**Structure and Dynamics of Atoms, Ions, Molecules, and Surfaces:**
**Mechanisms for Transfer Ionization in High Z Ions on He**

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The scope of the JRML research program is to study experimental and theoretical problems in ionic and photonic collisions with atoms, ions, molecules, laser cooled atoms, laser excited atoms, and surfaces. The experimental program is based on the study of collision physics using ion accelerators and laser systems in the J. R. Macdonald Laboratory, and the ALS synchrotron facility at Berkeley. The goal is to provide fundamental understandings of energy, momentum and charge transfer in interactions where one or more electrons and/or nuclear charge centers of the system are disrupted. This abstract presents recent progress and future plans in one of the experimental research projects. I. Ben-Itzhak, C. L. Cocke, B. D. DePaola and S. Hagmann present abstracts on other subjects in our experimental research program and can be found in these proceedings. Abstracts on subjects in our theoretical research program are presented by C. D. Lin, U. Thumm and B. D. Esry and also can be found in these proceedings.

## Recent progress and future plans:

### Mechanisms for Transfer Ionization in High Z Ions on He:

(R. Unal, P. Richard, I. Ben-Itzhak, C. L. Cocke, C. D. Lin, and H. C. Tseng) The process of removing two electrons from He by a charged ion has been studied for several years.[1-3] One of the interesting questions is the behavior of the transfer ionization process, TI, in which the projectile captures one of the electrons and the other is emitted to the continuum. Several features existing in the data are not understood to date[4] and to add intrigue to the problem, recent new data on $H^+$ + He showed a completely unexpected result[5] at collision velocities above 4.0 au. Below 4 au the ratio of TI-to-single electron capture, SC, is flat at a value of ~2.5%. The new results showed the ratio linearly increasing with velocity up to a value of ~4.4% in the range of 4.0 to 7.5 au. It was expected that the ratio would slowly fall with increasing velocity to the shake-off value of ~1.6%. The shake-off value is defined as the probability that a second electron will be lost by the He ion in its final state readjustment following SC. The electron emission is due to the incomplete overlap of the wave function of the intermediate $He^+$ state with that of the $He^+$ ground state. We have studied the TI/SC ratio for high velocity highly charged ions on He at velocities in the range of 6 to 10 au and observed, conversely, that the ratio is monotonically decreasing with velocity.[6] If we assume that the two-electron removal from He is occurring by independent interactions with the projectile, the ratio of TI-to-SC is expected to vary as $Z^2$, where Z is the projectile charge. Using this assumption, we can compare our results for $F^{9+}$ projectiles to that of $H^+$ on He by using the appropriate scaling.

A comparison of the different data sets is shown in Fig. 1. The low velocity data (V ~ 2 to 4 au) from Shaw and Gilbody *et al*.[1] for $H^+$ + He are shown as solid squares, the new higher velocity data (V ~ 4.5 to 7 au) from Mergel *et al*.[5] are shown as solid squares and the $F^{9+}$ + He data from Unal *et al.*[6] are shown as solid circles. The plotted $F^{9+}$ data are $R(scaled) = \frac{R(measured) - R(shake)}{Z^2} + R(shake)$, where R(shake) is taken as the theoretical value. This formula is used since the shake-off limit is independent of projectile Z.

This was the status of the TI/SC ratio until a few weeks ago, when Schmidt *et al.*[7] extended the $H^+$ + He measurements to higher velocity (V ~ 10 to 14 au) using the storage ring at Stockholm. Their results were reported at ICPEAC 2001 in Santa Fe this summer and are given in Fig. 1 as solid squares. The value of the ratio is observed to decrease from ~4 % to ~3% with velocity in the range of 10 au to 17 au. These latter results compare favorably with the behavior of our $F^{9+}$ data. Earlier $F^{9+}$ + He results from Shinpaugh *et al.*[2] show a turnover at lower energies similar to the $H^+$ + He data at about 7 au. These data were not taken with the COLTRIMS method used by Mergel *et al.*,[5] Unal *et al.*,[6] and Schmidt *et al.*[7] and suffer from fairly large errors. For this reason they are not used in the comparison, however those data are very suggestive of a favorable comparison between the velocity dependence of $H^+$ + He to a scaled $F^{9+}$ + He assuming an independent electron model. This suggests that we attempt the difficult measurements of $F^{9+}$ + He at velocities below 6 au using our COLTRIMS apparatus. C. D. Lin and H. C. Tseng have performed coupled channel calculations for the energy dependence of TI and SC for $F^{9+}$ + He and find values slightly higher than our measured values, but with approximately the same energy dependence. We show this calculation scaled with the same formula as used for the experimental data. One of the difficulties of performing accurate calculations is the large basis set needed to properly describe the collision system.

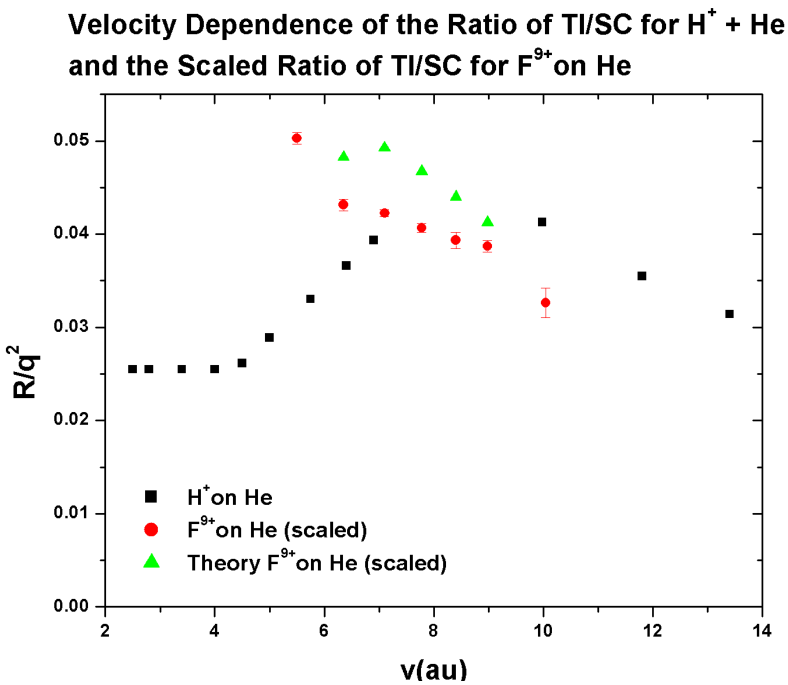

Fig. 1 Transfer Ionization to Single Capture Ratio

The TI process can proceed via two independent e-projectile ion interactions as discussed above [sometimes referred to as kinematical TI or TS2(two-step, two e-nuclear interactions)] or it can proceed via the Thomas scattering mechanism [sometimes referred to as e-e Thomas TI of TS1(two-step, one e-nuclear interaction)]. The Thomas scattering mechanism transfers little momentum to the recoiling target nucleus, whereas kinematical SC transfers longitudinal momentum to the recoiling target nucleus. The same holds true for the corresponding TI processes. By using COLTRIMS one can separate the two TI processes based on the observed longitudinal momentum transfer to the recoiling target ion. Schmidt *et al.*[7] has done this for $H^+$ + He and reported that the e-e Thomas TI is 35% of the total TI. The e-e Thomas TI scattering becomes negligible for high Z projectiles due to the $Z^2$ scaling expected for the kinematical TI. The resulting kinematical TI/SC ratio for $H^+$ + He then compares very favorably with the scaled TI/SC ratio for $F^{9+}$ + He in Fig. 1.

The other question that we have addressed with the TI/SC ratio is the projectile q dependence for projectiles greater than q=9. The big unanswered question here is the sudden fall in the TI/SC ratio for values of q above q = 20, as reported by Datz *et al.*[8] We have extended our studies[3,4] to new measurements for Si, Ti, and Cu as shown in Fig 2. We see a ratio that follows a $q^2$ dependence up to approximately q = 9. Above q = 9 the experiment exceeds the $q^2$ dependence prediction due to antiscreening. The new data go only up to q = 20 and show a smooth monotonically increasing TI/SC ratio. The inverted triangles are data for $Ti^{15+}$ and $Ti^{18+}$ from Montenegro *et al.*[3] The new data points for $Ti^{15,17,18+}$ have smaller errors, and when combined with the $Cu^{18,20+}$ reflect a more gently increasing behavior than might be inferred from the earlier Ti data. Our plan to complete this phase of the experiment is to push the charge state measurements up to q = 30 in order to overlap with the high q data of Datz *et al.*,[8] which showed TI/SC ratios of approximately 2, which is 5 times smaller than our TI/SC ratio for q = 20.

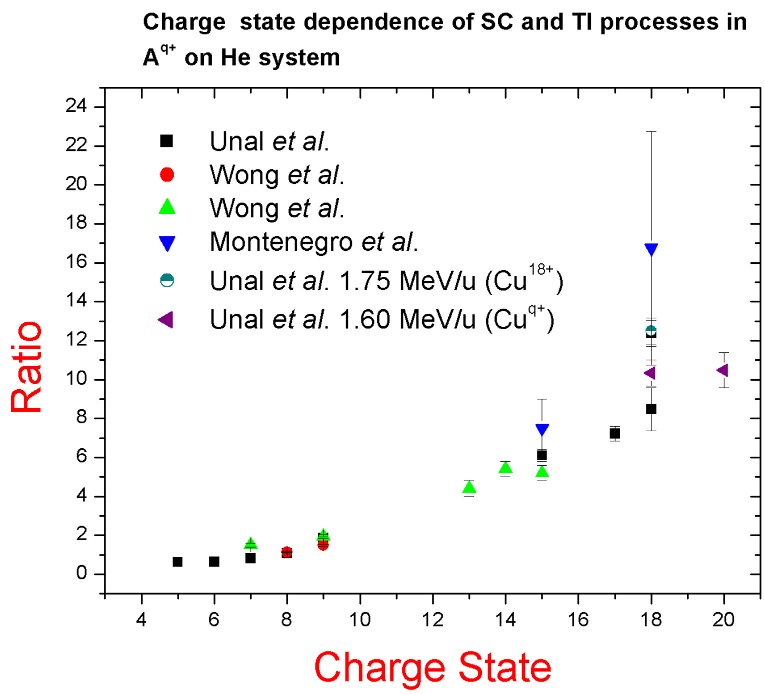


Fig. 2 Charge Dependence of TI to SC Ratio

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