# Structure and Dynamics of Atoms, Ions, Molecules, and Surfaces: MOTRIMS: A New Tool for the Dynamical Study of Atoms interacting with Their Environment

*B. D. DePaola, Department of Physics, Kansas State University*
*Manhattan, KS 66506; depaola@phys.ksu.edu*

This abstract reports the progress and future plans of the MOTRIMS project, which is only one part of the J. R. Macdonald Laboratory's overall AMO program. The personnel involved in this project include Dr. C. Fehrenbach (Research Associate Professor), Dr. X. Flechard (Research Associate), and H. Nguyen (Graduate Student).

**Recent progress and future plans:**

**MOTRIMS: A new tool for the dynamical study of atoms interacting with their environment:**
Over the past few years, the COLd Target Recoil Ion Momentum Spectroscopy (COLTRIMS) technique has come into its own.[1,2] In this technique ionization processes of atoms and molecules are studied through the reverse kinematics approach of measuring the recoiling target's momentum vector. For this approach to give meaningful results, the momentum received by the target in its interaction must be large compared to its thermal momentum distribution. In COLTRIMS this condition is accomplished by cooling the target atoms or molecules, and then introducing the target into the interaction region *via* a supersonic expansion. The recoil ion momentum vector is measured by extracting the recoils using an electric field, and measuring their flight times and final positions. In an ion-atom collision, the component of the momentum lying perpendicular to the projectile axis is simply related to the projectile scattering angle, while the momentum component lying parallel to the projectile axis is simply related to the Q-value, or difference in the electron's initial and final binding energies. In general, because an electric field is used to extract all of the recoil ions, COLTRIMS is extremely efficient, having $4\pi$ steradian acceptance angle and nearly unity detection efficiency. Using the COLTRIMS technique, several different ionizing interactions of atoms and molecules have been studied, including electron- and ion-impact ionization of atoms and molecules, ion-induced dissociative ionization, and photo-ionization.

A recent variation on the COLTRIMS method is MOTRIMS, for Magneto Optically Trapped Recoil Ion Momentum Spectroscopy. In this approach, the target atoms are optically cooled and confined in the interaction region. The extraction and measurement methods are identical to COLTRIMS. MOTRIMS brings with it two main advantages over COLTRIMS. The first is that atoms can be cooled to a much lower temperature in a MOT than through supersonic expansion. Therefore, while in COLTRIMS the ultimate limitation in resolution is due to target temperature, in MOTRIMS the limit is due to position and timing resolution. Thus for example, the best COLTRIMS momentum resolution reported in the literature[1] is 0.06 atomic units for a helium target, whereas in our MOTRIMS setup we have obtained 0.03 atomic units for a rubidium target. (In principle, the more massive the target the *worse* the momentum resolution, all else being equal. Thus one might expect even better momentum resolution with trapped lithium atoms.)

The second, and perhaps more significant, advantage of MOTRIMS is that the trapped atoms are of necessity accessible to optical excitation by lasers. In COLTRIMS, by contrast, the atoms which are most easily pre-cooled to very low temperatures and then expanded, are the noble gasses and simple molecules. Indeed, among this reduced set of possible targets, only helium comes close to allowing a momentum resolution even close to that possible with a typical MOTRIMS target. Nevertheless, there are many cases in which the conventional COLTRIMS technique is still superior to MOTRIMS. For example, it is not yet technically feasible to trap and cool a sufficient number of molecules to be useful as a target.

The remainder of this abstract addresses progress which has been made in the K-State MOTRIMS project, and includes a discussion of what studies we intend to pursue in the near future. The initial MOTRIMS experiment attempted was a charge transfer study in the $Cs^+$ + Rb(5s), Rb(5p) collision system.[3] Because the trapping laser was tuned to the 5s-5p transition, the target was a mixture of 5s and 5p states. Far from being a disadvantage, this circumstance allows for the simultaneous measurement of capture cross sections from *both* the 5s and 5p states. The key to this measurement is the MOTRIMS method's extraordinary Q-value resolution of 100 meV for this collision system. This allowed us to distinguish between capture from the two initial states, as well as the final states in the Cs into which the electron is captured. For each of these charge transfer channels we were able to measure the cross sections, differential in scattering angle to a resolution of 25 microradians. Thus these cross sections, differential in angle, and final and initial state provide theory with useful test values against which to test calculation. A typical Q-value spectrum and scattering angle plot are shown in Figure 1.

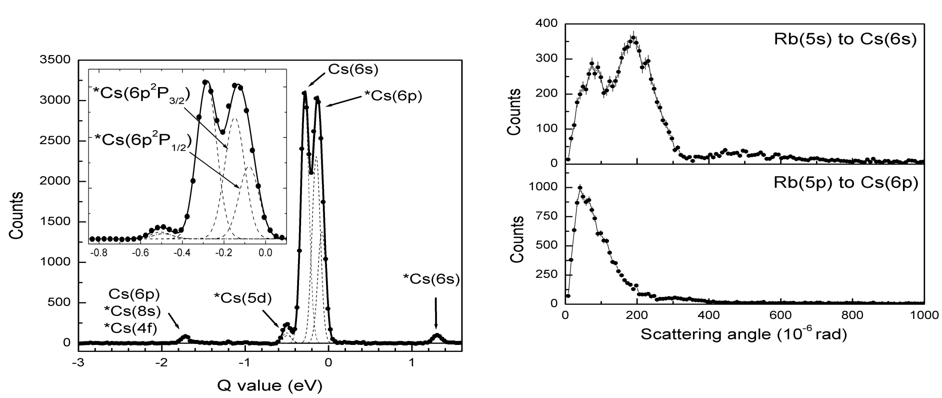


**Figure 1 Q-Value and scattering angle spectra**

What remains to be done along these lines is to continue the cross section measurements for a variety of alkali and alkali earth projectiles throughout a range of collision velocities. This will be efficiently accomplished through the use of only two different thermionic ion sources, one which outputs beams of $Li^+$, $Na^+$, $K^+$, $Rb^+$, and $Cs^+$, and the other which outputs beams of $Mg^+$, $Ca^+$, $Sr^+$, and $Ba^+$. Rather than mass select these ions and carry out charge transfer experiments one element at a time, we intend to allow all of the ions species to participate in collision events at the same time. This is possible since the time-of-flight measurements easily distinguish between the different mass projectiles. Proof of principle for this mode of data acquisition has already been carried out using a $Na^+$ source which (inadvertently) contained a contamination of $K^+$. Besides having the obvious time advantage of massive multiplexing, this mode has the practical advantage of allowing us to compare on a *single relative scale* the charge transfer cross sections for all the different alkali (or alkali earth) ions.

The second line of experiments which on which we have begun using the MOTRIMS apparatus involves the use of a second laser to excite the rubidium from 5p-4d. $Na^+$ ions are then used to probe the resulting mixture of states *as a function of time* as the second laser is blinked on and off. Remarkably, the same resolution in Q-value that allows one to distinguish between various initial and final state channels, also allows one to separately determine the relative level populations and the relative charge exchange cross sections. That is, in the same measurement we are able to determine $n_d/n_s$,$n_p/n_s$, $\sigma_d/\sigma_s$, and $\sigma_p/\sigma_s$, where $n_i$ and $\sigma_i$ the population and transfer cross sections, respectively, of the $i^{th}$ target state. This is possible since while the relative populations of the states vary on the tens of nsec time scale, the total target population remains constant on the ms time scale. Thus, the MOTRIMS apparatus used in this time-dependant mode can be seen as either a tool to measure relative cross sections from the various levels in a (laser-excited) MOT, or equally well as a technique which uses the ion beam as a diagnostic to study the dynamic development of the relative populations of the different levels in the MOT. The time dependant capture signals are represented in Figure 2.

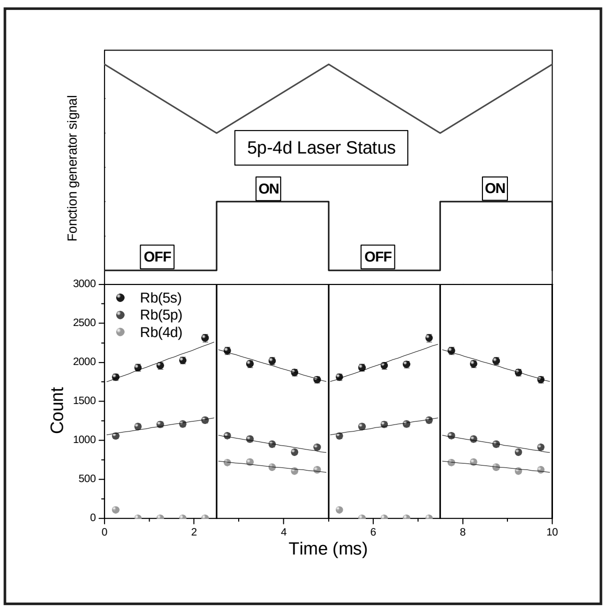


**Figure 2 Time dependance of capture signals**

The triangle wave is synchronous with the square wave, and both are sent to the data acquisition computer. The Q-value spectra are then sorted by the amplitude on the triangle wave and by whether or not the square wave has the value 0. Unlike a typical capture experiment, in which total charge transfer signals (*i.e.* capture from 5s, 5p, and 4d) would be collected and summed, the MOTRIMS technique allows one to distinguish between relative capture from each of these initial states. Thus, with this extra information, one can readily deduce both relative populations and relative cross sections. This technique is very general and could be used to analyze the effects of any number of processes taking place in a MOT. For example, in experiments in which one studies dimer formation[4] in cold collisions, the molecule production as well as the accompanying depletion of the 5s and 5p states could be measured. As another example, one could illuminate trapped ground state atoms with a femtosecond laser, and watch the time dependence of the decay of the various states excited in the process. The use of this technique as a probe of the dynamics of the trapped atoms under the influence of some external perturbation seems limited only by the ability of the technique to resolve the Q-values of the different capture channels.

**References:**


1. J. Ullrich, R. Moshammer, R. Dörner, O. Jagutzki, V. Mergel, H. Schmidt-Böcking, and L. Spielberger, J. Phys. B: At. Mol. Opt. Phys. **30**, 2917 (1997).
2. R. Dörner, V. Mergel, O. Jagutzki, L. Spielberger, J. Ullrich, R. Moshammer, and H. Schmidt-Böcking, Phys. Rep. **330**, 95 (2000).
3. X. Flechard, H. Nguyen, E. Wells, I. Ben-Itzhak, and B. D. DePaola, Phys. Rev. Lett. (accepted).
4. H. Wang, X. T. Wang, P. L. Gould, and W. C. Stwalley, Phys. Rev. Lett. **78**, 4173 (1997).


**Publications:**


"A Kinematically Complete Charge Exchange Experiment in the $Cs^+$ + Rb Collision System Using a MOT Target," X. Flechard, H. Nguyen, E. Wells, I. Ben-Itzhak, and B. D. DePaola, accepted for publication in Phys. Rev. Letters.

"Triple Photoionization of Lithium," R. Wehlitz, M.-T. Huang, B. D. DePaola, J. C. Levin, I. A. Sellin, T. Nagata, J. W. Cooper, and Y. Azuma, Phys. Rev. Letters 81, 1813 (1998)

"Absolute Charge Capture Cross Sections from a Rydberg Target: Experimental Results and Comparison with Theoretical Models," M. T. Huang, M. P. Stockli, C. W. Fehrenbach, S. R. Lundeen, and B. D. DePaola, J. Phys. B 30, 2425 (1998)

"Dynamics of Rydberg States in Crossed E and B Fields: Coherent Elliptic States," P. Sorensen, J. C. Day, B. D. DePaola, T. Ehrenreich, E. Horsdal-Pedersen, and L. Kristensen, J. Phys. B 32, 1207 (1999)

"Electron Capture from Elliptic Rydberg States: Impact Perpendicular to the Minor Axis," L. Kristensen, T. Bove, B. D. DePaola, T. Ehrenreich, E. Horsdal-Pedersen, and O. E. Povlsen, J. Phys. B 33, 1103 (2000)

"Electron-Capture Processes of Low-Energy $Si^{3+}$, $Si^{4+}$, and $Si^{5+}$ Ions in Collisions with Helium Atoms," H. Tawara, K. Okuno, C. W. Fehrenbach, C. Verzani, M. P. Stockli, B. D. DePaola, P. Richard, and P. C. Stancil, Phys. Rev. A 63, 062701 (2001)