3. PROGRESS REPORT

A. ATOMIC PHYSICS WITH HIGHLY CHARGED IONS: EXPERIMENT

A.1. Electron and X-Ray Production in Ion-Atom Collisions

A.1.1. Double Differential Cross Sections for Ionization of Atomic Hydrogen and Helium by High Velocity, Highly Charged Ions--*Patrick Richard and Lokesh Tribedi*

During the time period since our last proposal we completed a study of the production of low energy electrons emitted in the ionization of atomic H and He. We reported the first measurement of the double differential cross section of atomic H by highly charged ions and compared to calculations based on the Born approximation, B1, and on the continuum distorted wave eikonal initial state approximation, CDW-EIS. We also presented results for the ionization of He by bare carbon ions. We used the transformation scheme previously developed to obtain cross sections differential in longitudinal momentum of the electron, the recoil ion and the projectile. The results of these three works are briefly described below.

Double differential distributions of electron emission in a pure three-body collision: ionization of atomic hydrogen by highly charged ions.

The double differential ionization cross-sections, DDCS, for a pure three-body collision system can provide stringent tests to the most sophisticated theories on ionization. DDCS measurements for atomic H have been carried out for low charged projectiles such as electrons [1], protons [2], and helium ions [3], but no such measurements exist for highly charged ions. Because of the high charge of the projectile, the ejected electron spectra are strongly influenced by the two-center Coulomb potential and by the post-collision interactions. The theoretical method based on the continuum distorted-wave eikonal initial state, CDW-EIS, approximation has been developed [4] to explain the two-center effects on electron emission in a three-body collision. These two-center effects are expected to be largest at low collision velocity.

Bare carbon ions of energy 30 MeV were obtained from the tandem Van de Graaff accelerator and were bombarded on an atomic H jet of gas emitted from an RF source developed by Slevin and Sterling [5]. A dissociation fraction of approximately 80% was achieved with the source. The fraction was determined by measuring the intensity of the ~9 eV proton peak with the RF on and off.

The DDCS for atomic hydrogen was based on the DDCS we measured for H_2, which was reported in our last progress report [6], by measuring the electron yields with the RF on and off.

The procedure is described in Publication #33. The results of this work are best summarized by the data presented in Fig. 1. The lower figure has the single differential cross section as a function of angle. The post collision effects as described by the CDW-EIS gives rise to a large forward backward asymmetry, which is not present in the B1 theory (labeled FBA). The data show fairly good agreement with the CDW-EIS in the SDC, which indicates that post collision effects exist even at these high collision velocities. The DDCS for different energy electrons are shown in the upper part of the figure and show small disagreements with the CDW-EIS.

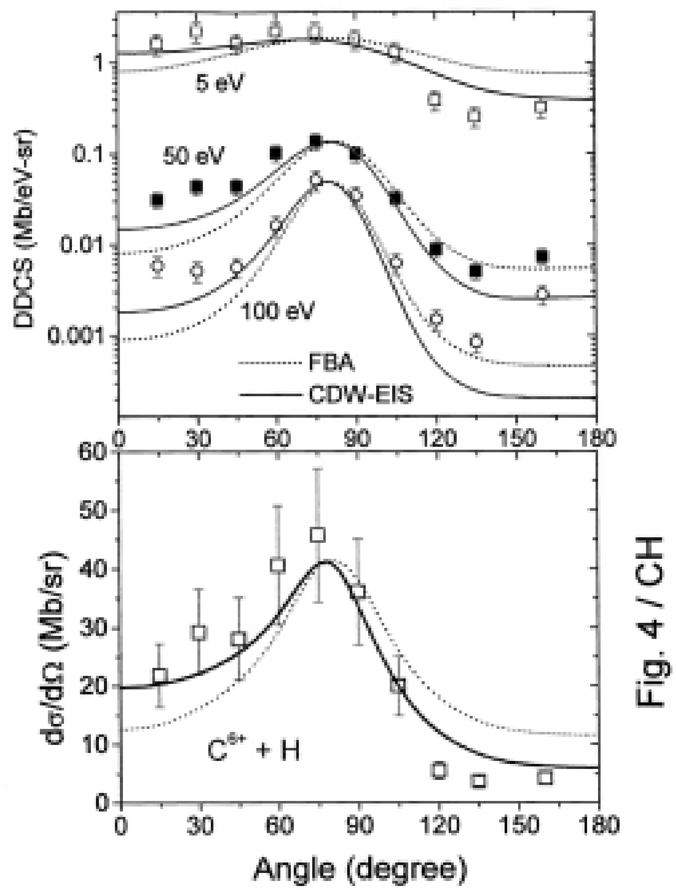

Figure 1. The DCCS for ionization of H by 2.5 MeV/u C^{6+} ions for different electron energies. The lower figure gives the angular distribution (SDC in Mb/sr) for electron emission. The CDW-EIS and the B1 or FBA predictions are also given for comparisons.

<u>This work is presented in:</u>

Pub. #1: "Double Differential Cross Section for Soft Electron Emission in Ionization of Hydrogen by Bare Carbon Ions," L.C. Tribedi, P. Richard, D.Ling, B. DePaola, Y.D. Wang, L. Gulyas, C.D. Lin and M.E. Rudd, Physica Scripta T <u>73</u>, 233 (1997).

Pub. #33: "Double Differential Distributions of Electron Emission in a Pure Three-body Collision: Ionization of Atomic Hydrogen by Highly Charged Ions," L.C. Tribedi, P. Richard, W. DeHaven, L. Gulyas, M.W. Gealy, and M.E. Rudd, J. Phys. B: At. Mol. Opt. Phys. 31**,** L369 (1998).

Ionization dynamics in fast ion-atom collisions. I. Energy and angular distributions of low-energy electrons emitted in ionization of He by bare carbon ions.

Ionization is one of the most important reactions in high-energy ion-atom collisions. The low-energy electrons are emitted with the largest probability. The measurement of these electrons' cross sections, differential in energy and emission angle, could provide crucial information on ionization dynamics. We have studied the two-center effect, TCE, in ion-atom ionization by measuring the energy and angular distributions of the double-differential cross sections of the low-energy electrons emitted in a collision of He atoms with 2.5 MeV/u C^{6+} ions. The electrons with energies between 0.1 and 300 eV were detected for 13 different emission angles between 15º and 160º. From the measured DDCSs we have deduced the single differential cross sections and the total cross section. The data have been compared with the continuum CDW-EIS with H-like and Hartree-Fock-Slater wave functions for the initial and final state of the electron [7].

The results of these measurements are typified by the DDCS for different energy electrons as shown in Fig. 2, and by the SDCs shown in Figs. 3 and 4. As in the case of C^{6+} on H discussed above, the data show a backward-forward asymmetry which is predicted by the CDW-EIS but not by the B1. The effect is 40% and is similar to the effects seen in the atomic H data. We take this as evidence of TCE. A more stringent test is a comparison of the experimental and theoretical DDCS. This comparison shows some disagreement between experiment and theory for electron emission at the forward and the backward directions.

This work is presented in Publication #51, "Ionization dynamics in fast ion-atom collisions. I. Energy and angular distributions of low-energy electrons emitted in ionization of He by bare carbon ions," L.C. Tribedi, P. Richard, Y.D. Wang, C.D. Lin, L. Gulyas, and M.E. Rudd, Phys. Rev. A 58**,** 3610 (1998).

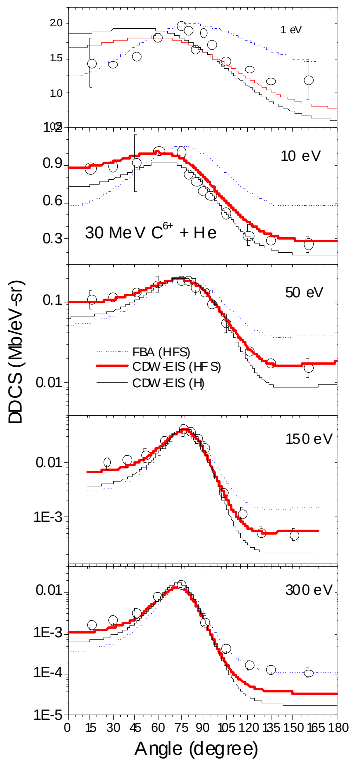

Figure 2. DDCS (Mb/eV-sr) of electrons for a few fixed electron energies in 30 MeV C^{6+} + He collisions. The thick solid, thin solid and dotted lines represent the CDW-EIS(HFS), CDW-EIS(H), and B1 calculations respectively.

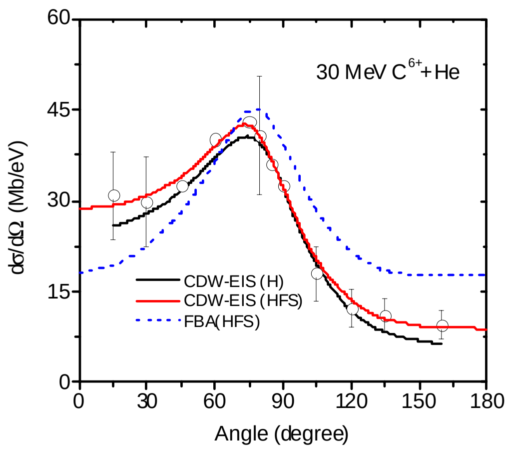

Figure 3. SDC (Mb/sr) for the same system as above and same symbols.

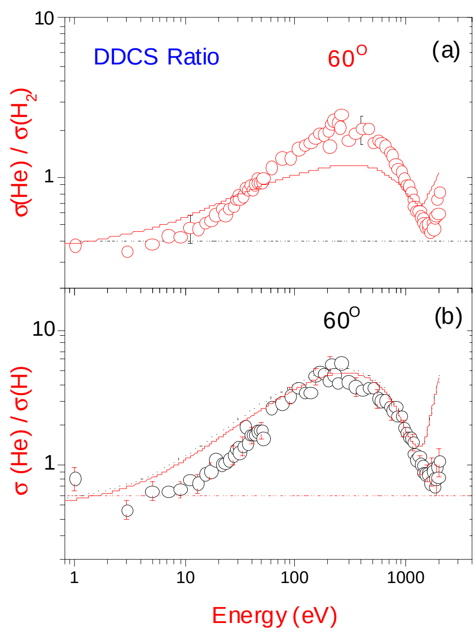

Figure. 4 Ratio of the DDCS for He to that of H_2 and for He to that of H for σ = 60º.

Ionization dynamics in fast ion-atom collisions. II. Final-State Momentum distributions of the Ionization Products in Collisions of He with Bare Carbon Ions

We have used the energy and angular distributions of the low-energy electron emission cross sections from the preceding section [Publication #51, Lokesh C. Tribedi, *et al.*, Phys. Rev. A 58, 3619 (1998)] to derive the doubly differential final-state longitudinal momentum distributions of the electrons, recoil ions, and projectiles in ion-atom ionization for C^{6+} + He. The complementary natures of electron spectroscopy and recoil-ion momentum spectroscopy have been investigated using a formulation based on three-body kinematics to explore the ionization dynamics in detail. The influence of the three-body ionization as well as the binary-encounter processes on the recoil-ion (and projectile) longitudinal momentum distributions has been investigated. The separation of the soft- and hard-collision branches of recoil-ion distributions is an important feature of the present technique. The present method also allows one to determine cross sections for very large electron momenta. The single-differential distributions are also derived by numerical integration of the double-differential distributions. The first Born approximation, the continuum distorted-wave eikonal initial state, and the classical trajectory Monte Carlo calculations are compared with the data.

Figure 5 shows the results of the calculation of the double differential longitudinal momentum distributions of electrons and recoil ions for forward angle emitted electrons. Similar results were obtained for all angles of emission. The transformation uses the DDCS for electron emission and the transformation equations based on the kinematics of the recoil ion, electron and projectile in small angle scattering (for details see Publication #52). The CTMC calculation for electron and recoil distributions $d^2\sigma/dp_{||}d\Omega_e$ are shown for comparisons. The 45º spectrum is particularly interesting in that it shows two branches in the recoil ion distribution. This effect had not been seen in any previous experiment.

This work is presented in Publication. #52, "Ionization Dynamics in Fast Ion-atom Collisions. II. Final-State Momentum distributions of the Ionization Products in Collisions of He with Bare Carbon Ions," L.C. Tribedi, P. Richard, Y.D. Wang, C.D. Lin, R.E Olson, and L. Gulyas, Phys. Rev. A 58**,** 3626 (1998).

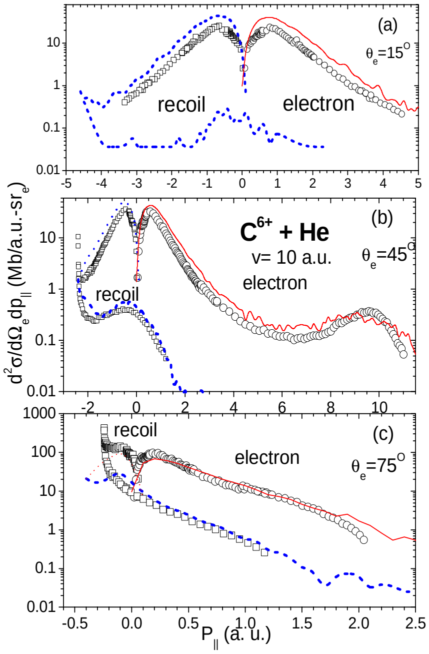

Figure 5. Double differential longitudinal momentum distributions of electrons (open circles) and recoil ions (open squares) for forward angles: (a) σ_e = 15º, (b) σ_e = 45º and σ_e = 75º. The thick solid (dotted) line is for the CTMC calculation for electron (recoil) distributions.

References

1. T. W. Shyn, Phys. Rev. A45, 2951 (1992).
2. M.W. Gealy, G.W. Kirby III, Y-Y. Hsu, and M.E. Rudd, Phys. Rev. A51**,** 2247 (1995).
3. Y-Y. Hsu, M.W. Gealy, G.W. Kirby III, and M.E. Rudd, Phys. Rev. A53**,** 297 (1996).
4. D.S.F. Crothers and J.F. McCann, J. Phys. B: At. and Mol. Opt. Phys. 16, 3229 (1983); P.D. Fainstein, V.H. Ponce, and R.D. Rivarola *ibid.*, 24, 3091 (1991).
5. J. Slevin and W. Sterling, Rev. Sci. Instrum. 52, 1780 (1992).
6. L.C. Tribedi, P. Richard, D. Ling, Y.D. Wang, C.D. Lin, R. Moshammer, G.W. Kirby III, M.W. Gealy, and M.E. Rudd, Phys. Rev. 54, 2154 (1996).
7. L. Gulyas, P.D. Fainstain, and A. Salin, J. Phys. B 28, 245 (1995).