EXPERIMENTAL STUDY OF INTERACTIONS OF
HIGHLY CHARGED IONS WITH ATOMS AT keV ENERGIES

Progress Report

for the Period

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Introduction

Experimental study of low energy, highly charged ions with other atomic species requires an advanced ion source such as an electron beam ion source, EBIS¹ or an electron cyclotron ion source, ECRIS². Five years ago we finished the design and construction of the Cornell superconducting solenoid, cryogenic EBIS (CEBIS). Since then, this source has been in continuous operation in a program whose main purpose is the experimental study of interactions of highly charged ions with atoms at keV energies. This progress report for the period February 16, 1993 to April 15, 1994 describes the work accomplished during this time.

Experimental work finished

Many of the experiments described in the last progress report³ have been written up and published in refereed journals, others have been submitted for publication. The following is a list of papers published in chronological order.

- 1) "An angle-resolved translational energy spectrometer for investigating low-energy , highly charged ion-atom (molecule) collisions" by J. Vancura, J.J. Perotti, J. Flidr, and V.O. Kostroun . Rev. Sci. Instrum. **64**, 3139 (1993).

Abstract

An experimental apparatus for investigating low-collision energy gas-phase reactions of highly charged ions with atoms and molecules by angle resolved translational energy spectroscopy is described. The basic function of the apparatus is to slow down highly charged ions extracted at 2-3 kV from the Cornell superconducting solenoid, cryogenic electron beam ion source (CEBIS) to energies below 100 qeV. The slowing down and monochromatization of the beam is done by an ion optical system that consists of two 180° hemispherical electrostatic analyzers with a tuneable deceleration lens located between them. The low energy beam available for experiments has an angular spread of 0.5° and an energy spread of 0.4 qeV. The ion optical system is mounted on a 550 mm by 625 mm electrically isolated platform inside a large vacuum chamber, and the modular nature of the apparatus allows for quick and easy rearrangement of the ion optical elements for different experiments. A brief overview of in plane scattering kinematics is given.

- 2) "Ionization and dissociation of N₂ and CO in collisions with 2.3 qkeV Ar^{q+} (8≤q≤14)" by J. Vancura and V.O. Kostroun, Phys. Rev. A **49**, 321 (1994).

Abstract

The charge state and energy distribution of molecular ions and fragments produced in low energy, highly charged argon ion-N₂ and CO collisions were measured. Ar^{q+} (8 ≤ q ≤ 14) ions produced by an electron beam ion source and extracted at 2.3 kV interacted with a molecular target gas jet

located in the ionization region of a time of flight spectrometer. The resulting molecular recoils and fragments were analyzed by time of flight. For a given molecular target, the measured spectra are all similar, and do not depend on the incident argon projectile charge state. The spectra are dominated by the singly charged ion, either N_2^+ or CO^+ . The stable/long lived metastable doubly charged molecular ion CO^{++} is the second most prominent feature in the Ar^{q+} on CO spectra. Similarly, N_2^{++} , which cannot be distinguished from N^+ , is also presumed to be present in the Ar^{q+} on N_2 spectra. The remaining peaks are associated with the dissociation of the N_2^{Q+} and CO^{Q+} ($2 \leq Q \leq 6$) molecular ions formed in the collision. The peak positions correspond to fragments of a given mass to charge ratio and kinetic energy calculated assuming vertical target ionization.

3) "Absolute total, one-, two, and three-electron-transfer cross sections for Ar^{q+} ($8 \leq q \leq 16$) on Ar at 2.3 qkeV", by J. Vancura, J.J. Perotti, J. Flidr and V.O. Kostroun, Phys. Rev. A, **49**, 2515 (1994)

Abstract

Absolute values for the total, one, two and three electron transfer cross sections for Ar^{q+} ions ($8 \leq q \leq 16$) colliding with argon at 2.3 qkeV laboratory energy were measured by the growth rate method. The Ar^{q+} ions were produced by the Cornell superconducting solenoid, cryogenic electron beam ion source CEBIS and extracted at 2.3 kV. Selected charge states traversed a gas cell, after which they were detected and charge state analyzed by the energy retardation method and by a $\pi/\sqrt{2}$ cylindrical electrostatic analyzer. The target gas pressure in the cell was measured directly by the orifice flow method used for absolute pressure gauge calibration. The overall error in the Ar^{q+} on Ar cross section measurements is $\pm 10\%$.

The following is a list of papers submitted to Phys. Rev. A (in chronological order). Reprints of the papers are appended to this progress report.

4) "Even-odd projectile charge-capture state variation in low energy Ar^{q+} ($8 \leq q \leq 14$) Ar collisions" by J. Vancura and V.O. Kostroun

Abstract

Energy gain spectra of projectiles with final charge ($q-1$) were measured for Ar^{q+} ($8 \leq q \leq 14$) on Ar collisions at 30 qeV lab energy and 0.3 qeV energy resolution. The spectra exhibit an even-odd variation with incident projectile charge q : even q value spectra show two distinct peaks, odd ones only one. For Ar^{8+} on Ar the two peaks commonly attributed to one electron capture into 5f,g and 6s respectively exhibit different angular distributions at 746 eV projectile energy. The data are interpreted in terms of Q values calculated for different projectile one, two and three electron capture states.

5) "Angular and energy distribution of $\text{Ar}^{(q-1)+}$ in Ar^{q+} ($8 \leq q \leq 10$) on Ar at laboratory collision energies below 100 qeV" by J. Vancura, M. Sadilek, and V.O. Kostroun

Abstract

Energy gain spectra of $\text{Ar}^{(q-1)+}$ ions in Ar^{q+} in Ar^{q+} ($8 \leq q \leq 10$) on Ar collisions were measured at different scattering angles at laboratory collision energies below 100 qeV. For argon 8+ and 10+, angular distributions of projectiles for kinetic energy gains associated with the two sharp peaks commonly observed in 0° energy gain spectra were obtained. The angular distribution of product ions scattered with an energy characteristic of the lower Q value was found to be significantly different from that of the higher Q value. This would suggest, that the common interpretation of the sharp peaks in Ar^{q+} on Ar 0° energy gain spectra as being due to single electron capture might not be the only possible interpretation. Energy gain spectra measured at different scattering angles were integrated over scattering angles, and the resulting function, proportional to the Q-value distribution function, reflects the density of capture states.

6) "Spectroscopic study of electrons emitted in Ar^{q+} ($8 \leq q \leq 16$) on Ar at 2.3 qkeV collision energy", by J. Vancura, P.J. Mucha and V.O. Kostroun

Abstract

The spectra of electrons emitted in Ar^{q+} on Ar ($8 \leq q \leq 16$) collisions at 2.3 qkeV were measured in the 30 to 400 eV energy range. Ar^{q+} ions were produced by the Cornell superconducting solenoid, cryogenic electron beam ion source CEBIS, and the emitted electrons analyzed by a $\sqrt{\pi}/2$ cylindrical electrostatic analyzer at 90° to the ion beam. The observed spectral features are interpreted in terms of energy differences between total electronic energies of final states of the collision system [$\text{Ar}^{q+} + (\text{electron configuration})$] + Ar^{r+} measured with respect to the initial $\text{Ar}^{q+} + \text{Ar}$ ground state total electronic energy at infinite separation. The spectra appear to have a common interpretation.

Work in progress

We are continuing with measurements of angular distributions and energy gains in Ar^{q+} on Ar collisions along the lines described in paper 6. Figure 1 below shows the results of preliminary measurements of energy gain spectra at different laboratory scattering angles for Ar^{12+} on Ar collisions at 72 qeV. In this case, the energy gain spectra of the Ar^{12+} projectiles, whose final charge state had decreased by one unit, are essentially raw spectra that have not been corrected for the slight energy shift of the primary beam from one measurement to another. The spectra are similar to those observed for Ar^{8+} and Ar^{10+} on Ar at comparable energies, paper 5, except that the scattering angles are larger. Figure 2 shows the angular distribution of projectiles whose final charge is 11+, and which have undergone collisions associated with energy gains corresponding

Figure 1. The kinetic energy distributions of the Ar^{11+} product ion in 72 qeV Ar^{12+} on Ar collisions at different laboratory scattering angles.

Figure 2. Laboratory angular distributions of product Ar^{11+} ions in 72 qeV Ar^{12+} on Ar collisions. Top shows the angular distribution of Ar^{11+} product ions whose kinetic energy gain corresponds to the first peak in the energy gain spectrum, figure 2. Middle shows the angular distribution for Ar^{11+} ions associated with the second peak in the energy gain spectrum. Bottom shows the angular distribution for Ar^{11+} ions associated with the third peak in the energy gain spectrum. The angular spread of the incident Ar^{12+} beam is shown for comparison.

Figure 3. Angular distribution in the c.m. of all projectiles scattered in Ar^{12+} on Ar collisions calculated according to the molecular coulomb barrier model.^{4,5} The solid line shows the experimental angular spread of 0.46° folded in.

to the first, second, and third peak in figure 1. That is, 80.4, 81.4 and 83.4 qeV respectively. In this case, the spectra were recorded from 0° to θ and reflected about the origin. The angular distribution corresponding to the highest energy gain peak shows appreciable scattered intensity up to 4° laboratory scattering angle. This is the highest scattering angle we have observed thus far. Figure 3 shows the angular distribution in the c.m. for Ar^{12+} on Ar calculated according to the molecular coulomb barrier model.^{4,5} In this case we have calculated the scattered distribution of all the projectiles. Since in the experiment we selected Ar^{11+} , we would not expect the measured relative intensity of the peaks to agree with the calculated ones. However, Ar^{11+} accounts for more than 85% of the final projectile charge states⁶, so that it is reasonable to compare this calculation with experiment. In any case, the peak positions should agree with experiment. From the figure, we see that the molecular coulomb barrier model peaks extend to slightly higher angles. (The laboratory scattering angle is one half the c.m. scattering angle for Ar^{q+} on Ar.)

Personnel associated with the project

The work described in this progress report was carried out mostly by Jan Vancura, postdoctoral associate, and myself, Jaroslav Flidr, graduate research assistant, Peter Mucha, undergraduate research assistant and James Perotti, research technician. When Jan left the group in August 1993 after 3 years, he was sorely missed. He was replaced by Martin Sadilek, another postdoctoral associate. Peter Mucha graduated in May 1993. We would like to mention that Peter won a Churchill Fellowship, and has spent the past year at Cambridge University in England. In the Fall of 1994, he will be a graduate student at Princeton University in the Department of Applied Mathematics. Peter continues to help us with calculations via Internet.

Publications

- 1) "An angle-resolved translational energy spectrometer for investigating low-energy , highly charged ion-atom (molecule) collisions" by J. vancura, J.J. Perotti, J. Flidr, and V.O. Kostroun Rev. Sci. Instrum. **64**, 3139 (1993).
- 2) "Ionization and dissociation of N_2 and CO in collisions with 2.3 qkeV Ar^{q+} ($8 \leq q \leq 14$)" by J. Vancura and V.O. Kostroun, Phys. Rev. A **49**, 321 (1994).
- 3) "Absolute total, one-,two, and three-electron-transfer cross sections for Ar^{q+} ($8 \leq q \leq 16$) on Ar at 2.3 qkeV", by J.Vancura, J.J. Perotti, J. Flidr and V.O. Kostroun, Phys. Rev. A, **49**, 2515 (1994).

References

1. E.D. Donets, Sov. J. Part. Nucl. **13**, 387 (1982).
2. Y. Jongen and C.M. Lyneis in *The Physics and Technology of Ion Sources*, I.G. Brown, Editor (John Wiley and Sons, Toronto 1989) Chapter 10.
3. V.O. Kostroun DOE/ER/13519-7, January 23, 1993.
4. A. Niehaus, J. Phys.B **19**, 2925 (1986).
5. A. Niehaus, J. de Phys. (Paris) **C9**, 137 (1987).
6. J.Vancura, J.J. Perotti, J. Flidr and V.O. Kostroun, Phys. Rev. A, **49**, 2515 (1994)

Preprints removed