Two Accel/Decel Experiments: Electron Capture for 6-20 MeV Si\(^{10-16+}\) on He and Ar and Interference Effects in Mo K X-Ray Spectra for 5, 10, and 20 MeV Cl\(^{16+}\) on Ar

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The recent development of four-stage accel-decel operation of the dual MP tandem accelerators at Brookhaven National Laboratory has made it possible to extend atomic collision experiments over an unprecedented range of high charge states and low velocities.\(^1,2\) Briefly, this mode of operation uses the first MP tandem conventionally for two stages of acceleration, then with a negative terminal voltage the second MP tandem provides a third stage of acceleration to high velocity, stripping to high charge state and a final stage of deceleration to low velocity. Details of operation and recent upgrades of the facility were reviewed earlier.\(^3,4\) An overview of present capabilities and the results of two experimental studies using accel-decel beams will be presented here.

Fig. 1 gives a schematic representation of the operational modes of the Brookhaven dual MP tandem facility. The coupled and decoupled configurations are used to produce negative ions at MeV energies (1-stage), positive ions at tens and hundreds of MeV (2- and 3-stage), and highly-stripped positive ions at energies down to a few MeV (4-stage).

This versatility provides the opportunity to study atomic-collision phenomena with variable-charge-state projectiles over an extremely wide range of collision energies. Presently, the maximum terminal voltages for V\(_{\text{MP6}}\) and V\(_{\text{MP7}}\) are -8 and +12 MV and -11 and +16.5 MV, respectively.

An excellent example of the need for widely variable beam energies

**Figure 1.** Modes of operation for the Brookhaven dual MP tandem facility.
and charge states can be found in the study of single-electron-capture (SEC). Universal scaling laws such as those reported by Knudsen et al.\textsuperscript{5} are in reasonable agreement with the data from various laboratories for many different projectiles, charge states, and collision energies. Systematic discrepancies are apparent, however, and varying uncertainties in the compiled data cause non-statistical fluctuations which inhibit further theoretical progress. What is needed are systematic measurements of SEC cross sections over extended ranges of beam energy with a single-charge-state projectile.

The feasibility of using four-stage accel-decel to produce high-charge-state, low-velocity projectiles for SEC studies was recently demonstrated.\textsuperscript{6} Total- and single-electron-capture cross sections were measured for $S^{10-16+}$ at 20 MeV, for $S^{12+}$ at 12 MeV, and for $S^{13+}$ at 6, 8, and 10 MeV. The SEC results are plotted in Fig. 2 in terms of the semi-empirical model of Knudsen et al.\textsuperscript{5} The magnitude of the $S^{9+} + Ar$ and the trend of the $S^{9+} + He$ data are well represented by the model.

The study of quasimolecular or molecular-orbital (MO) x rays can also be enhanced by employing accel-decel beams.\textsuperscript{7} Primarily due to collision broadening

![Figure 2. Single-electron-capture cross sections plotted in the reduced form of Knudsen et al.\textsuperscript{5}](image)

![Figure 3. Energy dependence of K x rays for Cl$^{16+} + Ar$ collisions at 10 MeV. The solid curve is the calculation by Anholt.\textsuperscript{10}](image)
at high velocities, previously observed MO K x-ray spectra exhibited a structureless shape, essentially independent of impact parameter. Merely using slower projectiles to reduce collision broadening is not sufficient to overcome this problem, because the probability to both form and fill a K-shell vacancy would be too low to provide adequate coincidence counting rates. The solution is to use a low-velocity one-electron projectile, such as Cl\(^{16}\)+, with a large probability of bringing a 1s\(\sigma\) vacancy into the collision. Under these conditions, the K vacancy does not have to be formed, only filled; the decay rate of 1s\(\sigma\) vacancies is increased due to the longer collision time; the collision broadening is reduced; and the adiabaticity condition is better fullfilled. In addition, since the 1s\(\sigma\) vacancy can decay either on the way in or on the way out of the collision, interference effects should be observable.

The impact-parameter dependence of MO K x-ray production in Cl\(^{16}\)+ + Ar collisions has recently been measured at 20, 10, and 5 MeV. Fig. 3 shows the x-ray energy spectrum recorded at an impact parameter of 1200 fm for a collision energy of 10 MeV. The peak near 8 keV is well reproduced by dynamical calculations of Anholt. The structure in the calculated curve arises from the interference between the 1s\(\sigma\) decay amplitudes in the incoming and outgoing parts of the trajectory. These experiments, which have recently been extended to 5 and 20 MeV, mark the first demonstration that quasimolecular x-ray spectroscopy is possible, and reveal the potential for quantitative studies of transient molecular orbitals formed during ion-atom collisions.

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References
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