To be published in *Book of Invited Papers, XX. International Conference on the Physics of Electronic and Atomic Collisions, Vienna, Austria, July 23-29, 1997*, World Scientific.

CONF-970710--1

# STATE AND ANGULAR RESOLVED ELECTRON CAPTURE IN A MERGED-BEAMS APPARATUS

W. Wu* and C. C. Havener
*Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*

**An important feature of the merged-beams technique is that the heat of a reaction in the center-of-mass frame is kinematically amplified when transformed to the laboratory frame. A multi-grid energy analyzer is used in a merged-beams apparatus to study state-selective cross sections and angular distributions for electron capture between multicharged ions and atomic D at eV/u collision energies. Product $D^+$ energy spectra are measured for $Si^{4+}$ + D at collision energies 3.6 eV/u to 98.6 eV/u, and for $O^{5+}$ + D at 17.1 eV/u. Comparison is made to state-selective and angular scattering calculations where possible.**

RECEIVED
SEP 23 1997
OSTI

The experimental, unambiguous identification of underlying transition mechanisms in collision reactions often requires that measurements go beyond total cross sections to differential measurements. At low energies (0.02-5000 eV/u), total capture cross sections for multicharged ions on atomic H (or D) have been measured using the merged-beams technique[1]. Low energy partial cross section measurements[2,3] with atomic H are difficult and state-selective information has only recently been reported[4] at eV/u energies using a technique based on vacuum ultraviolet Photon Emission Spectroscopy in an RF octopole trap. State-selective measurements[5] using the merged-beams technique take advantage of the fact that the heat of reaction is amplified when kinematically transformed from the center-of-mass frame to the laboratory frame. This amplification increases with decreasing collision energy. Extracting state-selective cross sections at very low eV/u energies is complicated by angular scattering which decreases the energy shift. While this reduces the effective energy resolution for low energy collisions, it does provide angular scattering information.

The experiment was carried out at the Oak Ridge National Laboratory Multicharged Ion Research Facility using the ion-atom merged-beams apparatus[1,5]. Briefly, a multicharged ion beam produced by a CAPRICE Electron Cyclotron Resonance (ECR) ion source is electrostatically merged with a neutral D beam of 7-9 keV, obtained by photodetachment of a $D^-$ beam as it passes through the resonant cavity of a 1.06 $\mu$m cw Nd:YAG laser. After a 47 cm interaction region, the primary and product beams are magnetically demerged. The product $D^+$ ions are sent through an energy analyzer and then detected by a channel-electron multiplier. The energy analyzer is a five-grid potential retarding system similar to the one adopted by Newman *et al*[6] where the center three grids are held at the desired retarding potential. Deuterium

19980330 072



MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DTIC QUALITY INSPECTED 3

"The submitted manuscript has been authored by a contractor of the U.S. Government under contract DE-AC05-96OR22464. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes."

# DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

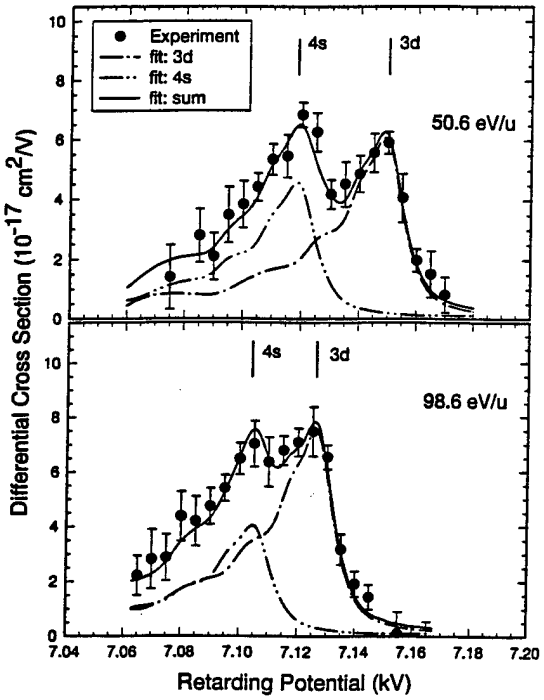


**Figure 1: Energy shift spectra for single capture by $Si^{4+}$ from D. The symbols are the experimental data and the lines are fits to the distributions. The locations for the expected positions for the captured states are also indicated.**

was used instead of hydrogen in order to maximize the angular collection of the signal ions. No isotope effects[7] are expected above 2 eV/u for the ions presented here.

Differential yields of the $D^+$ produced as a function of retarding potential applied to the energy analyzer were measured for collisions of $Si^{4+}$ with D at center-of-mass energies of 3.6-98.6 eV/u. The spectra are put on an absolute scale by normalizing to experimental total cross sections[7]. The data indicate that the capture proceeds into both the $Si^{3+}(3d)$ and $Si^{3+}(4s)$ states with more $Si^{3+}(3d)$ contribution at higher energies (see Figure 1). With the decrease of collision energy, the contribution of the $3d$ state decreases and the $4s$ state becomes more favored. The general picture observed is consistent with theoretical predictions[7,8].

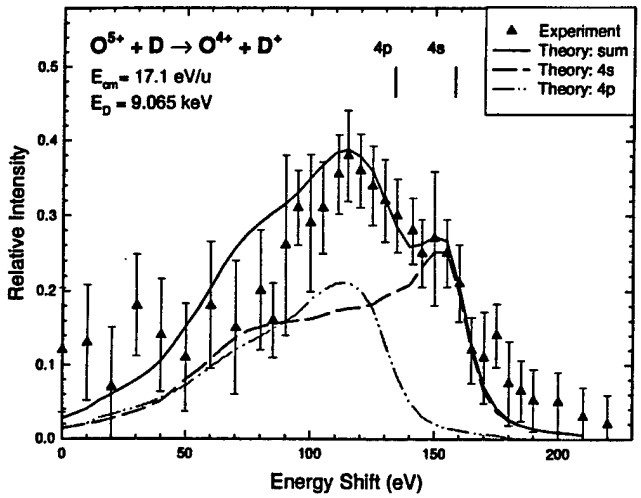


**Figure 2: Energy shift spectra for single capture by $O^{5+}$ from D. The sysmbols are the experimental data and the lines are model distributions converted from the theoretical angular differential cross sections.**

For collisions at 50.6 and 98.6 eV/u, we extracted partial cross sections for the $3d$ and $4s$ population. Although there is no angular scattering calculation available, the calculation[9] for the system of $O^{5+}$ on H suggests that the angular scattering at these energies should be smaller than a few degrees in the center-of-mass frame. Since the difference in energy shift at such small scattering is negligible in comparison to the experimental resolution (22 eV), we neglected the effect of angular scattering in the energy shift spectra, and the experimental resolution was directly used as the shape for the $3d$ and $4s$ distributions to fit the data. The positions and heights of the distributions were kept as free parameters. The resulting distributions are plotted in Figure 1 and show good agreement with the experimental points. From the fitting, the ratio of the $3d$ partial cross section over the $4s$ is found to be 1.3 and 1.8 for collisions at 50.6 eV/u and 98.6 eV/u, respectively. The estimated error due to the fit is 15%. The results are significantly lower than the theoretical predicted values of 2.3 and 3.2[7,8], respectively.

At the lowest energies, 3.6 eV/u and 9.9 eV/u , the dominant capture channel is observed to be the $Si^{3+}(4s)$ state. The measured energy spectra (not shown) are broad, indicating the large angular scattering typical at these low energies. A simple transformation converts the energy spectra to angular

distributions indicating that at 9.9 eV/u the scattering extends to $35^0$ and increases to $45^0$ at 3.6 eV/u . No theory exists for comparison.

Theoretical calculations[9] for the angular distributions do exist for $O^{5+}$ + D . Product energy spectra were measured for $O^{5+}$ + D at 17.1 eV/u . For comparison, energy shift distributions were calculated by transforming the angular differential cross sections to the energy-shift differential cross sections and then folding in the experimental resolution. The resulting "theoretical" distributions are compared to the measured distribution in Figure 2. The agreement is reasonable, especially at the highest energy shifts.

## Acknowledgments

This research was supported by the Division of Chemical Sciences, Office of Basic Energy Sciences and the Office of Fusion Energy Sciences, U.S. Department of Energy, under contract No. DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp. W.W. was supported in part by an appointment to the ORNL Postdoctoral Research Associates Program administered jointly by ORISE and ORNL.

* Present address: Electroglas Inc., 2901 Coronado Dr., Santa Clara, CA 95054, email: wwu@electroglas.com

## References

1. C. C. Havener in *Accelerator-based Atomic Physics Techniques and Applications*, ed. S. Shafroth and J. Austin (New York: AIP Press, 1997)
2. R. Hoekstra, F. J. de Heer and R. Morgenstern, *J. Phys. B: At. Mol. Phys.* **24**, 4025 (1991).
3. H. B. Gilbody, *Adv. At. Mol. Phys.* **32**, 149 (1994).
4. F. W. Bliek, G. Lubinski, R. Hoekstra and R. Morgenstern in *Abstracts of the XX Int. Conf. on the Physics of Electronic and Atomic Collisions, Vienna*, ed. F. Aumayr, G. Betz and HP. Winter, Th157.
5. W. Wu and C. C. Havener, *J. Phys. B: At. Mol. Opt. Phys.* **30**, L213 (1997).
6. J. H. Newman *et al.*, *Phys. Rev. A* **25**, 2976 (1982).
7. Marc Pieksma ,M. Gargaud, R. McCarroll and C. C. Havener, *Phys. Rev. A* **54**, R13 (1996).
8. M. Gargaud and R. McCarroll, *J. Phys. B: At. Mol. Opt. Phys.* **21**, 513 (1988).
9. L. R. Andersson, M. Gargaud and R. McCarroll, *J. Phys. B: At. Mol. Opt. Phys.* **24**, 2073 (1991).

M98000123

Report Number (14) CONF-970710--1

Publ. Date (11) 199708

Sponsor Code (18) DOE/ER, XF

UC Category (19) UC-400, DOE/ER

DOE