ELECTRON TRANSFER PROCESSES IN
ION COLLISIONS WITH ATOMIC HYDROGEN

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Electron Transfer Processes in Ion Collisions with Atomic Hydrogen

Final Report, Contract No. E(11-1)-2562

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Abstract

Presented are the results of experiments completed with Yale equipment coupled to the Oak Ridge Test Bench and Tandem Accelerator facilities. Electron transfer cross sections have been measured at keV collision energies for B, C, N and O ions colliding with H, H₂, Ar and He gas targets. The ion charge states studied range from +2 through +5. Also reported are cross sections for Si and Fe ions on H, H₂ and Ar at energies between 1.5 and 14 MeV, with charge states varying between +5 and +13. Also measured were the cross sections for H⁺ collisions with H, H₂ and Ar for energies between 0.8 and 2.5 MeV.

At keV energies the cross sections for highly charged B, C, N and O ions are found to be $1 \times 10^{-14} \text{ cm}^2$. The cross sections for 4 MeV Fe ions scale roughly with the square of the ion charge, and have values as high as $0.5 \times 10^{-14} \text{ cm}^2$ for Fe¹⁰⁺ + H collisions. A strong energy dependence is found for Fe ion collisions between 4 and 14 MeV. Previous results for MeV H⁺+Ar collisions are nicely reproduced, while our first results for the fundamental MeV H⁺-H collision problem are cross sections higher than many theoretical predictions.

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ELECTRON TRANSFER PROCESSES IN ION COLLISIONS WITH
ATOMIC HYDROGEN

J.E. Bayfield, Yale University

GENERAL CONSIDERATIONS

Historical Background. The experimental program began in the late 1960's with Air Force support for a series of studies on electron transfer (also called charge exchange or electron capture) in H^+ and He^{++} collisions with hydrogen atoms. Studies of the various final excited states were made. The key aspect of this early part of the program was the successful development of a special atomic hydrogen scattering target.¹ The work has been reviewed.² In 1973 the program became dormant, only to be revived eighteen months ago by ERDA because of an increased interest in electron transfer processes involving multiply-charged ions with atomic hydrogen, occurring in impure Tokamak plasmas and in proposed charge-exchange pumped X-ray lasers.³ The principal investigator proposed a series of experiments with hydrogen, helium, carbon, nitrogen and oxygen ions on atomic hydrogen, some to be conducted at Yale and some at Oak Ridge National Laboratory where the Penning Ion Source Test Bench Facility provided a unique opportunity to study the higher charge states at low (keV) collision energies. It soon became clear that there were urgent needs in the CTR program for some results for the heavier ions. So our greatly improved apparatus was

moved to ORNL where all the experimental work was completed. Experiments with the CTR impurity ions Si and Fe supplanted our proposed studies with helium ions.

Experiments and Collaborators. The summer and fall of 1975 found us at the Test Bench Facility. Two early one week runs were devoted to the solving of problems in coupling the Yale experiment to the Test Bench. A third two week run gave us data for multiply-charged B, C, N and O ions on H_2 , He, and Ar gases as well as some calibration data using He^{++} beams. This run established that the apparatus was working properly and that our techniques would lead to accurate cross section results. A last two week run gave us data with the atomic hydrogen target in operation. Collaborators in this work were

Yale University: J. Bayfield, L. Gardner, P. Koch

ORNL: D. Crandall, M. Mallory

University of Tennessee: I. Sellin, R. Peterson, D. Pegg

During the spring of 1976 we moved our apparatus to the ORNL Tandem Accelerator Facility, where two one week runs were scheduled and successfully completed. These were first an MeV proton experiment performed by

Yale University: J. Bayfield, L. Gardner, P. Koch

University of Tennessee: I. Sellin, D. Pegg, R. Thoe, R. Forester

University of Connecticut: H. Haydon

This was followed by the heavy ion experiment (Si, Fe) done by

Yale University: J. Bayfield, L. Gardner, P. Koch

ORNL: P. Stelson, Y. Kim

Vanderbilt University: R. Ronnigen

The tandem experiments required major revisions of both the Yale and ORNL portions of the apparatus. In all experiments Yale provided the scattering target, ion analyzers and detectors; our collaborators provided a clean ion beam in ultrahigh vacuum compatible with the Yale apparatus. All the experiments received the active support of C.F. Barnett of ORNL; he has been a major source of encouragement for which we are all very thankful.

Calibrations of the Apparatus. The measurement of absolute atomic collision cross sections involves an absolute scattering target thickness measurement, something we have done a number of times in the past. A number of cross sections are by now well-studied in independent absolute measurements done in a number of laboratories. Experience tells us that no one such study should be completely trusted; rather, a number of these cross-correlated by cross section ratio measurements provides a surer target thickness determination. Some twenty calibration experiments were performed during the runs at ORNL. At the Test Bench the processes used were

At the tandem facility a low energy beam was available, and calibration was performed using

In addition, several previous MeV energy H^+ measurements⁴ were reproduced and can be considered as calibration experiments. The processes here are

Experiments with atomic hydrogen targets are further complicated by thermal transpiration and incomplete thermal dissociation of H_2 into H within the target. Using techniques developed by us in the past the transpiration effect was measured by studying all collision processes for Ar targets both hot and cold, i.e. with the target dissociation heater turned both on and off. The molecule dissociation fraction was measured using a double electron transfer technique.⁵ For instance, at the Test Bench the process

was found to have a sizeable cross section leading to useful B^+ signals. If the dissociation is turned on and all H_2 converted to 2H , then the B^+ signal should go to zero. Insofar as it doesn't, some H_2 remains, with an amount that then can be determined once thermal transpiration is accounted for. At the tandem,

the process used was

Again some twenty values of the dissociation fraction were determined during the year's runs, with values usually near 0.89 ± 0.03 .

Since we were conducting experiments into the last month of the contract period, insufficient time has been since available to carefully analyze the immense amount of accumulated data with respect to any possible real time dependence of our standardized target thickness and dissociation fraction values. Because of this, all cross section values reported here are somewhat preliminary and can be believed accurate to better than $\pm 50\%$. A final computer statistical analysis should lead to values accurate to about $\pm 20\%$.

RESULTS OF THE ELECTRON TRANSFER EXPERIMENTS

B,C,N and O Ions at keV Energies. The preliminary experiments conducted at the Test Bench led us to conclude that work with these ions was possible except for the totally stripped cases and the one electron cases for C,N and O. (Actually a 20 Hz B^{5+} beam was briefly obtained one day, but the ion source conditions changed before data could be taken.) Surveys of electron transfer cross sections were made for H_2 , Ar and He target gases and for incident ion charge states 2, 3 and 4, all at one accelerator voltage. As boron beams were the only ones useful for dissociation fraction measurements, the energy dependences of their cross sections were next determined. During the subsequent atomic hydrogen run similar experiments were done with the target furnace hot. A determination of the energy dependences for C, N and O ions (necessarily for both hot and cold targets, see the previous section on calibrations) would have required a factor of three more beam time, which was not available. These measurements remain to be done.

The results of the survey for the atomic hydrogen target are shown in Figure 1 and are discussed further in Appendix A. The data were taken at fixed Test Bench accelerator voltage V , since retuning the apparatus for different values of V was often time consuming. Since the beam energy for an ion of charge q was qV , the ion velocities differed for different charges as well as different masses. What is remarkable about Figure 1 is our ability to draw smooth curves through all the data for a given charge state. This suggests that a simple picture may unify all these collision processes.

Figure 1: Cross sections for electron transfer in collisions of multiply-charged B, C, N and O ions with hydrogen atoms, obtained at the ORNL Penning Ion Source Test Bench Facility operating at constant acceleration potential.

Such a picture can be based upon a three body model where the incident ion is considered as a structureless point charge q , and the electron in the hydrogen atom is captured into an empty, highly excited shell of the ion with a hydrogenic principal quantum number n about equal to q . This author has developed a model theory based upon this idea; while it predicts a unified picture of all these collisions, as yet it doesn't explain the detailed behavior of the curves in Figure 1. Clearly measurements of the energy dependences for these cross sections would greatly further our understanding of the fundamental nature of the multiply-charged ion, atomic hydrogen collision problem.

The energy dependences for boron ion beams on H, H₂, Ar and He targets are shown in Figures 2, 3, 4 and 5 respectively. Most but not all of these cross sections are fairly energy-independent, something also observed in past results for carbon and oxygen beams on H₂.⁶

Figure 6 shows the charge state dependence at fixed collision velocity for boron ion collisions on Ar, He and H₂. A closed shell effect is observed, with local cross section minima found for $q=3$ in Ar and H₂, but a maximum in He. The H target data is similar to H₂ and Ar. Some theoretical curves obtained by L. Gardner using the Landau-Zener curve crossing model are also shown in Figure 6. A conclusion reached is that one can explain perhaps 50% of the data in terms of such a model, but numerous notable exceptions exist.

Figure 2. The energy dependence of the electron transfer cross sections for beams of B^{2+} , B^{3+} and B^{4+} ions incident on an atomic hydrogen gas target. The quantity $\sigma_{q,q-1}$ is the cross section for $B^{q+} + H \rightarrow B^{(q-1)+} + H^+$.

Figure 3. Single and double electron transfer cross sections for multiply-charged boron ions in H_2 .

Figure 4. Single and double electron transfer cross sections for multiply-charged boron ions in argon gas.

Figure 5. Single and double electron transfer cross sections for multiply-charged boron ions in helium gas.

Figure 6. The initial charge state dependence of boron ion electron transfer at constant collision velocity. Open circles: Single electron transfer data; solid circles: theoretical Landau-Zener estimates, with level crossing distances given in Å; squares: double electron transfer data. Note the dips at $q=3$ for Ar and H₂ targets, a behavior inverted for an He target.

Among the CTR-related conclusions that can be reached upon consideration of our Test Bench data are the following:

1. keV energy charge exchange cross sections for multiply charged ions on atomic hydrogen are often even larger than for H_2 . Values can be 10^{-14} cm^2 , that is, very large. This has serious consequences for the neutral injection technique when used with impure Tokamak plasmas.
2. The charge state dependences at keV energies are not simple and can have local minima, producing "bottle necks" in the equilibrium charge distributions of impurity ions in plasmas.

Si and Fe Ions at MeV Energies. The Tandem Accelerator runs in 1976 required considerable preliminary effort. Several schemes were considered or tried for obtaining from a tandem beam a keV energy beam for calibration purposes; finally a second complete accelerator system was assembled for this purpose, using primarily ORNL equipment. Various schemes for obtaining low MeV energy highly stripped ions were tried, including final foil and gas stripping targets and various charge states of Fe and Si from the tandem. The best combination found was Fe^{2+} finally stripped in about 10^{-5} Torr of air in the beam line between the first and second analyzing magnets which were between the accelerator itself and our experimental apparatus. A beam of ten ions per second of 14 MeV Fe^{13+} was our highest charge state obtained this way; this beam intensity was through collimation of 1 milliradian in angle and 0.7 mm nominal beam diameter. Transmissions through our apparatus of the charge-state selected beam produced in the air stripping region varied with beam energy and charge state, with values between 10^{-2} and 10^{-5} .

The following lists the various cross sections measured; results are shown in Figure 7, with cross sections plotted as a function of incident ion charge q .

$\text{Si}^{q+} + \text{H}_2, \text{Ar}$	at 4 MeV, $q = 5, 6, 7, 8, 9$
$\text{Fe}^{q+} + \text{H}_2, \text{Ar}$	at 1.5 MeV, $q = 4, 5, 6, 7$
$\text{Fe}^{q+} + \text{H}_2, \text{Ar}$	at 4 MeV, $q = 7, 8, 9, 10$
$\text{Fe}^{q+} + \text{H}_2, \text{Ar}$	at 14 MeV, $q = 9, 10, 11, 12, 13$
$\text{Fe}^{q+} + \text{H}$	at 4 MeV, $q = 6, 7, 8, 9, 10$
$\text{Fe}^{q+} + \text{H}$	at 14 MeV, $q = 9, 10, 11, 12, 13$

Figure 7.

A study of Figure 7 reveals the following trends in the data for these electron transfer reactions:

1. At the lower energies (1.5 and 4 MeV), Fe ion cross sections are similar for H_2 and Ar, with Ar having a values a little higher. This situation is similar to that for the test bench data of Figures 3 and 4 for keV energy boron ions. For higher collision velocities, however, the cross sections for Fe and Si begin to fall, with rates more rapid for H_2 than Ar. This is seen in the 4 MeV Si ion data and the 14 MeV Fe ion data of Figure 7.

2. At 4 MeV the cross sections for atomic hydrogen are larger than either H_2 or Ar, again similar to the test bench data of Figures 2,3, and 4. The largest cross section measured in the tandem run was $0.4 \times 10^{-14} \text{ cm}^2$ for $Fe^{10+} + H$ at 4 MeV.

3. On the other hand, the smallest cross sections measured were again for atomic hydrogen, for Fe ions at 14 MeV. Now the values for H are smaller than for either H_2 or Ar. Thus the energy dependence for H is strongest, and badly needs to be carefully determined because of its relevance to the CTR program. A tandem run to work on this is planned for the early fall of 1976.

4. The charge state dependences are not simple, but roughly exhibit the q^2 variation used in CTR computer codes on the impurity problem. As in the Test Bench data of Figure 6, the 4 MeV $Fe^{q+} + H$, H_2 and Ar data of Figure 7 show a closed shell effect at $q = 8$.

H⁺ Ions at MeV Energies. Log-log plots of our results for MeV H⁺ + Ar and H⁺+H electron transfer cross sections are shown in Figures 8 and 9 respectively. These cross sections fall rapidly with increasing collision energy, and depend in magnitude a great deal upon the nature of the target atom. The 10⁻²³ cm² magnitude of the H⁺+H cross section near 2 MeV is really small, partially explaining why no earlier measurements for this process have been made above 400 keV.

The points indicated as "x" in the Ar data of Figure 8 are values obtained previously.^{4,7} Our data for H₂ also agree well with previous results.^{4,7} It is seen that the H⁺+Ar data does not lie on a straight line in Figure 8, i.e. its energy dependence is not a simple power law.

The atomic hydrogen cross sections shown in Figure 9 do satisfy a power law dependence on the collision energy with an exponent of about five. The higher energy magnitudes of these cross sections are larger than theoretical values using either the First Born, Second Born or First Order Faadeev-Watson Approximations. We have no reason to suspect this data, although because of its great importance to fundamental atomic physics, it should be reproduced in a further tandem run, also extending the results to lower energies. Our present results are stimulating considerable interest in possible new theoretical contributions to the measured values, due to capture into highly-excited and continuum states as well as to possible radiative and relativistic corrections.

Figure 8. The cross section for $H^+ + Ar \rightarrow H + Ar^+$. Solid circles: present data; "x": earlier data.⁽⁴⁾ The cross section values shown should be multiplied by a factor 1.25.

Figure 9. Present results for $H^+ + H(1s) \rightarrow H + H^+$. The cross section values shown should be multiplied by a factor 0.54.

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AN EXPERIMENTAL SURVEY OF ELECTRON TRANSFER IN keV COLLISIONS OF MULTIPLY CHARGED IONS WITH ATOMIC HYDROGEN

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The ORNL Penning Ion Source Facility¹ has been coupled with a new apparatus containing the Yale atomic hydrogen scattering target² to measure various kilovolt energy electron transfer cross sections. The extension of earlier measurements with proton and helium ion beams³ to heavier multiply charged species is of fundamental interest as a further test of theoretical calculations. Cross sections for multiply charged C, N and O ions are also needed for the assessment of impurity problems in thermonuclear fusion devices. As the electron transfer is expected to be primarily into excited states, future X-ray laser applications may arise.⁴

The basic procedures for making the measurements follow those previously developed.^{2,5} The charge-selected ion beam was initially brought into 10^{-8} Torr vacuum, then magnetically reanalyzed, collimated to an angular spread of 1 mrad, and passed through the target at a pressure of 10^{-5} Torr. Cross sections for cold H_2 , cold Ar and hot Ar targets were measured in addition to (hot) H. Dissociation fraction values of nominally 90% were routinely measured using a variation of the double electron capture technique^{2,5}, employing B^{3+} incident ions. A large parallel plate electrostatic analyzer was used to separate scattered and incident charge states. Ion-counting detection involved a Johnston MMI particle multiplier. The absolute target thickness was determined by a number of calibration runs on $He^{++} + Ar$, $He^{++} + H_2$, $B^{3+} + He$ and $B^{3+} + H_2$, processes where previous independent absolute measurements exist. The present absolute cross section values are believed accurate to better than $\pm 30\%$.

Figure 1.

Figure 1 shows values of the cross sections for fourteen incident ions, obtained at a single Penning Facility accelerator voltage. The energy dependences for $B^{2+}, 3+, 4+$ have also been obtained. The interesting features of the data shown are first that the cross sections for ion charges >3 are 10^{-14} cm^2 , quite large. Second, the $2+, 3+$ and $4+$ points each lie on curves, suggesting that a simple theoretical model for these electron transfer processes might be found. As the electron transfer for incident $3+, 4+$ and $5+$ is expected to be into unfilled shells of the final state ion, one-electron initial and final states should make these processes amenable to calculation.

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