim 2 \times 10^{-7}$ torr and $P_1 \sim 3 \times 10^{-7}$ torr. The very rapid initial decay is associated with the $1/\beta^5$ - dependent cross section component. This same type of initial behavior is observed for $Ar^{18+}$ ions, and causes substantial reductions in accelerated fully stripped argon intensities if the machine vacuum is not at its peak. These similarities between $Ar^{17+}$ and $Ar^{18+}$ initial decay curves point to the type of interaction mechanisms discussed at length by Betz. The slower decay rate in Figure 2 which dominates after about 40 milliseconds, can be fitted well with a $1/\beta^2$ - dependent cross section, and thus conforms to the Born approximation-type behavior.

The $Ne^{9+}$ data for three pressures, $P_o \sim 3 \times 10^{-7}$ torr, $P_1 \sim 4 \times 10^{-7}$ torr and $P_2 \sim 5 \times 10^{-7}$ torr, are shown in Figure 3. These data do not show the same type of two-component decay curve seen for $Ar^{17+}$. The velocity at injection, $4.0 \times 10^9$ cm/sec (8.5 MeV/amu) is close to Betz's limit of $Zv_o$ for argon ($3.9 \times 10^9$ cm/sec), but is well above the limit for neon ($2.2 \times 10^9$ cm/sec). Thus one might expect the argon data to exhibit a rapid fall-off of cross section at the lower velocities, but one is not surprised in not seeing this behavior for neon.

Table I summarizes cross section parameters for best fits to the decay data, and compares these values with calculations made by Gillespie[5] for these ions on (molecular) nitrogen. The uncertainties quoted for the experimental numbers arise mainly from the estimated possible systematic errors in pressure measurements. The agreement between theory and experiment is quite good.

Further confirmation of the consistency of the overall picture has been supplied by the preliminary analysis of experiments performed by Raisbeck et al[6] at the Bevalac using carbon, neon and argon ions at energies from 250 MeV/amu to 1.05 GeV/amu. These experiments were designed to measure electron pick-up cross sections for fully stripped ions passing through a gas-filled portion of the beam pipe. This effect was observed, and a saturation in the pick-up rate led to a determination of the electron loss cross section for single-electron ions. These cross sections could be fit to within about a factor of two with the coefficients predicted by Gillespie. This factor of two is well within the presently-determined experimental uncertainties.

## Conclusions

The agreement between the present experiments and theory indicates a good understanding of the interactions of high energy hydrogenic heavy ions with residual gas atoms. The next step is to use this understanding, and the experimental techniques developed, to explore the interactions of multiple-electron ions. $Ar^{16+}$ experiments are being contemplated at the Bevalac, and also studies using $Fe^{24+}$ and $Fe^{25+}$ ions. Very low beam intensities for multiple-electron iron ions will require more sophisticated Bevatron beam detection instrumentation, but the trends in cross sections indicate that survival of these ions in the presently obtainable Bevatron vacuum should be quite high.

## Acknowledgements

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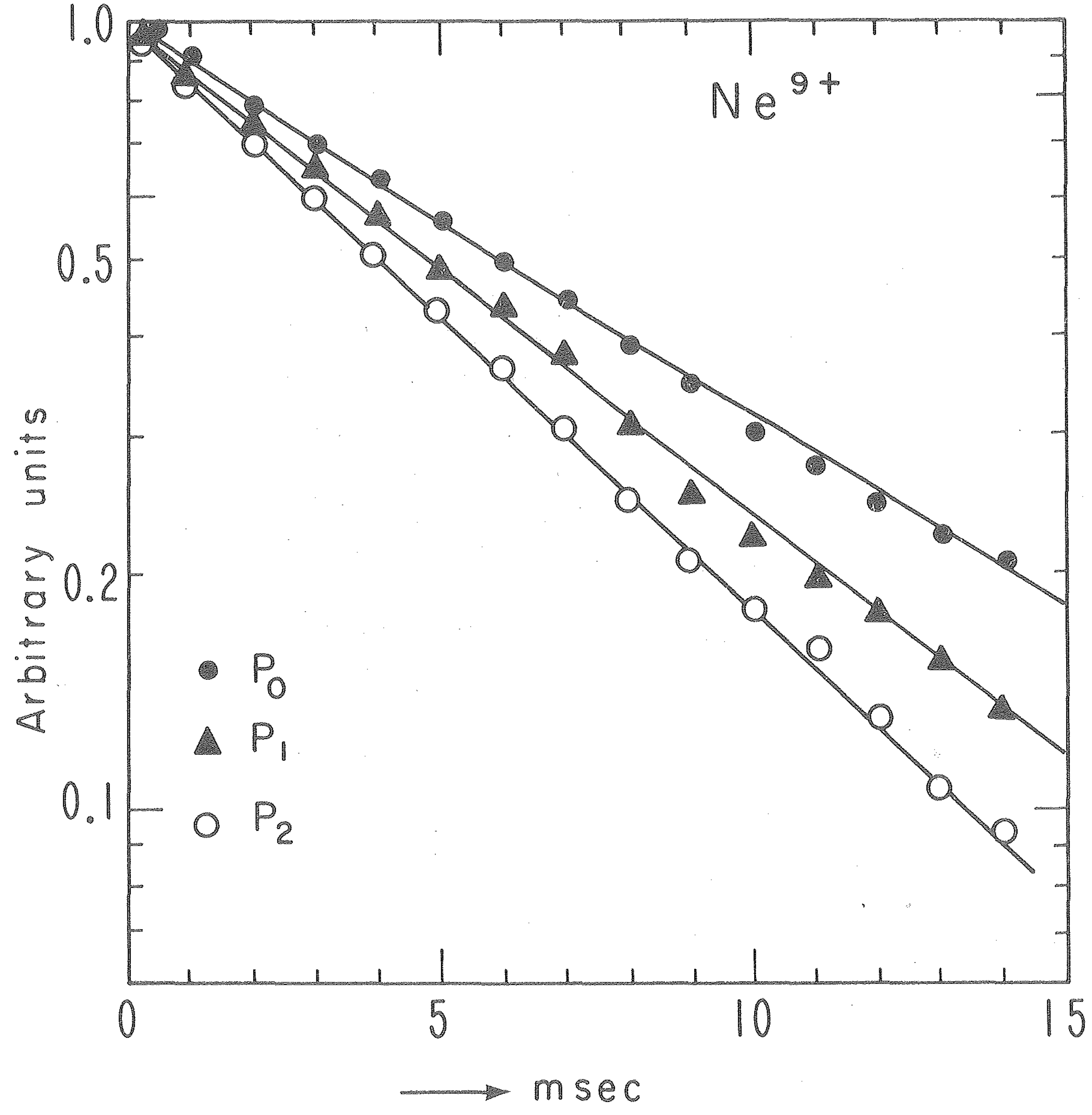

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Figure 3 Decay of $Ne^{9+}$ beam at $P_0 \sim 3 \times 10^{-7}$ torr, $P_1 \sim 4 \times 10^{-7}$ torr and $P_1 \sim 5 \times 10^{-7}$ torr. The almost purely exponential fall off of the beam intensity is indicative of a slow velocity dependence for the cross section, thus minimizing the possibility of a $1/\beta^5$ term.