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ATOMIC-COLLISION EXPERIMENTS UTILIZING LOW-VELOCITY, HIGHLY-CHARGED ION BEAMS

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Summary

Intense beams of highly-stripped ions are now routinely produced at low velocities using the Brookhaven dual MP-tandems in a unique four-stage accel/decel mode. This mode of operation combines three stages of acceleration, stripping at high energy, and one stage of deceleration to near-zero velocity. To date, experiments have used 10-100 nA beams of bare and few-electron heavy ions at energies as low as 0.2 MeV/amu, and upgrades of the facility should push the lower limit below 0.1 MeV/amu. Recent experiments, such as measurements of charge transfer and x-ray production for S^{6-16+} on He and Ar at 6-20 MeV and P(b) measurements for MO x-rays produced in Cl^{16+} + Ar collisions at 20, 10 and 5 MeV have demonstrated the usefulness of highly-stripped, low-velocity projectiles. These experiments and a few possibilities for *future experiments are discussed.*

Introduction

The ultimate constraint on atomic-collision experiments is the restricted range of beam energies and/or charge states imposed by a particular ion source or accelerator. There is currently considerable interest in pushing to lower collision velocities and to higher incident charge states. For example, such projectiles are needed to extend energy and charge-state dependence studies, to test theoretical models within their range of validity, and to address the data needs of laboratory[1] and astrophysical[2] plasma research. Recently developed sources of highly charged ions, such as electron-beam ion source (EBIS),[3] electron cyclotron resonance (ECR),[4] recoil-ion,[5] and laser-induced plasma[6] are useful for some experiments. It is difficult, however, to extract from these sources the intense, very highly-stripped, variable-energy projectiles which are required by many atomic-collision experiments. An excellent ion source for such experiments is an accelerator facility which can produce highly-stripped projectiles at energies up to a few hundred MeV when operated in conventional acceleration modes, and down to near-zero energy when run in an accel/decel configuration. Any combination of machines which can first accelerate to high energy, then strip to high charge state, and finally decelerate to low energy could be used, but dual tandem facilities have been shown to be ideally suited for this purpose.

The first dual tandem accel/decel experiment was performed by Bayfield et al.[7] using the Pittsburgh EN tandems in a three-stage accelerator/decelerator mode of operation. Cross sections for single electron capture in O^{5-8+} + He collisions were measured at 0.15-1.6 MeV. The production of heavier highly-stripped ions was limited by the maximum terminal voltages of an EN tandem. Beam intensities were low and partially overlapping charge states restricted low energy operation. Bayfield et al.[7] predicted, however, that a 300-fold increase in the O^{8+} beam at 4 MeV would be realized if both halves of the injector tandem were used in a four-stage accel/decel configuration. The superposition of many beams with different final charge state near the zero-energy limit can also be avoided. Of the four laboratories in the world with two tandems (Brookhaven, the University of Oxford, the University of Pittsburgh, and the University of Washington), only the Brookhaven MP tandems have been developed for use in the four-stage tandem accel/decel mode.

Figure 1 shows the basic layout and modes of operation for the Brookhaven National Laboratory dual-MP tandem Van de Graaff accelerator facility. Although it was designed and has been repeatedly upgraded[8] to provide high energy heavy ion beams primarily intended for nuclear physics research, the versatility of employing coupled and decoupled modes of operation has been exploited to develop a nearly ideal facility for atomic physics research. In the one-stage mode, beams from a terminal negative ion source[8] have been used to measure electron stripping of Li^-, C^-, O^-, and Si^- at 2-7 MeV.[9] Energetic positive ion beams from two- and three-stage operation have been used for numerous atomic physics experiments, but the high projectile energy was often dictated by the desire for high charge states, not high velocities. The four-stage accel/decel mode overcomes this limitation by providing highly-charged ions at near-zero velocity. *The early development of four-stage operation was* reviewed previously,[10] and the more recent and near future improvements are described elsewhere in these proceedings.[11]

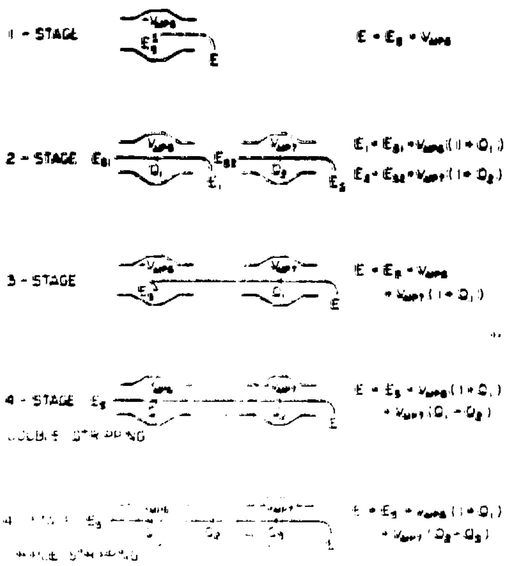

Figure 1. Schematic representation of the modes of operation for the Brookhaven dual MP tandem facility. Negative atomic and molecular ions are produced at MeV energies in the one-stage mode originating from a terminal negative ion source. Positive ions are produced at tens and hundreds of MeV in two- and three-stage modes of acceleration. By operating the first accelerator as a conventional two-stage tandem, and running the second tandem with negative terminal potential, low-velocity, highly-stripped ions are produced in the four-stage tandem accel/decel mode. See references 8, 10 and 11 for further details.

Thus far, there have been three experimental studies using accel/decel beams from the Brookhaven tandems.[12] The most recent measurements[13] have employed one-electron chlorine projectiles, Cl^{16+}, at 20, 10 and 5 MeV to dramatically enhance experimental results for quasimolecular or molecular orbital (MO) x rays. The potential for studying transient molecular orbitals formed during an ion-atom collision, by resolving structure in impact-parameter dependent MO x-ray spectra has long been realized.[14] Partly due to collision broadening at high velocities, however, the observed MO K x-ray spectra always exhibited a structureless shape, essentially independent of impact parameter.[15] Structure should be resolvable at lower collision velocities and the adiabaticity condition[16] would be better fulfilled, but merely using slower projectiles is not enough. The probability to both form and fill a K-shell vacancy during the time of a low-velocity collision is too low to provide good coincidence counting rates.

The solution is to use accel/decel to provide a one-electron projectile, such as Cl^{16+}, with a large probability of bringing a $1s\sigma$ vacancy into the collision, and to preserve the low collision velocity to minimize broadening. The decay rate of $1s\sigma$ vacancies is also enhanced with decreasing velocity, beacause the collision time is increased. These conditions produce a considerable increase in the quasimolecular radiation cross section. Another important and interesting effect accrues from bringing a $1s\sigma$ vacancy into the collision. There is equal probability for the vacancy to decay on the way in, or on the way out. Impact parameter dependent measurements should reveal predicted interference structures in the x-ray spectra resulting form the coherent sum of the incoming and outgoing amplitudes.

Figure 2 shows the x-ray energy spectrum recorded at an impact parameter of 1200 fm for Cl^{16+} + Ar collisions at 10 MeV. The peak near 8 keV is well reproduced (solid line) by the dynamical calculations,[17] which included transitions only from the $2p\pi$ and $2p\sigma$ orbitals to the $1s\sigma$ orbital. The structure in the calculated curve arises from the interference between the $1s\sigma$ decay amplitudes in the icoming and outgoing parts of the trajectory. The other coincidence x-ray spectra, with corresponding peaks moving from 6 keV at 2600 fm to 9 keV at 500 fm, are also in reasonable agreement with the calculations.[17] These results have recently been extended to 5 and 20 MeV. The structure is even more clearly resolved at 5 MeV, and is less apparent at 20 MeV, as would be expected. These experiments open wider the door to quasimolecular x-ray spectroscopy, which was already ajar from previous pioneering efforts.

Another area of atomic-collision physics which can benefit from accel/decel beams is the study of the projectile charge-state dependence of characteristic K x-ray production. In general, K-shell ionization cross sections are independent of incident charge state as long as the projectile L-shell is filled and then increase nearly linearly with the number of L-shell vacancies. This result is consistent with the predictions of the $2p\pi$ - $2p\sigma$ rotational coupling model,[18] but is not sufficient to demonstrate its validity. For example, the aforementioned charge state dependence was observed by both Tserruya et al.[19] and Lennard et al.[20] not only for nearly-symmetric collision systems, but also for very asymmetric systems. In the latter case, rotational coupling should not operate, and only direct ionization or excitation of the projectile K-shell can occur. Tserruya et al.[19] concluded that the striking similarity in charge-state dependences suggested a common K-shell vacancy production mechanism, namely direct K-shell excitation into empty bound states. Lennard et al.,[20] on the other hand, pointed to the large differences in magnitude of the absolute cross sections as evidence that two different mechanisms were operating, albeit with similar chage-state dependent behavior. These authors also indicated that accel/decel experiments might further these investigations.

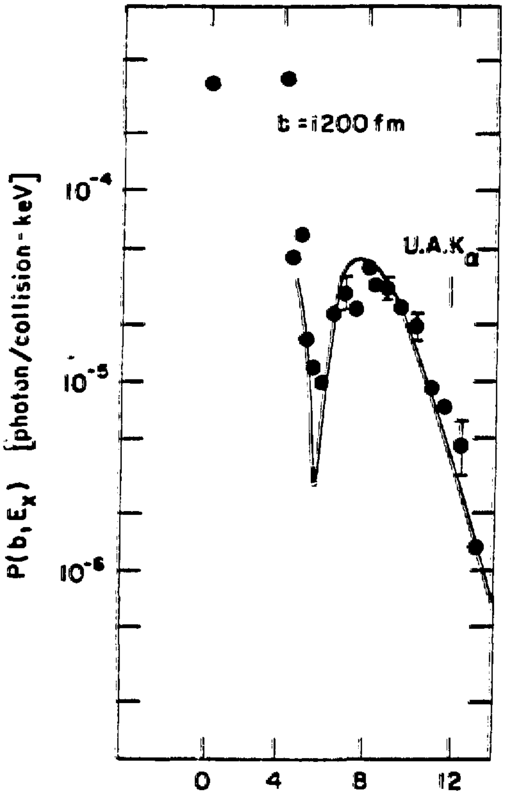

Figure 2. Energy dependence of K x rays produced at an impact parameter of 1200 fm in collisions of Cl^{16+} with Ar. The solid curve is the result of a normalized theoretical calculation by Anholt,[17] which includes interference effects between incoming and outgoing amplitudes.

The primary results of a recent extension of these studies[21] are shown in Figure 3. Similar charge-state dependences are again observed in the nearly-symmetric S + Ar and the very-asymmetric S + He collision systems. The low collision energy, 10-30 MeV, provided by accel/decel operation insured that the adiabaticity condition[16] is fullfilled so that the rotational coupling model is assumed valid for the S + Ar case. Definite conclusions about the operative vacancy production mechanisms must await further theoretical work on the relative magnitudes of contributions from direct Coulomb excitation in these collisions.

The third utilization of accel/decel beams was in the measurement of total and single-electron-capture (SEC) cross sections for S^{6-16+} ions in collision with He and Ar at 6-20 MeV.[22] The experiment amply demonstrated the potential for systematic studies of electron capture over a wide range of projectile charge states and collision energies which should reveal subtle shell-structure effects not yet included in calculations. The measured SEC data was in reasonable agreement both with scaled results of other experiments with lower charge state projectiles and with the semiemirical scaling laws of Knudsen et al.[23]

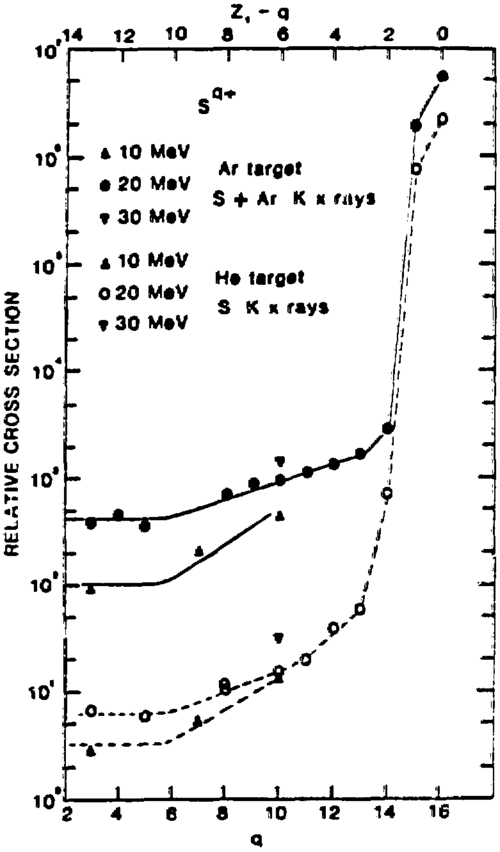

Figure 3. The projectile charge state dependence of x-ray production cross sections for the nearly-symmetric S + Ar and the very-asymmetric S + He collision systems. Note the striking similarity in charge-state dependences.

Future Plans and Other Possibilities

Several new investigations are being planned to exploit the usefullness of tandem accel/decel beams. Over the next year, a group of researchers from Kansas State University and the Federal Republic of Germany will come to Brookhaven to extend their measurements of quasiresonant charge transfer[24] and double K-K transfer[25] to lower collision velocities. In the earlier experiments the impact-parameter dependence of single and double K-K transfer was investigated for the F^{q+} + Ne collision system. For a collision energy of 4.4 MeV, the impact-parameter distribution for projectiles with one incoming K vacancy (F^{8+}) showed distinct structure which was attributed to destructive interference of contributions to the excitation amplitude from the incoming and outgoing parts of the trajectory. With lower collision velocity, more "beats" in the interference pattern are possible and the precision of the measurement will be improved. It should be possible to directly determine the interatomic potential-energy curves and to discriminate between mechanisms for multiple ionization of outer-shell electrons. For the other experiment,[25] more information concerning the dynamics of double K-K charge transfer should be obtained through a detailed study of the impact-parameter dependent structure revealed at lower collision energies. For both of these investigations, the tandem accel/decel method is apparently the only source of the projectiles required.

An important, if not quite as dramatic, utilization of accel/decel beams is also planned. S^{13+} beams produced by the Brookhaven tandems at 70-160 MeV were used recently to investigate correlated electron capture and K-shell excitation in S + Ar collisions.[26] The first clear evidence for a resonant process in ion-atom collisions which is analogous to dielectronic recombination in free-electron-ion collisions was observed. These measurements will soon be extended to helium and/or neon targets. In addition to measurements in the "resonance" region, data must be obtained for beam energies considerably above and below the expected maximum in order to gain a better understanding of the uncorrelated non-resonant contribution to the meaured cross section. Although energies well above 160 MeV are difficult to obtain from the Brookhaven tandems, the low energy data can be extended down to a few MeV using accel/decel. Further discussions on this topic may be found elsewhere in these proceedings.[27]

With the planned improvements in the Brookhaven tandem facility,[11] the charge-state and impact-parameter dependence studies of quasimolecular and characteristic x-ray production, and the charge exchange measurements discussed in the previous section can soon be extended. The same collision systems could be investigated at lower collision velocities or complimentary systems could be explored at comparably low velocities. Electron capture cross sections could be measured systematically over wide ranges of energy and charge state for a single collision system. This would provide sensitive excitation curves to stimulate further theoretical effort to include shell structure and other effects in calculations of SEC, and to encourage thoretical studies of multiple-electron capture. Additional refinements in experimental technique are also possible. For instance, anisotropies in x-ray emission could be studied and/or counting rates might be improved to enchance statistics. A few of the possibilities, which will more than occupy currently active researchers, have been mentioned here. Since nearly any atomic-collision experiment can be extended to this velocity and charge-state regime, many other uses for accel/decel beams will surely be found.

Acknowledgements

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