CORRELATED CHARGE-CHANGING ION-ATOM COLLISIONS

PROGRESS REPORT

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I. INTRODUCTION

This report summarizes the progress and accomplishments in accelerator atomic physics research supported by DOE grant DE-FG02-87ER13778 from February 16, 1990 through February 15, 1993. This work involves the experimental investigation of atomic interactions in collisions of charged projectiles with neutral targets or electrons, with particular emphasis on two-electron interactions and electron-correlation effects. The processes studied are of interest both from fundamental and applied points of view. In the latter case, results are obtained which are relevant to the understanding of laboratory and astrophysical plasmas, highly-excited (Rydberg) and continuum states of atoms and ions, atomic structure effects, the interaction of ions with surfaces, and the development of heavy-ion storage rings. The results obtained have provided the basis for several M.A. thesis projects at Western Michigan (a thesis is required of all M.A. students), and several Ph.D. dissertation projects are currently underway.

Summaries of work completed and work in progress are given below in Section II. This research has resulted in 26 papers (in print and in press), 12 invited presentations at national and international meetings, and 28 contributed presentations as detailed in Section III. Section IV contains a listing of the personnel involved in this work, and a short overview of our future plans is given in Section V.

II. RESEARCH COMPLETED AND IN PROGRESS

In work completed during the project period, processes involving excitation, ionization, and charge transfer, and combinations of these, were investigated. Individual collision processes were identified, for the most part, using coincidence techniques in which projectile charge-changing events were 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, (3) continuum-electron emission, and (4) other effects. Experiments were conducted using accelerators at the Lawrence Berkeley Laboratory, the Indiana University Cyclotron Facility, Michigan State University, the Institute of Nuclear Research, Debrecen, Hungary, and Western Michigan University.

A. 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 intermediate doubly- (or multiply-) excited 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 corresponding to outgoing Auger-electron energies. 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). Several new studies of RTE/DR have been conducted.

1. Resonant Transfer Excitation for F^{6+} and $Mg^{9+} + H_2$

In a study by Schulz et al.,¹ it was found that the measured resonant transfer excitation (RTE) cross sections for $F^{6+} + H_2$ were nearly a factor of two smaller than those calculated from DR theory² as shown in Fig. 1a. A difficulty in this earlier study was the determination of the absolute x-ray detection efficiency which, for F K x rays, is very low. In our work, conducted using the Western Michigan EN tandem Van de Graaff, a combined experimental and theoretical investigation of RTE was made for $F^{6+} + H_2$ and $Mg^{9+} + H_2$. A very careful determination, by three independent methods, was made of the x-ray detection efficiency for the F and Mg K x rays. The results of these measurements, combined with the more accurate determination of the x-ray detection efficiencies, showed there to be, in fact, excellent agreement between experiment and theory for RTE in both F^{6+} and Mg^{9+} as seen in Figs. 1a and 1b. These results thus remove the previous discrepancy between theory and experiment.

Fig. 1. (a) Experimental cross sections for K x-ray emission associated with single-electron capture in $F^{6+} + H_2$ collisions compared with theoretical RTE calculations. Data and theory are as follows: ○, Ref. 1; ●, present; — — —, Ref. 2; — — —, present. (b) Experimental cross sections for K x-ray emission associated with single-electron capture in $Mg^{9+} + H_2$ collisions compared with theoretical calculations.

Publication resulting from this work:

"Resonant Transfer Excitation in Collisions of F^{6+} and Mg^{9+} with H_2 ," E. M. Bernstein, A. Kamal, K. E. Zaharakis, M. W. Clark, J. A. Tanis, S. M. Ferguson, and N. R. Badnell, Phys. Rev. A **44**, 4210 (1991).

M.A. theses: This work constituted the M.A. thesis research of Mr. Konstantinos Zaharakis (awarded June 1991) and Mr. Anwar Kamal (awarded December 1991).

2. Resonant Transfer Excitation for $\text{Fe}^{q+} + \text{H}_2$

RTE was investigated for 5.8-9.2 MeV/u Fe^{q+} ions ($q=23, 24$, and 25) colliding with H_2 using the SuperHILAC at the Lawrence Berkeley Laboratory. For each charge state, cross sections for RTE were obtained from measurements of Fe K x rays, emitted from the doubly-excited intermediate state, coincident with single-electron capture by the incident ion. These x-ray-single-capture coincidences gave cross sections which were in good agreement with RTE calculations based on theoretical cross sections for dielectronic recombination (DR). More notably, for Fe^{25+} cross sections for RTE were also obtained from measurements of coincidences between the two Fe K x rays emitted from the decay of the intermediate excited state. Since metastable states can be present following emission of the first x ray, these metastable states must be taken into account when comparing experiment and theory. The cross sections obtained from the x-ray-x-ray coincidence measurements were found to be nearly equal in magnitude to those obtained from the x-ray-single-capture coincidences as shown in Fig. 2, and, furthermore, comparison with theory shows the measured cross sections to agree with the RTE calculations for x-

Fig. 2. Comparison of RTE cross sections for $\text{Fe}^{25+} + \text{H}_2$ obtained from x-ray-single-electron capture coincidences (O) with those obtained from x-ray-x-ray coincidences (●). The smooth curve is the calculated RTE cross section associated with single x-ray emission, while the broken curve is the calculated RTE cross section associated with the emission of two Fe K x rays, assuming that metastable states do not decay within the detector viewing region.

ray-single capture coincidences. These results thus imply that any metastable states formed in the RTE process are sufficiently short-lived so that they essentially all decay within the viewing region of the detectors. This latter result is contrary to expectations based on the experimental geometry and the calculated lifetimes of the most probable metastable states.

Publication resulting from this work:

"Cross Sections for Resonant Transfer and Excitation in $\text{Fe}^{9+} + \text{H}_2$ Collisions," M. W. Clark, J. A. Tanis, E. M. Bernstein, N. R. Badnell, R. D. DuBois, W. G. Graham, T. J. Morgan, V. L. Plano, A. S. Schlachter, and M. P. Stockli, Phys. Rev. A 45, 7846 (1992).

3. Resonant Transfer Excitation for $\text{U}^{90+} + \text{H}_2$

A consequence of RTE is that it competes with direct electron capture, and, under some circumstances, it can contribute significantly to the total single capture.³ For U^{90+} projectiles, RTE is expected to occur for incident energies between 26 and 45 GeV.⁴ In this work, conducted at the Lawrence Berkeley Laboratory BEVALAC facility, the energy dependence of total single-electron capture was measured for 100-151 MeV/u (24-36 GeV) $\text{U}^{90+} + \text{H}_2$ collisions. Distinct maxima, attributed to RTE contributions from specific intermediate excited states, superimposed on a monotonically decreasing background due to direct capture were observed in the measured cross sections. By subtracting the monotonically decreasing "background" from the measured cross sections, the RTE cross sections for $\text{U}^{90+} + \text{H}_2$ were derived as shown in Fig. 3. The magnitude and positions of the maxima are seen to be in good agreement with calculations.⁵ These results provided the first test of relativistic dielectronic recombination theory.

Publications resulting from this work:

"Resonant Transfer and Excitation for U^{90+} Projectiles in Hydrogen," W. G. Graham, K. H. Berkner, E. M. Bernstein, M. W. Clark, B. Feinberg, M. A. McMahan, T. J. Morgan, W. Rathbun, A. S. Schlachter, and J. A. Tanis, Phys. Rev. Lett. 65, 2773 (1990).

"Resonant Transfer Excitation in $U^{89+} + C$ and $U^{90+} + H_2$ Collisions," J. A. Tanis, W. G. Graham, K. H. Berkner, E. M. Bernstein, M. W. Clark, B. Feinberg, M. A. McMahan, T. J. Morgan, W. Rathbun, and A. S. Schlachter, Nucl. Instrum. Meth. Phys. Res. B53, 442 (1991).

"Measurements of Resonant Transfer and Excitation Cross Sections for U^{90+} Projectiles in H_2 ," W. G. Graham, K. H. Berkner, E. M. Bernstein, M. W. Clark, B. Feinberg, M. A. McMahan, T. J. Morgan, W. Rathbun, A. S. Schlachter, and J. A. Tanis, Z. Phys. D21, S213 (1991).

Fig. 3. Cross sections for U^{90+} in H_2 . (a) Data points are the measured total single-electron capture cross sections. Error bars show the relative uncertainties. The dashed curve is an empirical fit to the direct capture background. (b) Data points show the experimentally derived RTE cross sections (total capture cross sections minus the empirical fit). Error bars give the absolute uncertainty in these cross sections. The solid curve is the predicted⁵ RTE cross section.

4. Projectile Z and Charge-State Dependences of RTE

Important tests of RTE and DR theory are those which test the theory along isoelectronic sequences and along isonuclear charge-state sequences. Extensive RTE results now exist for Li-like ions with $9 \leq Z \leq 92$, and the substantial agreement between theory and experiment is shown in Fig. 4. For Z values ≥ 20 , KLL and KLn, $n \geq M$ can be separately identified. The U^{90+} result (these measurements were for He-like ions) is significant because it provides a test of relativistic DR theory. From the figure, it is seen that there is generally good agreement between theory and experiment over the entire Z range investigated to date. The only exception is the large value (> 2.5) of the

Fig. 4. Ratio of theoretical-to-experimental RTE cross section maxima as a function of atomic number Z . Results for KLL (●) and $KLn, n \geq M$ (○) transitions are separately identified. See Ref. 6 for key to experimental data and theoretical calculations.

ratio for F^{6+} obtained from the measurements of Schulz et al.¹ However, the later measurements for F^{6+} and Mg^{9+} discussed above apparently remove this discrepancy. Thus, it is concluded that RTE (and, consequently, DR) theory and experiment are in good agreement for the Li-like isoelectronic sequence.

Another important test of DR theory is its accuracy in predicting the charge-state dependence of DR cross sections. In Fig. 5 results from RTE studies are shown, where the maximum values of the measured and calculated RTE cross sections are plotted against the number of electrons on the incident ion. Results are shown for incident Ca^{10-19+} ions, Fe^{23-25+} ions, and Nb^{28-31+} ions. The results for Ca and Fe involve K-shell excitation while those for Nb ions involve L-shell excitation. The near factor-of-two decrease between two electrons and one electron on the incident ion reflects the fact that, in the former case, there are two K electrons which can participate in

Fig. 5. Charge-state dependence of RTE cross-section maxima. See Ref. 6 for key to experimental data and theoretical calculations.

the RTE process, whereas, for the latter there is only one. The good agreement between theory and experiment for KLL and KLM transitions displays the accuracy with which DR involving K-shell excitation may be calculated for these very highly-charged ions. In view of the K-shell results, the large discrepancy between theory and experiment for RTE involving L-shell excitation as seen in Fig. 5 is difficult to understand, and this discrepancy has yet to be resolved.

5. Resonant Transfer Double Excitation for $\text{Kr}^{34+} + \text{H}_2$

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 a multiply-excited intermediate state. The analogous process in electron-ion collisions has been observed⁷ for Li^+ ions, but has not been previously investigated in ion-atom collisions. RT2E was investigated for $\text{Kr}^{34+} + \text{H}_2$ collisions using the Michigan State University 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. The measurements show the existence of coincidences between x rays and single-capture events at the collision energies (~ 41.2 MeV/u) appropriate for RT2E; however, the energies of the observed x rays (> 20 keV) are about twice the energy (~ 13 keV) of Kr K x rays as seen in Fig.

6. The origin of these coincidences is unclear. Several possible sources of

Fig. 6. X-ray emission associated with single-electron capture in 41.2 MeV/u $\text{Kr}^{34+} + \text{H}_2$ collisions.

these x rays have been considered, e.g., x rays or gamma rays from the beam or the material used in the construction of the apparatus, radiative electron capture (REC), and electronic pile-up, but each of these explanations appears to be inadequate. Additional measurements, incorporating several improvements to the experimental apparatus, are planned to further investigate the RT2E process.

Publication resulting from this work:

"Search for Resonant Electron Transfer and Double Excitation in $\text{Kr}^{34+} + \text{H}_2$ Collisions," K. E. Zaharakis, R. R. Haar, J. A. Tanis, M. W. Clark, and V. L. Plano, AIP Conference Proceedings, edited by M. Stockli and P. Richard, (American Institute of Physics, New York, 1993), in press.

Ph.D. thesis: This work constitutes part of the Ph.D. dissertation research of Mr. Konstantinos Zaharakis.

6. Dielectronic Recombination in He^+ Ions

Dielectronic recombination (DR) was investigated for $1s + e^- \rightarrow nln'l'$ transitions in $\text{He}^+ + e^-$ collisions using the electron cooler at the Indiana University Cyclotron Facility (IUCF). In this work, a beam of He^+ ions (current ~ 300 nA) was merged with the electron cooling beam (current ~ 0.3 A) over an interaction length of ~ 2.8 m. For $\text{He}^+(1s)$ ions, DR is expected to occur for relative energies E_{rel} of 33-40 eV between the ion and the electron. By ramping the relative electron energy through the range $|E_{\text{rel}}| = 0-50$ eV, DR could be investigated for electron velocities less and greater than the ion beam velocity. For $E_{\text{rel}}=0$, a peak due to radiative recombination (RR) (inverse photoelectric effect) was expected.

In our earlier work^{8,9} at IUCF, insufficient energy resolution prevented the observation of expected structure resulting from the different n, n' configurations formed in the DR process. In our most recent run (the third), measurements were conducted for two different $^3\text{He}^+$ beam energies, 25 and 44 MeV, to test for changes in the electron energy resolution with ion beam

energy. The absolute electron energy was determined accurately and the resolution was improved considerably (< 1 eV in the ion frame) compared to the earlier work. A typical spectrum for 44 MeV $^3\text{He}^+$ ions is shown in Fig. 7 in which DR maxima are observed for electron velocities smaller ($v_e < v_i$) and greater ($v_e > v_i$) than the ion velocity and in which the RR maximum for $v_e = v_i$ is also seen. Nearly identical results were obtained for the 25 MeV $^3\text{He}^+$

Fig. 7. Intensity of neutral He atoms formed in the electron cooler region as a function of electron energy for 44 MeV $^3\text{He}^+$ ions.

beam. Peaks associated with $n=2$, $n'=2$ intermediate states are seen at relative energies of 33 and 35 eV, and transitions involving intermediate states with $n=2$, $n' > 2$ occur near 39 eV. An unexpected, broader peak near relative energies of 45 eV is believed to result from DR for $n, n' \geq 3$ intermediate states. These results indicate that most of the dielectronic recombination occurs into states with $n=2$, $n' \geq 3$ in agreement with theoretical predictions.¹⁰

Publications resulting from this work:

"Dielectronic Recombination in He^+ Ions," J. A. Tanis, E. M. Bernstein, S. Chantrenne, M. W. Clark, T. Ellison, C. C. Foster, W. G. Graham, W. W. Jacobs, J. R. Mowat, T. Rinckel, A. Ross, D. Schneider, M. P. Stockli, and N. R. Badnell, Nucl. Instrum. Meth. Phys. Res. B56/57, 337 (1991).

"A Measurement of the Dielectronic Recombination of He^+ Ions," J. R. Mowat, J. A. Tanis, R. R. Haar, J. L. Forest, T. Ellison, C. Foster, W. Jacobs, T. Rinckel, P. F. Dittner, W. G. Graham, M. W. Clark, D. E. Schneider, and M. P. Stockli, Recombination of Atomic Ions, edited by W. G. Graham, W. Fritsch, Y. Hahn, and J. A. Tanis, (Plenum Press, New York, 1992), pp. 203-207.

"Measurement of Dielectronic Recombination in He^+ Ions," R. R. Haar, J. A. Tanis, V. L. Plano, K. E. Zaharakis, W. G. Graham, J. R. Mowat, T. Ellison, W. W. Jacobs, and T. Rinckel, Phys. Rev. A (Rapid Comm.), to be published.

7. Resonant Transfer Excitation for $\text{Ca}^{17,18+}$ Ions Channeled in Au

When ions are channeled between the ordered rows of a crystal lattice, the ions interact mainly with the valence electrons. This is expected to give rise to resonant recombination with a very narrow width. In earlier work¹¹ by us, done at the Argonne National Laboratory using the ATLAS facility, we found evidence for such a resonant maximum for $\text{Ti}^{19,20+}$ ions channeled along the $\langle 110 \rangle$ axis in a Au crystal; the observed maximum was 5 to 10 times narrower than any observed for RTE. Although this result sparked a theoretical explanation,¹² the measurement has been criticized by other investigators.¹³

In an effort to further investigate RTE in ion channeling, measurements were conducted for $\text{Ca}^{17,18+}$ ions in Au crystals. In this new study no resonant maximum corresponding to recombination could be clearly identified for either 17+ or 18+ incident ions, although in the latter case (18+) there was a hint of a maximum near the energy where RTE is expected to occur. The reason for this apparent large discrepancy between the results obtained for $\text{Ca}^{17,18+}$ ions and for $\text{Ti}^{19,20+}$ ions is unresolved. A possible explanation could be stripping of the doubly-excited intermediate state in Ca^{q+} prior to deexcitation as observed in similar channeling measurements by Datz et al.¹⁴ Subsequently, measurements were again conducted for $\text{Ti}^{19,20+}$ in an effort to substantiate our earlier results for this ion. 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.

Publication resulting from this work:

"Resonant Transfer and Excitation in Ion Channeling: Work at Argonne National Laboratory," M. W. Clark, A. Belkacem, K. H. Berkner, E. M. Bernstein, S. M. Ferguson, E. P. Kanter, K. E. Rehm, D. Schneider, and J. A. Tanis, Recombination of Atomic Ions, edited by W. G. Graham, W. Fritsch, Y. Hahn, and J. A. Tanis, (Plenum Press, New York, 1992), pp. 319-325.

B. Double Ionization of Helium

The double ionization of helium by fast ions, as well as by electrons and photons, is a few-body problem of fundamental interest which has received considerable attention in recent years. Double ionization of helium by intermediate- to high-velocity charged ions is generally attributed to two mechanisms:¹⁵ (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. The former process is due to independent-particle interactions, while the latter involves electron correlation, as in the case of double ionization of helium by photons. It can be inferred¹⁵⁻¹⁷ that the 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 $0.2 \geq q/v \geq 0.05$.

1. Ratio of Double-to-Single Ionization: General Considerations

The ratio R of double-to-single ionization is the parameter used most frequently to exhibit and test double ionization mechanisms. It can be shown^{15,16} that R is mainly a function only of q/v , and, furthermore, that in the TS regime R should vary as $(q/v)^2$, while for $q/v \ll 1$ R is predicted to be

independent of both the incident projectile charge and the velocity. If R is mainly a function only of q/v (or v/q), then a degree of universality should be exhibited in a plot of R vs. v/q . Values of R for a diverse set of projectile ions with different velocities and charges are shown in Fig. 8. Most of the available data are found to fall along a common curve with the "crossover" from the TS to the SO regime being clearly evident. Furthermore, in the TS regime, i.e., $v/q = 1-5$, the data agree quite well with the predicted $(v/q)^{-2}$ behavior (solid line in the figure); for $v/q > 15$, R approaches a constant value in agreement with predictions of the SO mechanism. The results demonstrate 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.

Fig. 8. Ratios of double-to-single ionization of helium by several ions as a function of v/q . See Ref. 18 for key to data.

Publications resulting from this work:

"Comment on 'Double and Single Ionization of Helium by High-Velocity N^{7+} Ions,'" J. A. Tanis, R. D. DuBois, and A. S. Schlachter, Phys. Rev. Lett. 68, 897 (1992).

"Testing Double Ionization Mechanisms with Highly-Charged Ions," J. A. Tanis, AIP Conference Proceedings, edited by M. Stockli and P. Richard, (American Institute of Physics, New York, 1993), in press.

2. Double Ionization of Helium by Relativistic U^{90+} Projectiles

Double ionization of helium was investigated for 60-, 120-, and 420-MeV/u ($v/c=0.34-0.72$) U^{90+} ion impact. This work was done using the BEVALAC facility at the Lawrence Berkeley Laboratory. The measured double-to-single ionization ratios indicate that, even for these relativistic velocities, double ionization of helium results predominantly from independent interactions of the projectile ion with both target electrons as seen in Fig. 8 above (uranium data are the solid circles). From these results, it was concluded that the asymptotic high-velocity regime for one-step ionization (i.e., "shakeoff") has not yet been reached even for U^{90+} projectiles at 420 MeV/u ($v/c=0.72$). Furthermore, it was concluded that the asymptotic limit most probably cannot be reached for projectiles with $q > 7$, again showing that the ionic charge is fully as important as the velocity in determining the importance of a given ionization mechanism.

Publication resulting from this work:

"Double Ionization of Helium by High-Velocity U^{90+} Ions," H. Berg, O. Jagutzki, R. Dörner, R. D. DuBois, C. Kelbch, H. Schmidt-Böcking, J. Ullrich, J. A. Tanis, A. S. Schlachter, L. Blumenfeld, B. d'Etat, S. Hagmann, A. Gonzales, and T. Quinteros, Phys. Rev. A **46**, 5539 (1992).

3. Double Ionization of Helium by He^+ and $S^{6,13+}$ Projectiles

Ionization of helium by 0.125-3.0 MeV/u He^+ and 0.16-1.8 MeV/u $S^{6,13+}$ ions was investigated in measurements done at Western Michigan. This particular choice of charge states involves both pointlike (S^{13+}) and structured (He^+ and S^{6+}) ions. These new results can be combined and compared with our previous results¹⁹ for 0.5-2.5 MeV/u $O^{6,7+}$ ions, thus providing information covering charge states and energies over the range $q/v=0.1-3.0$ ($v/q=0.33-10$). By comparing the resulting double-to-single ionization ratios to those obtained for bare ions, information on the contribution of the

projectile electrons to double ionization can be obtained.

Furthermore, target ionization was measured for projectiles undergoing electron capture, loss, or no charge change. The resulting double-to-single ionization ratios were found to depend strongly on the outgoing charge of the projectile as shown in Fig. 9. The ratios associated with projectile electron capture and loss are seen to be substantially enhanced and their dependence on charge and velocity is altered significantly compared to the case of no charge change. These results apparently reflect the different impact parameter regimes associated with the different outgoing projectile charge states. While several features of the double ionization of helium by these ions are qualitatively understood, it is clear that many of the data are not explained within the framework of existing theories.

Fig. 9. Measured ratios of double-to-single ionization as a function of projectile energy (MeV/u) for He⁺, O⁷⁺, and S¹³⁺ ions striking He targets. Symbols represent target ionization ratios associated with projectiles undergoing electron capture ($\diamond$), electron loss ($\times$), or no charge change ($\circ$), respectively. The dashed lines are drawn to guide the eye. The solid curves are the predicted ratios obtained from the empirical scaling of Knudsen et al.¹⁶ for target ionization associated with no projectile charge change.

The origins of these various observations are currently being investigated. Additional measurements to investigate the contribution of projectile electrons to the double ionization of helium are planned for incident Li^{q+} ($q=1, 2, \text{ and } 3$) ions.

Publications resulting from this work:

"Target Ionization Accompanied by Projectile Electron Loss in Fast $\text{O}^{6,7+} + \text{He}$ Collisions," J. A. Tanis, E. M. Bernstein, M. W. Clark, S. M. Ferguson, and R. N. Price, *Phys. Rev. A* **43**, 4723 (1991).

"Double Ionization of Helium by Intermediate to High-Velocity He^+ , $\text{O}^{6,7+}$, and $\text{S}^{6,13+}$ Ions," J. A. Tanis, S. M. Ferguson, J. L. Forest, R. R. Haar, K. Lifrieri, and V. L. Plano, Atomic and Molecular Physics: Third US/Mexico Symposium, edited by C. Cisneros, I. Alvarez, and T. J. Morgan, (World Scientific, Singapore, 1991), pp. 83-95.

"Double Ionization of Helium by Intermediate-to-High Velocity He^+ Projectiles," J. L. Forest, S. M. Ferguson, K. Lifrieri, J. A. Tanis, and V. L. Plano, submitted to *Phys. Rev. A*.

M.A. theses: This work constituted the M.A. thesis research of Ms. Jun Forest (awarded June 1991) and Ms. Karen Lifrieri (awarded April 1992).

C. Continuum-Electron Emission at Zero Degrees

Recently, there has been great interest in continuum electrons and the processes from which they originate.²⁰ In this work, the emission of electrons along the beam direction, i.e., at 0° , is investigated. In addition to the direct emission of such electrons, continuum-electron emission may be accompanied by the capture or loss of a second active electron. As such, continuum electrons are often emitted as part of a two-electron process. A primary objective of this work is to evaluate the role of the electron-electron interaction in giving rise to the various two-electron processes considered. Studies are conducted for bare and partially-stripped ions colliding with helium and other gas targets. Results to date indicate that

certain of the processes involving the emission of continuum electrons are sensitive functions of the collision velocity.

1. Continuum-Electron Emission from Low-Energy O^{q+} + He Collisions

In previous work²¹ for 3.75 keV/u O^{6+} colliding with He, it was found that continuum-electron emission at 0° occurred only when accompanied by bound-state capture. Furthermore, this combined continuum-bound-state capture could not be fully accounted for in terms of independent-particle interactions, thus indicating that electron correlation played a role.

New measurements of continuum-electron emission at 0° were conducted for 1.1-6.2 keV/u O^{8+} and 2.63 keV/u O^{q+} ($q=3, 6$, and 8) colliding with He. This work was done at the Lawrence Berkeley Laboratory using the ECR ion source at the 88" cyclotron facility.

As for 3.75 keV/u O^{6+} + He,²¹ continuum-electron emission at 0° for 1.1-6.2 keV/u O^{8+} + He was found to occur only when accompanied by bound-state capture, indicating that these forward-going electrons originate as part of a two-electron process. Only for 2.63 keV/u O^{3+} + He was there some evidence of continuum-electron emission associated with no projectile charge change. Cross sections for 0° continuum electrons are found to be increasing functions of both the projectile energy and the charge state over the ranges investigated as shown in Fig. 10. At present there are no quantitative calculations to compare with these results.

Publications resulting from this work:

"Origin of Cusp Electrons in Slow ($v \sim 0.4$ a.u.) O^{6+} + He Collisions," J. A. Tanis, D. Schneider, S. Chantrenne, M. H. Prior, R. Herrmann, R. Hutton, and G. Schiwietz, *Phys. Rev. A* **42**, 5776 (1990).

"Low-Energy Continuum-Electron Emission at 0° from O^{q+} + He Collisions," J. A. Tanis, R. R. Haar, D. Schneider, M. W. Clark, M. H. Prior, R. D. DuBois, and K. Randall, AIP Conference Proceedings, edited by M. Stockli and P. Richard, (American Institute of Physics, New York, 1993), in press.

Fig. 10. Relative cross sections for continuum-electron emission along the beam direction associated with single bound-state capture (a) vs. projectile energy for $O^{8+} + He$, and (b) vs. incident projectile charge state for 2.6 keV/u $O^{9+} + He$. The lines are to guide the eye.

2. Cusp-Electron Production in 18.75-75 keV/u He^+ + Ar Collisions

Cusp-electron (i.e., continuum electrons emitted at 0° moving with the beam velocity) yields were measured in 18.75-75 keV/u He^+ + Ar collisions. These cusp electrons originate from three distinct processes: (1) electron capture to the continuum (ECC), (2) transfer ionization (TI), or (3) electron loss to the continuum (ELC). The measurements were carried out at the Institute of Nuclear Research, Debrecen, Hungary. Cusp electrons were detected in coincidence with He^+ ions undergoing electron capture (TI), electron loss (ELC), or no charge change (ECC). Over the 18.75-75 keV/u range, the ECC fraction decreases from about 86% to 79%, the ELC fraction increases from about 2% to 20%, and the TI fraction decreases from about 12% to 1% as shown in Fig. 11. These new results are consistent with the earlier

Fig. 11. Relative contributions of the various cusp-electron production mechanisms for 18.75-75 keV/u He^+ + Ar collisions. The symbols represent: ◆, ECC; ■, TI; ●, ELC.

results found by Kövér et al.²² The TI results are to be contrasted with the low-energy $O^{9+} + He$ results, discussed immediately above, for which continuum-electron emission occurs only when accompanied by bound-state capture.

Although the TI fraction increases significantly with decreasing energy in these $He^+ + Ar$ collisions, it reaches a maximum value of only about 12%.

Publications resulting from this work:

"Cusp Electron Production in 75-300 keV $He^+ + Ar$ Collisions," V. L. Plano, L. Sarkadi, P. Závodszky, D. Berényi, J. Pálincás, L. Gulyás, E. Takács, L. Toth, and J. A. Tanis, AIP Conference Proceedings, edited by M. Stockli and P. Richard, (American Institute of Physics, New York, 1993), in press.

"Projectile Energy Dependence of the Contributions of the Different Mechanisms to the Cusp Electron Production in $He^+ + Ar$ Collisions," P. A. Závodszky, L. Sarkadi, J. A. Tanis, D. Berényi, J. Pálincás, V. L. Plano, L. Gulyás, E. Takács, and L. Toth, Nucl. Instrum. Meth. Phys. Res. (1993).

Ph.D. thesis: This work constitutes part of the Ph.D. dissertation research of Ms. Vicki Plano.

3. Continuum-Electron Emission at Intermediate Velocities

Currently, we are in the process of constructing a sophisticated electron-spectrometer system at Western Michigan University. Funding for this project was obtained from a U.S. DOE University Research Instrumentation Program grant. Most of the equipment for this system has been acquired, and installation is underway. Preliminary operation of the system is expected to occur during the Spring of 1993. Measurements to investigate the dynamics of continuum-electron emission associated with electron capture, electron loss, or no charge change, respectively, will be conducted for bare and nearly bare MeV/u ions with atomic numbers ranging from 1 to about 20.

Ph.D. theses: This work constitutes part of the Ph.D. dissertation research of Ms. Vicki Plano and Mr. Ming Zhu.

D. Other Studies

In addition to the three principal areas of investigation discussed above, certain other studies were conducted:

1. Radiative Auger Emission from Lithiumlike Ions

In the radiative Auger effect (RAE), inner-shell vacancy filling is accompanied by the simultaneous emission of a photon and the ejection of an electron into the continuum. Relatively large probabilities for RAE in comparison with $K\alpha$ emission (ranging from ~ 4% to ~ 12% with increasing Z) are observed for Li-like S^{13+} , Ca^{17+} , V^{20+} , and Fe^{23+} ions excited in collisions with He or H_2 . These results are shown in Fig. 12. The origin of the

Fig. 12. Ratios of the RAE yield to $K\alpha$ yield vs. Z . Symbols are as follows: (●) Li-like ions excited in He targets; (Δ) Li-like ions excited in H_2 targets; (○) experimental values for few-vacancy ions. The solid curve gives theoretical "shakeoff" values for few-vacancy ions. See Ref. 23 for key to experimental and theoretical data.

increase in the relative RAE yield is not understood since it is expected that the excitation of various intermediate states would be nearly independent of Z in the range of atomic numbers investigated. A possible explanation for the observed Z dependence is that most of the RAE emission is from metastable states, but additional experimental and theoretical work is needed to verify this.

Publications resulting from this work:

"Enhanced Radiative Auger Emission from Lithiumlike 16S^{13+} ," E. M. Bernstein, M. W. Clark, C. S. Oglesby, J. A. Tanis, W. G. Graham, R. H. McFarland, T. J. Morgan, B. M. Johnson, and K. W. Jones, Phys. Rev. A **41**, 2594 (1990).

"Enhanced Radiative Auger Emission from Lithiumlike 20Ca^{17+} ," E. M. Bernstein, M. W. Clark, J. A. Tanis, W. G. Graham, T. J. Morgan, M. P. Stockli, K. H. Berkner, A. S. Schlachter, and J. W. Stearns, Z. Phys. D **21**, S231 (1991).

"Semi-Auger Process in Heavy Lithiumlike Ions," E. M. Bernstein, Proceedings of Energiereiche Atomare Stosse, Riezlern, Austria, 28 January - 1 February 1991.

2. Target Z-Dependence of Nonresonant Transfer Excitation (NTE)

Nonresonant transfer excitation (NTE)²⁴ occurs in an ion-atom collision when projectile excitation and electron capture take place independently in a single collision encounter. In work done at Western Michigan, NTE has been investigated for 20-70 MeV S^{13+} colliding with He, Ne, and Ar by measuring K x-ray emission associated with projectile-electron capture. In these collisions, NTE occurs by means of projectile K-shell excitation accompanied by electron capture to the L-shell resulting in the formation of a doubly-excited intermediate state. Previously, NTE was investigated in detail for $\text{S}^{13+} + \text{He}$ collisions.²⁵ The present measurements for Ne and Ar targets were conducted in order to establish the target Z-dependence of NTE, while the present measurements for $\text{S}^{13+} + \text{He}$ were made to ensure consistency with the earlier work. For the Ne and Ar targets, it was found that the maximum cross sections for NTE occur at about 50 MeV and 60 MeV, respectively, compared to a maximum NTE cross section at 30 MeV for He; this result is shown in Fig. 13. Furthermore, the maximum values of the NTE cross sections in Ne and Ar are nearly equal ($\sim 5 \times 10^{-20} \text{ cm}^2$) and about 50 times larger than the maximum NTE cross section in He ($\sim 1 \times 10^{-21} \text{ cm}^2$).

Fig. 13. Position of the NTE cross section maximum as a function of the target atomic number for S^{13+} + He, Ne, and Ar.

M.A. thesis: This work constitutes the M.A. thesis research of Mr. Liang Duo (expected completion, April 1993).

3. Ionization of H_2

Single and double ionization of molecular hydrogen by 0.5-2.5 MeV/u O^{7+} ions were studied at Western Michigan. The charge state of the projectile after the collision was measured in coincidence with the recoiling target ions to yield information about the collisions at different ranges of impact parameters. In the case of double ionization, the Coulomb explosion of the molecule imparts an additional velocity to the resulting protons. This effect, in conjunction with the detector geometry, allows protons from double ionization to be differentiated from those associated with single ionization. These measurements are used to obtain relative cross sections and ratios for the yields of H_2^+ , $H^0 + H^+$, and $2H^+$.

M.A. thesis: This work constitutes the M.A. thesis research of Ms. Beverly Carroll (expected completion August 1993).

4. Triple Ionization of Lithium

Closely related to the study of double ionization (see Section II.B) is triple ionization. This latter process can provide insight into the probability 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 oven which will be used to

provide a Li vapor jet target with which we plan to measure the triple ionization of lithium by protons and other ions. A preliminary design was already constructed and tested, but the operating characteristics were not acceptable. Construction of an improved design is currently underway.

M.A. thesis: This work constituted the M.A. thesis research of Mr. Oliver Voitke (awarded August 1992).

Ph.D. thesis: Future work on this project will constitute the Ph.D. dissertation research of Mr. Oliver Voitke.

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III. PUBLICATIONS AND PRESENTATIONS

Publications - in print

1. "Enhanced Radiative Auger Emission from Lithiumlike 16S^{13+} ," E. M. Bernstein, M. W. Clark, C. S. Oglesby, J. A. Tanis, W. G. Graham, R. H. McFarland, T. J. Morgan, B. M. Johnson, and K. W. Jones, *Phys. Rev. A* **41**, 2594 (1990).
2. "Origin of Cusp Electrons in Slow ($v \sim 0.4$ a.u.) $\text{O}^{6+} + \text{He}$ Collisions," J. A. Tanis, D. Schneider, S. Chantrenne, M. H. Prior, R. Herrmann, R. Hutton, and G. Schiwietz, *Phys. Rev. A* **42**, 5776 (1990).
3. "Resonant Transfer and Excitation for U^{90+} Projectiles in Hydrogen," W. G. Graham, K. H. Berkner, E. M. Bernstein, M. W. Clark, B. Feinberg, M. A. McMahan, T. J. Morgan, W. Rathbun, A. S. Schlachter, and J. A. Tanis, *Phys. Rev. Lett.* **65**, 2773 (1990).
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1. "Cusp Electron Production in 75-300 keV He^+ + Ar Collisions," V. L. Plano, L. Sarkadi, P. Závodszky, D. Berényi, J. Pálincás, L. Gulyás, E. Takács, L. Toth, and J. A. Tanis, AIP Conference Proceedings, M. Stockli and P. Richard eds., (American Institute of Physics, New York, 1993).
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4. "Testing Double Ionization Mechanisms with Highly-Charged Ions," J. A. Tanis, AIP Conference Proceedings, M. Stockli and P. Richard eds., (American Institute of Physics, New York, 1993).
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Invited Presentations

1. "Electron-Electron Interactions in High Velocity Collisions," J. A. Tanis, US-Japan Seminar on Excitation by Exotic and Highly Charged Ions, Anchorage, Alaska, 18-22 June 1990.
2. "Transfer Excitation in Ion-Atom Collisions," J. A. Tanis, Fifteenth International Conference on X-Ray and Inner-Shell Processes, Knoxville, Tennessee, 9-13 July 1990, Program and Book of Abstracts, p. S23.

3. "Resonant Recombination in Ion-Atom Collisions," J. A. Tanis, 4th Workshop on High-Energy Ion-Atom Collision Processes, Debrecen, Hungary, 17-19 September 1990, Abstracts, pp. 7-8.
4. "Atomic Physics at the IUCF Cooler Storage Ring," J. A. Tanis, Eleventh International Conference on the Application of Accelerators in Research and Industry, Denton, Texas, 5-8 November 1990; Bull. Am. Phys. Soc. 35, 1761 (1990).
5. "Double Ionization of Helium by Intermediate to High-Velocity He^+ , $\text{O}^{6,7+}$, and $\text{S}^{6,13+}$ Ions," J. A. Tanis, Third US-Mexico Atomic and Molecular Physics Workshop, Cocoyoc, Mexico, 13-16 March 1991.
6. "Dielectronic Recombination of He^+ Ions," R. R. Haar, XIIth International Seminar on Ion-Atom Collisions, Gold Coast, Queensland, Australia, 18-19 July 1991.
7. "Resonant Transfer and Excitation Associated with Single X-Ray Emission," J. A. Tanis, NATO Advanced Research Workshop on Recombination of Atomic Ions, Newcastle, Northern Ireland, 6-9 October 1991.
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9. "Testing Double Ionization Collision Mechanisms with Highly-Charged Ions," J. A. Tanis, VIth International Conference on the Physics of Highly-Charged Ions, Manhattan, Kansas, 28 September-2 October 1992, Book of Abstracts, p. I-14.
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Contributed Presentations

1. "Resonant Transfer and Excitation in Collisions of Highly Charged Ions with Atoms," W. G. Graham, J. A. Tanis, M. W. Clark, E. M. Bernstein, R. D. DuBois, T. J. Morgan, A. S. Schlachter, M. P. Stockli, V. L. Plano, and N. Badnell, 1st National Conference on Atomic, Molecular, and Optical Physics, Belfast, Northern Ireland, 2-5 April 1990.

2. "Cross Sections for Resonant Transfer and Excitation in $\text{Fe}^{9+} + \text{H}_2$ Collisions," J. A. Tanis, M. W. Clark, E. M. Bernstein, W. G. Graham, R. D. DuBois, T. J. Morgan, A. S. Schlachter, L. Blumenfeld, L. Ferrand, M. P. Stockli, V. L. Plano, and N. Badnell, Division of Atomic, Molecular, and Optical Physics Meeting of the American Physical Society, Monterey, California, 21-23 May 1990; Bull. Am. Phys. Soc. 35, 1144 (1990).
3. "Double Ionization of Helium by Fast He^+ Projectiles," J. L. Forest, J. A. Tanis, M. W. Clark, S. M. Ferguson, K. Lifrieri, and V. L. Plano, 12th International Conference on Atomic Physics, Ann Arbor, Michigan, 29 July-3 August 1990, Abstracts of Contributed Papers, X-15.
4. "Dielectronic Recombination in He^+ Ions," J. A. Tanis, E. M. Bernstein, S. Chantrenne, M. W. Clark, T. Ellison, C. C. Foster, W. G. Graham, W. W. Jacobs, J. R. Mowat, T. Rinckel, A. Ross, D. Schneider, and M. P. Stockli, Vth International Conference on the Physics of Highly-Charged Ions, Giessen, Germany, 10-14 September 1990, Book of Abstracts, 2.8.
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23. "Double Ionization of Helium by Intermediate-to-High-Velocity Projectiles," J. A. Tanis, R. D. DuBois, and A. S. Schlachter, Division of Atomic, Molecular, and Optical Physics Meeting of the American Physical Society, Chicago, IL, 20-22 May 1992; Bull. Am. Phys. Soc. 37, 1106 (1992).
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IV. PERSONNEL

A. Co-Principal Investigators

John A. Tanis	- Professor and Chair, Department of Physics
Eugene M. Bernstein (retired Jan. 1992)	- Professor, Department of Physics

B. Professional Research Staff

Dr. Roger R. Haar	- Research Associate
Dr. Stephen M. Ferguson	- Accelerator Physicist

C. Technical Support Staff

Mr. Robert Hiltbrand	- Electronics Technician
Mr. Tyrone Bynum	- Electronics Technician
Mr. James Cornell	- Instrument Maker

D. Graduate Students

Ms. Beverly Carroll	- M.A., expected completion August 1993
Mr. Liang Duo	- M.A., expected completion April 1993
Ms. Jun Forest	- M.A., June 1991
Mr. Anwar Kamal	- M.A., December 1991
Ms. Karen Lifrieri	- M.A., April 1992
Ms. Vicki Plano	- Ph.D.
Mr. Oliver Voitke	- Ph.D.
Mr. Konstantinos Zaharakis	- M. A., June 1991; currently working on Ph.D.
Mr. Ming Zhu	- Ph.D.

E. Undergraduate Students

Ms. Layle Griffioen
Mr. Corey Leon

V. BRIEF OVERVIEW OF FUTURE PLANS

The primary emphasis in all of our work is the study of two-electron processes occurring in atomic collisions, and, in particular, the determination of the importance of the electron-electron interaction. In the past the central focus of our work has been the study of resonant recombination, namely resonant transfer excitation (RTE) and dielectronic recombination (DR). Over the past couple of years, however, our emphasis has been shifting toward studies of multiple ionization and continuum-electron emission. In connection with this latter area, it is noted that a U.S. DOE grant in the amount of \$102,750 has been received from the University Research Instrumentation Program, along with additional matching funds in the amount of \$34,250 from Western Michigan University, for the construction of a sophisticated electron spectrometer system at WMU. This apparatus will be used to study the dynamics of two-electron processes involving continuum-electron emission. Additionally, a grant in excess of \$45,000 has been received from the U.S.-Hungarian Science and Technology Program to carry out an international collaborative research effort on continuum-electron emission with Professor Dénes Berényi of the Institute of Nuclear Research, Debrecen, Hungary.

END

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