CORRELATED CHARGE-CHANGING ION-ATOM COLLISIONS

PROGRESS REPORT

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I. RESEARCH PROGRESS

This report summarizes the progress and accomplishments in accelerator atomic physics research supported by DOE grant DE-FG02-87ER13778 from March 16, 1991 through March 15, 1992. This work involves the experimental investigation of fundamental atomic processes in collisions of charged projectiles with neutral targets or electrons, with particular emphasis on two-electron interactions and electron correlation effects. Processes involving combinations of excitation, ionization, and charge transfer are investigated utilizing coincidence techniques in which projectile charge-changing events are associated with x-ray emission, target recoil ions, or electron emission. New results have been obtained for studies involving (1) resonant recombination of atomic ions, (2) double ionization of helium, and (3) continuum electron emission. Experiments were conducted using accelerators at the Lawrence Berkeley Laboratory, Argonne National Laboratory, Michigan State University, Western Michigan University, and the Institute of Nuclear Research, Debrecen, Hungary. Brief summaries of work completed and work in progress are given immediately below:

Resonant Recombination

Resonant recombination of an atomic ion occurs when electron capture (transfer) is accompanied by simultaneous excitation of the ion, resulting in the formation of an excited intermediate state, followed by subsequent radiative stabilization. The formation of the intermediate state is mediated by the electron-electron interaction, and is resonant for relative velocities equal to outgoing Auger-electron velocities. In an ion-atom collision, resonant recombination is referred to as resonant transfer excitation (RTE), while in electron-ion collisions it is called dielectronic recombination (DR). Two new studies have been conducted.

1. Resonant Transfer Excitation for Ti^{19+20+} Ions Channeled in Au - When an ion travels between the ordered rows of a crystal lattice the ion does not interact strongly with the nuclei of the crystal. In this scenario, the ion interacts essentially only with the weakly bound valence electrons, and, consequently, free-electron-ion collisions are expected to be very closely approximated. If this is the case, then resonant recombination is expected to occur at appropriate (i.e., Auger) relative energies between the ion and electrons, and the maximum probability for this process should be sharply peaked. In earlier work¹ at Argonne we found evidence for a resonant maximum which was 5 to 10 times narrower than any previously observed for RTE. Although this result sparked a theoretical explanation,² the measurement has been criticized by other investigators.³ In an effort to substantiate our results, new measurements were conducted at Argonne. Unfortunately, the Au crystals used in this later work proved to be of poor quality, and consequently, the fraction of well-channeled ions traversing the crystal (i.e., those ions which interact only with the valence electrons) was significantly smaller than in the earlier work. As a result, the narrow resonant maximum observed in the earlier work could not be reproduced. A future effort with higher quality crystals is planned.

2. Resonant Transfer and Double Excitation for $Kr^{34+} + H_2$ Collisions - Resonant electron transfer double excitation (RT2E) is a three-electron process which is expected to occur in an ion-atom collision when electron transfer is accompanied by simultaneous excitation of two electrons forming an excited intermediate state. The analogous process in electron-ion collisions has been observed⁴ for Li^+ ions, but has not been previously investigated in ion-atom collisions. RT2E was investigated for $Kr^{34+} + H_2$ collisions using the Michigan State cyclotron. As in the case of RTE, coincidences between single-electron capture and K x-ray emission provide a signature for RT2E, but the resonant collision energies for RT2E are about twice those for RTE. Results obtained indicate the existence of coincidences between x rays and single capture events at the collision energies appropriate for RT2E, however, the energies of the x rays responsible for the observed coincidences are about twice the Kr K x-ray energy. The origin of these coincidences is not yet clear, and additional measurements are planned to further investigate the RT2E process.

Multiple Ionization by Intermediate- to High-Velocity Charged Particles

Multiple ionization of target atoms by intermediate- to high-velocity charged ions is attributed to two mechanisms: (a) a two-step (TS) process in which both target electrons are removed in separate direct interactions with the projectile, and (b) a one-step mechanism in which one electron is liberated in a single projectile-target interaction followed by subsequent "shakeoff" (SO) of the second electron. This latter process involves electron correlation and is expected to dominate in the limit of high projectile velocities. New studies include:

1. Double ionization of helium: General considerations-- From various studies, it can be inferred that the two-step (TS) mechanism should dominate for projectile charges q and velocities v (in atomic units) such that $q/v > 0.2$, while shakeoff (SO) should dominate for $q/v < 0.05$. Both TS and SO are likely to be important in the intermediate range $0.2 \geq q/v \geq 0.05$. Ratios of double-to-single ionization for a diverse set of projectile ions with different velocities and charges were examined as a function of v/q . Most of the available data, including recent measurements⁵ with N^{7+} , are found to fall along a common curve with the "crossover" from the TS to the SO regime being clearly evident. The results demonstrate⁶ conclusively that the important factor in determining the regions of validity for TS and SO is the ionic charge divided by the impact velocity q/v and not just the impact velocity itself. An experimental investigation for relativistic $Nb^{40,41+}$ ions which will test the regions of validity of the TS and SO mechanisms for very high charges and velocities has been approved at the LBL BEVALAC.
2. Double ionization of helium by He^+ and S^{12+} projectiles - Ionization of helium by 0.125-3.0 MeV/u He^+ and 0.16-1.8 MeV/u S^{12+} ions was investigated in measurements done at WMU. This particular choice of charge states involves both pointlike (S^{12+}) and structured (He^+ and S^{4+}) ions. By comparing the resulting double-to-single ionization ratios to those obtained for bare ions, the contribution of the projectile electrons to double ionization can be determined. Double ionization was measured for different ranges of impact parameters by associating target ionization

with projectiles undergoing electron capture, loss, or no charge change. The double-to-single ionization ratios were found to depend strongly on the outgoing charge of the projectile. The ratios associated with projectile electron capture and loss are substantially enhanced and their dependence on charge and velocity is altered significantly compared to the case of no charge change. The origins of these observations are being investigated. Additional measurements of the double ionization of helium are planned for incident Li^{q+} ions.

3. Triple Ionization of Lithium - Closely related to the study of the double ionization of helium is the triple ionization of lithium. This latter process can provide insight into the respective probabilities for three separate projectile-target electron interactions compared to the probability for three-electron correlation in the ionization process. To this end, we are constructing a Li vapor oven which will be used as a target to measure the triple ionization of lithium by protons and other heavy particles.

Continuum Electron Emission Associated with Bound-State Capture

In previous work for 3.75 keV/u O^{6+} (Ref. 7) and 3.5 MeV/u Ne^{10+} (Ref. 8) ions colliding with He, it was found that continuum electron emission along the beam direction (i.e., at 0°) associated with bound-state capture could not be fully accounted for in terms of independent-particle interactions, thus indicating that electron correlation played a significant role. New measurements of continuum electron emission have been conducted for 1.25-7.0 keV/u $\text{O}^{q+} + \text{He}$ collisions and for 2.63 keV/u $\text{O}^{q+} + \text{He}$ with $q=3, 6$, and 8 using the ECR ion source at the Lawrence Berkeley Laboratory 88" cyclotron facility. As in the earlier work⁷ for 3.75 keV/u $\text{O}^{6+} + \text{He}$, continuum electron emission at 0° was found to occur only when accompanied by bound-state capture, thus indicating that these forward-going electrons are produced as the result of a two-electron process. In the new measurements, the cross sections for the emission of these continuum electrons are found to be increasing functions of both the projectile energy and charge state over the ranges investigated. Very recently, similar measurements were also carried out at the Institute for Nuclear Research, Debrecen, Hungary for 20-75 keV/u $\text{He}^+ + \text{Ar}$ collisions. In this work, continuum electron emission at 0° associated with bound-state capture was found to increase sharply as the incident beam energy is decreased. At present there are no quantitative calculations to compare with these various results, although there has been much speculation concerning the dynamics of such collisions.⁹

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II. PERSONNEL

A. Principal Investigator

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Ms. Karen Lifrieri - M.A. (April 1992)
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E. Undergraduate Students

Ms. Layle Griffioen
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III. PUBLICATIONS AND PRESENTATIONS

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