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Final REPORT OF GRANT NAGW-4279

TITLE: Laboratory Studies of Thermal Energy Charge  
Transfer of Silicon and Iron Ions in  
Astrophysical Plasmas

PRINCIPAL  
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INTRODUCTION:

The laser ablation/ion storage facility at the UNLV Physics Department is dedicated to the study of atomic processes in low temperature plasmas. Our current program is directed to the study of charge transfer of multiply charged ions and neutrals that are of importance to astrophysics at energies less than 1 eV ( about  $10^4$  K). Specifically, we measure the charge transfer rate coefficient of ions such as  $N^{2+}$ ,  $Si^{3+}$ ,  $Si^{4+}$ , with helium and  $Fe^{2+}$  with molecular and atomic hydrogen. All these ions are found in a variety of astrophysical plasmas. Their electron transfer reactions with neutral atoms can affect the ionization equilibrium of the plasma.

A. SUMMARY OF ACCOMPLISHMENTS OF GRANT YEAR (NAGW-4279)

ION	NEUTRAL	RATE COEFFICIENT		TEMPERATURE (K)
		MEASUREMENT	CALCULATION ( $cm^3 s^{-1}$ )	
$O^{2+}$	He	$1.12(0.15) \times 10^{-12}$	$0.45 \times 10^{-9}$ [Gargaud et al., 1993] $1.0 \times 10^{-10}$ [Butler et al., 1980]	4200 5000 5000
	$H_2$	$2.36(0.22) \times 10^{-9}$	N/A	2500
	$N_2$	$3.15(0.26) \times 10^{-9}$	N/A	13000
	CO	$3.40(0.29) \times 10^{-9}$	N/A	13000
$N^{2+}$	He	$8.67(0.76) \times 10^{-11}$	$8 \times 10^{-11}$ [Sun et al., 1996]	3900
	$H_2$	$3.38(0.35) \times 10^{-11}$	N/A	2900
	$N_2$	$2.10(0.18) \times 10^{-9}$	N/A	13000
	CO	$3.37(0.29) \times 10^{-9}$	N/A	13000
$Si^{3+}$	He	$6.27(0.52) \times 10^{-10}$	$4.5 \times 10^{-13}$ [Butler et al. 1980] $2 \times 10^{-10}$ [Honvault et al. 1995]	3900
	$Si^{4+}$	He	$4.54(0.48) \times 10^{-12}$	$7 \times 10^{-10}$ [Stancil et al. 1997] $1 \times 10^{-9}$ [Opradolce et al. 1985] $1 \times 10^{-9}$ [Butler and Dalgarno, 1980]
$Fe^{2+}$	$H_2$	$< 10^{-14}$	N/A	4000

B. Of the five measurements undertaken by our laboratory, two measurements ( $O^{2+} + He \rightarrow$  products and  $Si^{4+} + He \rightarrow$  products) are smaller than the calculated value by more than two orders of magnitude while the third measurement ( $Si^{3+} + He \rightarrow$  products) is about a factor of three larger than the calculated value. Only one calculation ( $N^{2+} + He \rightarrow$  products) is within the experimental uncertainties of the measurement. This clearly indicates that more sophisticated theoretical work is needed to improve the accuracy of the calculation. These measurements also call to question the continual use of untested calculations in modeling astrophysical plasmas.

### C. CHARGE TRANSFER OF $\text{Fe}^{2+}$ WITH $\text{H}_2$ AND H:

We have completed a measurement of the charge transfer rate coefficient of  $\text{Fe}^{2+} + \text{H}_2$ . This rate coefficient is less than  $10^{-14} \text{ cm}^3 \text{ s}^{-1}$ . This is an unexpectedly small rate since  $(\text{FeH}_2)^{2+}$  has a complex molecular structure with numerous low lying energy states where charge transfer can occur. This measurement is vital in the measurement of  $\text{Fe}^{2+} + \text{H}$  where small amounts of  $\text{H}_2$  are expected to be present in the atomic hydrogen beam. Since the rate coefficient for  $\text{Fe}^{2+} + \text{H}$  is of the order of  $10^{-9} \text{ cm}^3 \text{ s}^{-1}$ , the uncertainty created by the presence of small quantities of molecular hydrogen is less than 1:10<sup>5</sup>. We are in the process of calibrating the absolute particle density of the atomic beam, the H/ $\text{H}_2$  ratio, and the profile of the atomic hydrogen beam using the method developed by Wise et al. (1993), and Stock et al. (1994) for their polarized atomic hydrogen source. Analysis on the rf discharge emission spectrum of the hydrogen source confirms that the ratio of H/ $\text{H}_2$  is more than 97%. We expect to begin the measurement by late November.

### D. OTHER ACTIVITIES IN THE RESEARCH PROGRAM:

A graduate student, J. B. Wang, joined our program in 1994 to study the charge transfer in low temperature plasmas. As part of his Ph.D. dissertation, he completed the design, construction and testing of a new reflection time-of-flight mass spectrometer facility. This facility has been used to measure the cross-section of a specific charge transfer channel of an  $\text{C}^{2+} + \text{H}_2 \rightarrow$  products at low energies (Wang, and Kwong 1997). He graduated in August 1997. Dr. Wang is now with the Electrical Engineering Department of Stanford University.

Two new graduate students, Mr. De Chen and Ms. Dew-Ann Carroll have joined the research program. Mr. De Chen will carry out his Ph.D. research on state select charge transfer of multiply charged ions while Ms. Dew-Ann Carroll has begun her study on the properties of laser ablation ion source as part of her M.S. project.

During the summer of 1995 and 1996, four undergraduates, Bryan Fry, Aaron Bostwich, Brian Webber, and Patrick Cyr, participated in the summer NSF REU program in the testing of the atomic hydrogen source. This year, two more undergraduates, Thomas Butler and Amy Baadsgaard from UNLV joined us for the 1997 NSF REU program. They worked with us on the data collection and data reduction for the  $\text{Fe}^{2+} + \text{H}$  experiment.

### E. PAPERS PUBLISHED AND SUBMITTED:

Charge transfer between  $\text{Si}^+$  ion and helium at electronvolt energies, Z. Fang and V.H.S. Kwong, Submitted to Physical Review Letters, November 1997.  
Reflection time-of-flight mass spectrometer for charge transfer cross section measurements, Jiebing Wang and Victor H.S. Kwong, Rev. Sci. Instrum.

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Charge transfer between ground-state  $\text{Si}^{3+}$  and He at electron-volt energies, Fang, Z and V.H.S. Kwong, Ap.J.483, 527, 1997.

Charge transfer between ground-state  $\text{N}^{2+}$  and  $\text{H}_2$ ,  $\text{N}_2$ , and CO at electron-volt energies, Fang, Z and V.H.S.Kwong, Phys.Rev.A55, 440,1997.

Measurement of charge transfer rate coefficients between ground-state  $\text{N}^+$  ion and He at electron-volt energies, Fang, Z and V.H.S. Kwong Ap.J.,474,529, 1997.

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