MASTER

DEVELOPMENT AND TESTING OF A THREE-STAGE DOUBLE
TANDEM ACCELERATOR-DECELERATOR SYSTEM FOR LOW ENERGY, HIGHLY STRIPPED IONS

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IONS WITH ATOMIC HYDROGEN

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ABSTRACT

Three-stage operation of the University of Pittsburgh accel-decel double tandem source of highly stripped ion beams is described. The system has produced O^{5+} , O^{6+} , O^{7+} and O^{8+} ions at specific energies as low as 15 keV per AMU. The design of the new decelerator tubes is discussed. The present performance and limitations of the overall system are outlined. Some new charge exchange cross sections have been measured, for combined higher ion charge states and lower ion energies than heretofore was possible. Future four-stage operation with very heavy ions is considered.

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INTRODUCTION

The study of atomic collision processes involving multiply-charged ions has developed rapidly in the last few years. A major stimulus has been a DOE need for cross section values as input into the design of fusion machines. This is particularly true for the assessment of impurity radiation losses and neutral beam plasma heating effectiveness. Our past research (along with that of others) has utilized existing sources of multiply-charged ions, namely low energy Penning ionization sources for the lower charge states and high energy tandem accelerator sources for the higher charge states. Yet the important region of low ion energy and very high ion charge has remained experimentally uninvestigated because of ion source limitations; only very recent theoretical information is available for such ion collisions.

Two years ago we conceived of a new scheme for the practical production of low energy, highly charged ions, based upon operation of two tandem accelerators in a new configuration.⁽¹⁾ The basic idea was not only to inject the ion beam from one accelerator into the other for further acceleration, but also to adjust accelerator terminal voltages and polarities so as to achieve a final deceleration of a highly-stripped beam. Over a year ago we demonstrated deceleration with the two Pittsburgh EN tandem accelerators. During the past contract period we have concentrated upon the technical problems to be solved for the practical application of the accel-decel technique. At this point we have established our capability of measuring charge exchange cross sections for all possible charge states of the light ions such as carbon and oxygen. The newly-

accessable energy range for one-electron and totally-stripped oxygen (O^{7+} and O^{8+} respectively) extends from 10 to 250 keV per atomic mass unit. Our charge-exchange cross section program has now resumed, using the new accel-decel source of ions.

DEVELOPMENT OF A THREE-STAGE ACCELERATOR-
DECELERATOR SOURCE OF HIGHLY STRIPPED IONS

Two versions of the accel-decel idea have been considered, three-stage and four-stage. Both are feasible using University of Pittsburgh facilities. The four-stage approach utilizes one more stage of ion acceleration before deceleration, and thus has applications in studies with heavier elements such as nickel or tungsten. However, the three-stage approach is adequate for work with carbon or oxygen. As three-stage operation required fewer changes in our double tandem facility, experimental work has been confined to just three-stages so far.

APPARATUS.

Figure 1 schematically shows the experimental arrangement used both for the accel-decel production of ion beams and for their subsequent use in charge exchange cross section measurements. Tandem E-20 passes a negative ion beam through carbon stripping foil #1, producing a partially stripped positive ion beam for injection into tandem E-22. The terminal voltage polarity for E-22 is opposite to that normally used, i.e. it is negative. At the bottom of the figure it is shown how the final result is a low energy O^{8+} ion beam. The effect of up-stripping by foil #2 in the terminal of E-22 is a net reduction in beam energy below the injection energy determined by the terminal voltage of E-20.

Figure 1. Schematic Diagram of Our Apparatus. All equipment to the right of the final magnetic steering possesses an ultrahigh vacuum capability.

Theory of Operation

If the terminal voltages of E-20 and E-22 are $-V_1$ and $-V_2$ respectively, then final ion beams with charge Q have energies

$$E(Q, Q_i) = eV_1 - (Q - Q_i)V_2 \approx eV_1 - (\Delta Q)V_2. \quad (1)$$

Here Q_i is a particular charge state in the beam emerging from foil #1, and ΔQ is the net up-stripping in foil #2. The above expression assumes an atomic ion is produced in the negative ion source in the terminal of E-20; if a molecular ion is used, V_1 has to be corrected to a value E_1 , the actual product positive ion energy after dissociation of the molecular ion in foil #1.

Ions of charge Q and energy $E(Q, Q_i)$ are then selected for use by analyzing magnet #1. The magnetic field required is

$$B_1(Q, Q_i, V_1, V_2) = \frac{B_0}{Q} \left(1 - \frac{\Delta Q}{Q}\right) \left[1 - \frac{(\Delta Q)V_2}{eV_1}\right]^{1/2} \quad (2)$$

where B_0 is a magnet calibration constant determined at $\Delta Q = 0$ through NMR field measurements. Figure 2 shows calculated plots of B_1 versus V_2 for $V_1 = 4.4$ MV and an assumed initial O^- beam. A characteristic of accel-decel produced beams is the "bunching" of the values of B_1 for all beams with the same ΔQ , as V_2 approaches the ion turn-around value $eV_1/\Delta Q$.

Decelerator Tube Design and Performance

Consideration of the ion optics of deceleration in normal high energy accelerator tubes led us some time ago to a design of tubes specifically for deceleration purposes. Basically our decelerator tubes look like low energy accelerator tubes in reverse, although there are differences.

Figure 2. The variation in analyzer magnet field locations of some accel-decel produced oxygen ion beams, plotted versus the accel-decel voltage on the terminal of the second tandem. Totally-stripped O^{8+} beams are indicated by the heavy-set curves. An O^- injection energy of 4.4 MeV is assumed.

A decision was made to outfit E-22 with new spiral-electrode tubes, the final deceleration tube using partial magnetic electron suppression and a removable gridded lens. A final design that did not compromise normal high energy acceleration applications while optimizing deceleration capability was achieved by H. R. M. Hyder at Oxford, and the tubes were manufactured and purchased from Dowlish Developments, Ltd. Figure 3 shows calculated median ray trajectories through the two deceleration sections, for an energy deceleration factor of 600; complete tube transmission appears possible for beams of normal emittance. For convenience we have been operating without the gridded lens, at deceleration factors of 60 and transmissions of 0.1. This has not limited us so far; instead we are at present restricted by energy spreads due to foil straggling and terminal voltage fluctuations, to be discussed below.

TERMINAL

TUBE 3

TUBE 4

E_i 15.025 MeV

E_f 0.025 MeV

Figure 3. Median ray trajectory of decelerated beam

Performance of a Complete System for Charge Exchange Cross Section Measurements

The overall capability of the apparatus of Figure 1 is determined by a number of design parameters. For instance, there is the trade-off between resolution and transmission for each of the magnetic analyzers. Figure 4 shows a magnetic field scan by analyzer magnet #1 of a 4 MeV oxygen beam from E-20 passing through both stripping foils and with E-22's terminal voltage nominally zero. This "high resolution" scan is for ion detection in the on-line Faraday cup located after the charge exchange gas target, see Figure 1. It is seen that the apparent foil-straggling energy spread in the final oxygen beam is 40 keV fwhm, or .1%. Analyzer magnet #1 with its subsequent beam collimators is designed for adequate resolution while sacrificing transmission.

Figure 5 shows a scan by analyzing magnet #2 of an oxygen beam produced after charge exchange collisions in the gas target. Here the complete transmission essential for accurate cross section measurements is verified by the flat tops of the peaks for each charge state.

Scans similar to that in Figure 4 but with E-22's terminal voltage turned up to normal accel-decel values exhibit a 55 keV fwhm. The increase over 40 keV is presumably due primarily to terminal voltage ripple on E-22; for $\Delta Q = 2$, the increase is consistent with the observed ripple value of 20 kV characteristic of E-22 with its present charging belt.

Figure 6 shows "low resolution" scans of analyzer magnet #1 for various values of accel-decel voltage V_2 . In these scans the ion current is collected on the front face of the gas target, i.e. before the second collimation aperture. The purpose of these scans is to display experimentally the features of accel-decel. The spreading out of the spectra with

Figure 4. A "high resolution" charge state spectrum of an incident double-foil stripped, but undecelerated, 4 MeV oxygen ion beam.

Figure 5. A final charge state spectrum of the ions emerging from the charge exchange He gas target, for an incident 3 MeV O^{7+} beam. The target gas pressure is low for this spectrum.

Figure 6. Experimental Charge State Spectra of the Most Intense Accel-Decel Produced Ion Beams, for Various Values of the Accel-Decel Voltage on the Terminal of the Second Tandem.

Figure 7. A Comparison of Experimental and Expected Accel-Decel Ion Beam Spectra, for the Most Intense Beams. Given the uncertainties in the measured terminal voltages, the agreement is satisfactory.

increasing V_2 is as expected; Figure 7 compares theory and experiment. At high values of V_2 , the relative intensities of the different decelerated beams are critically dependent on final ion beam focussing and steering parameters, as is to be expected.

SOME CHARGE EXCHANGE CROSS SECTION RESULTS
FOR HIGHLY STRIPPED OXYGEN IONS ON HELIUM GAS

Figure 8 presents a few cross sections measured during our tests of the accel-decel system. The extension of past low energy data to higher charge states and the extension of past high energy, high charge state data to lower energies is evident. The helium target thickness for these cross section measurements was obtained by a gas cell conductance calculation combined with a target gas flow rate measurement. Our results are generally consistent with reasonable extrapolations of the other data,⁽²⁾ except for double charge exchange in O^{6+} -He collisions. Here anomalous behavior is observed, not atypical for double exchange involving closed shell ions, where cross sections are often abnormally large.

Figure 8. Measured Charge Exchange Cross Sections for Highly-Stripped Oxygen Ions on Helium. Accel-decel data can fill a gap of $\times 50$ in energy between the results of earlier investigators, as well as making O^{6+} and O^{7+} measurements possible in the region of large cross sections.

POSSIBLE IMPROVEMENTS IN THREE STAGE OPERATION

At this point in time it is clear that further improvements in our apparatus are possible.

- 1) Computer control of the accel-decel voltage V_2 is being attempted, to maximize the stability of this critical parameter. This should make quality measurements at high deceleration factors less time consuming.
- 2) A better charging belt should reduce the ripple in V_2 to below 10 kV.
- 3) Gas stripping in place of foils #1 and #2 when combined with the better belt should make possible an overall energy resolution of 10 to 20 keV. Gas stripping in place of foil #1 should increase our available final beam intensities by up to a factor 100 above present values of typically 10^6 ions per second or more.
- 4) For increased decelerator transmission the gridded output lens can be used; immediate magnetic focusing and steering at the decelerator output would also increase transmission.

We feel that improvement 1) is very important at the present time. However, the other improvements are not essential for many of our planned cross section measurements.

ON FUTURE FOUR-STAGE OPERATION WITH VERY HEAVY HIGHLY STRIPPED IONS

As pointed out in our original accel-decel proposal to DOE and in reference 1, three stages of acceleration followed by deceleration should make possible the production of heavy ions with $25 \leq Z \leq 92$ at specific energies in the region 3 to 10 keV/AMU. Table I shows some possibilities. The charge state conversion efficiencies can be estimated well for Br and I ions because of available foil stripping data⁽³⁾; other cases can be considered using semiempirical stripping formulae.⁽⁴⁾ Our double tandem accelerator is intrinsically a four stage system. It would be exciting to see the accel-decel predictions of Table I borne out; experiments at 5 keV/AMU with charge states of +40 would represent quite an advance in heavy ion atomic physics. The modifications of our apparatus needed for this are not insignificant, however. These include a new ion source and preaccelerator, two new accelerator beam tubes, and sufficient beam time support to justify the temporary removal of the negative ion source in E-20 before each of our accelerator runs.

TABLE I

Stripping Steps

Conversion Efficiency

Z = 28

6 MeV Ni ⁰⁻ → Ni ⁶⁺	~25%
42 MeV Ni ⁶⁺ → Ni ¹⁴⁺	~25%
126 MeV Ni ¹⁴⁺ → Ni ²¹⁺	~ 2%

Lowest possible final Ni²¹⁺ energy: ≈ 250 keV (5 keV/AMU)
 Final estimated Ni²¹⁺ overall foil charge conversion efficiency: $\sim 0.1\%$

Z = 35

6 MeV Br ⁻ → Br ⁹⁺	28%
60 MeV Br ⁹⁺ → Br ¹⁷⁺	24%
162 MeV Br ¹⁷⁺ → Br ²⁶⁺	6.5%

Lowest possible final Br²⁶⁺ energy: ≈ 300 keV (4 keV/AMU)
 Final Br²⁶⁺ overall foil charge conversion efficiency: 0.4%

Z = 53

6 MeV I ⁻ → I ¹⁰⁺	25%
66 MeV I ¹⁰⁺ → I ²³⁺	18%
214 MeV I ²³⁺ → I ³⁵⁺	3.5%

Lowest possible final I³⁵⁺ energy: ≈ 400 keV (3 keV/AMU)
 Final I³⁵⁺ overall foil charge conversion efficiency: 0.1%

Z = 79

6 MeV Au ⁻ → Au ¹²⁺	_____
78 MeV Au ¹²⁺ → Au ²⁸⁺	_____
246 MeV Au ²⁸⁺ → Au ⁴²⁺	_____

Appendix A. Other Research Conducted Under SRSA EG-77-S-02-4257.A001

1. After considerable deliberation over possible sources of discrepancies with other work, we have submitted for publication a final paper on our ORNL measurements with B, C, N and O ions at low energies and low charge states. The amount of data accumulated by different investigators on these collision processes is now sufficient for a fairly reliable assessment of the overall experimental situation, with regards to cross section value uncertainties in particular.

2. We have further analyzed possible sources of systematic error in our data on excited state production in C^{4+} -Ar collisions, with no change in conclusions from our last report in COO-4257-1. We have also studied the energy resolution of the filter lens analyzer used in these measurements, through new experiments at Pittsburgh. The resolution was no worse than 20 eV fwhm. We conclude that the excited state production experiments with the ORNL Test Bench Penning Ion Source Facility were limited by the energy spread in the Test Bench beam.

3. We have considered the measurement of cross sections for electron loss (by ionization and charge exchange) in ion-ion collisions, using our past merged beams techniques⁽⁵⁾ and Pittsburgh (accel-decel produced) highly stripped oxygen beams. This is discussed in Appendix B.

Appendix B. On the Measurement of Charge Exchange in $O^{8+} - O^{7+}$ Ion-Ion Collisions.

Figure 9 shows theoretical predictions for resonant charge exchange in collisions of bare nuclei with one-electron ions.⁽⁶⁾ At low energies the ion-ion Coulomb repulsion reduces the cross section dramatically; in addition, the maximum cross section for heavier ions decreases as Z^{-2} because of the decreasing size of electron orbits.

It is of some interest to see whether cross sections for such highly-stripped ion-ion collisions can possibly be measured. It appears that the answer is yes, but with difficulty, using the merged beam (i.e., overlapping colinear beams) technique.

Suppose two 1 cm diameter(d) ion beams of the same mass and with charges differing by one unit are overlapped for a length L of 2 meters. Let them be produced by partial charge exchange of an initially totally-stripped beam produced by the accel-decel technique. We could then hope for two colinear 4×10^{-9} Ampere ion beams, one O^{8+} and one O^{7+} , having the same laboratory ion inergy $E = 2$ MeV. The beams then pass into a two meter region maintained at a potential of +200 kV and at an ultra-high vacuum of $p = 10^{-11}$ Torr obtained by differential cryopumping⁽⁵⁾. The O^{8+}, O^{7+} ion energies become about $\bar{E} \sim 0.5$ MeV and are different by $\Delta E = 200$ keV, permitting $O^{8+} - O^{7+}$ collisions at a center-of-mass energy⁽⁵⁾

$$W \approx \frac{(\Delta E)^2}{8\bar{E}} = 10 \text{ keV}$$

This value is high enough for the predicted resonant charge exchange cross section to be near the $5 \times 10^{-17} \text{ cm}^2$ maximum value.⁽⁶⁾ The merged-beams production of product O^{8+} by charge exchange in

would occur at a rate estimated by⁽⁵⁾

$$S \approx (10^{31}) I_1 I_2 \left(\frac{W}{E}\right)^{1/4} \left(\frac{L}{d^2}\right) \sigma \approx 2 \text{ ions/second.}$$

The O^{8+} are separated from the incident ions O^{8+} by their different laboratory energies acquired upon leaving the region held at +200 kV.

The 2 ion/second signal must be separated from a background-gas produced 0.5 MeV. stripping signal B occurring at a rate⁽⁵⁾

$$B \approx (3 \times 10^{16}) (I_1/e) p L \sigma (\text{background}) \\ \approx (3 \times 10^{16}) (2.5 \times 10^{10}) (10^{-11}) (200) (10^{-16}) \approx 150 \text{ ions/second}$$

Such experiments with $S = 2 \text{ Hz}$ and $S/B \sim 10^{-2}$ are not impossible, but are sufficiently difficult as to be a major undertaking.

Figure 9. Cross Sections for $X^{Z+} + X^{(Z-1)+}(ls) \rightarrow X^{(Z-1)+}(ls) + X^{Z+}$ as Functions of Impact Energy. The axes are scaled quantities, $\tilde{E} = E/ZM$ and $\tilde{\sigma} = Z^2\sigma$, where M is the reduced mass in AMU.

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