Technical Progress Report: 01 September 1991 - 31 August 1992

DOE Document Number DOE/ER/13971 -- 13

DOE/ER/13971--13

DE92 010319

Measurements of Scattering Processes

in

Negative Ion - Atom Collisions

U.S. Department of Energy
Office of Energy Research, Office of Basic Energy Sciences
Division of Chemical Sciences, Fundamental Interactions Branch

Grant Number: DE-FG05-88ER13971

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Technical Progress Report* - Year 1: 09/01/1991 - 08/31/1992

I. Introduction

This Technical Progress Report describes the progress made on the research objectives during the past twelve months. This research project is designed to provide measurements of various scattering processes which occur in H^- collisions with atomic (specifically, noble gas and atomic hydrogen) targets at intermediate energies. These processes include: elastic scattering, single- and double-electron detachment, and target excitation/ionization. For the elastic and target inelastic processes where H^- is scattered intact, the experimental technique of Ion Energy-Loss Spectroscopy (IELS) will be employed to identify the final target state(s). In most of the above processes, cross sections are unknown both experimentally and theoretically. The measurements in progress will provide either experimentally-determined cross sections or set upper limits to those cross sections. In either case, these measurements will be stringent tests of our understanding in energetic negative ion - atom collisions. This series of experiments required the construction of a new facility and the initial ion beam was accelerated through the apparatus in April 1991. The schematic drawing of the apparatus is shown in Figure 1.

University of Toledo - Negative Ion Energy Loss Spectrometer (UT - NIELS)

Figure 1.

II. Work Performed This Past Year

A. Total Cross Sections

We are presently finishing a study of single- and double-electron detachment in collisions of H^- with helium. The present data were obtained by measuring the scattered ions in shielded Faraday cups located on the two 30° magnet ports. A secondary electron emission detector/Faraday cup was placed on the zero-degree magnet port in order to detect H^0 resulting from single detachment collisions. This results in the detection of all three beam charge (H^+ , H^0 , and H^-) components, and permits the simultaneous measurements of single- and double-electron detachment processes.

The charged-particle fraction growth/decrease was measured as a function of target thickness in order to obtain total cross sections. Our measurements to date have concentrated on helium as the target species due to its fundamental nature. All of the parameters involved in determining the total cross sections have been measured, thereby absolute, total cross sections (TCS) that are independent of normalization have been obtained. The data contained a small but non-negligible quadratic term for basically all target thicknesses employed in the measurements (less than or approx. equal to 3×10^{14} atoms/cm²) as is demonstrated in Figure 2. For this reason, the data were fit to second-order polynomials in target thickness and the total cross sections were obtained from the coefficient of the linear term. This is a proven technique and follows the discussion in Heinemeier, et al. [1]. If $F_j(nl)$ is the charge state fraction of the j^{th} beam component at target thickness nl , then

$$F_0(nl) = \sigma_{-1,0}nl + \frac{1}{2}[\sigma_{-1,1}\sigma_{1,0} - \sigma_{-1,0}(\sigma_{-1,0} + \sigma_{-1,1} + \sigma_{0,1} + \sigma_{0,-1})](nl)^2 + \dots \quad (1)$$

for the neutral (H^0) beam fraction, and

$$F_1(nl) = \sigma_{-1,1}nl + \frac{1}{2}[\sigma_{-1,0}\sigma_{0,1} - \sigma_{-1,1}(\sigma_{-1,0} + \sigma_{-1,1} + \sigma_{1,0} + \sigma_{1,-1})](nl)^2 + \dots \quad (2)$$

for the positive (H^+) beam fraction. All three charge components of the scattered ion beam were measured in our experiment, thus allowing a systematic check on the data and permitting absolute measurements of the single detachment total cross sections which are free of normalization to other experiments or theories. The remaining negative charge fraction (H^-) is given by the equation:

$$F_{-1}(nl) = 1 - [F_0(nl) + F_1(nl)] = 1 - (\sigma_{-1,1} + \sigma_{-1,0})nl + [\text{terms of order } (nl)^2] + \dots \quad (3)$$

In the above equations, n is the target number density and l is the interaction length. The measured scattering chamber pressure, p , is related to the number density by:

$$n = N_L(273.15/T(K))p \quad (4)$$

In this equation, N_L is Loschmidt's number. Thus, all the experimental parameters in the above equations are either measured or calculated from the present data. The size of the cross section which this apparatus can measure is in principle limited only by the stability of the apparatus and the magnitude of the ion beam current.

Figure 2.

A.i) Single-Electron Detachment

Graphs similar to Figure 2 were also obtained for the neutral H⁰ beam fraction corresponding to single-electron detachment. The H⁰ growth curve data were analyzed according to Equation 1, and the total cross section was obtained from the linear coefficient multiplying the target thickness in each curve. The growth curves however, display a slight negative curvature in the beam growth curve which can be understood by comparing the magnitudes of the various cross sections contributing

to the quadratic term shown in Equation 1. The negative curvature occurs because the $\sigma_{-1,1}\sigma_{1,0}$ term is less than the terms multiplied by $\sigma_{-1,0}$. Each individual total cross section determination from its target thickness growth curve was weighted by its standard deviation prior to being averaged together for the reported cross section. These cross sections are shown in Figure 3, along with selected, other measurements of the single-electron detachment process.[1-5] The error bars on the present data represent one standard deviation of the averaged numbers. Over 125 individual growth curve determinations contributed to the cross sections reported in Figures 3 and 4. An energy analysis was not performed on the exiting H^0 , so the total cross sections reported here are for single-detachment summed over all $He(nln'l')$ and $H^0(nl)$ states. The largest source of uncertainty in the single-electron detachment measurements is the neutral detector efficiency. One method of analysis would involve using the first part of Equation 3 to obtain the neutral detector efficiency. The growth of the neutral and positive beam components must be at the expense of the negative beam component. Once the neutral efficiency is found, it is assumed to vary only with impact energy and otherwise remain constant. This assumption has been checked by repeated measurements at common energies.

Figure 3.

A.ii) Double-Electron Detachment

Similarly, Figure 4 shows the present data and other measurements [1,2,5-8] for double-electron detachment. The data were analyzed according to Equation 2, and the total cross section was obtained from the linear coefficient multiplying the target thickness in each growth curve. The analysis for double detachment was not as complicated as it was for single detachment due to the equal detection efficiency for both H^+ and H^- charge beam components. As before with single-electron detachment, each individual total cross section determination from its target thickness growth curve was weighted by its standard deviation prior to being averaged together for the reported cross section. The error bars on the present data represent one standard deviation of the averaged numbers. A positive curvature in the target thickness growth data is present for this process, as is shown in Figure 2 for a typical dataset. This can be understood from the $\sigma_{-1,0}\sigma_{0,1}$ term being larger than the negative terms which are multiplied by $\sigma_{-1,1}$ in Equation 2. An energy analysis was not performed on the exiting protons, so the total cross sections reported here are for double-detachment to all $He(nln'l')$ states.

Figure 4.

The double-electron detachment total cross sections are at least a factor of ten smaller than the single-electron detachment total cross sections for the same impact energy. If the Massey criterion [9] applies, then:

$$\frac{\Delta E a}{\hbar v} = \pi \quad (5)$$

where ΔE ($=14.35$ eV) is the excitation energy for double-electron detachment, a is the effective interaction length, and v is the relative velocity of the collision for the maximum in the total cross section. The $\sigma_{1,1}$ total cross section has a maximum at approximately 10 keV, which corresponds to an interaction length of $a \approx 2\text{\AA}$. This compares to $a \approx 27\text{\AA}$ when the Massey criterion is applied to single-electron detachment where the total cross section has a maximum at approximately 5 keV and $\Delta E = 0.75$ eV. Since the H^- ion has a loosely bound outer electron and a more tightly bound inner electron, the results from the above calculation are consistent with the view that the H^- ion makes a close approach to the helium atom in order for the interaction to be sufficiently strong to result in double-electron detachment. However, $a \approx 2\text{\AA}$ indicates an interpenetration of the electron clouds, whereas the Massey criterion is better suited to describing distant collisions. A paper describing our results is in the final stages of preparation, which we plan to submit to Physical Review A.[10]

B. Ion Energy-Loss Spectroscopy (IELS)

We have completed the modeling and construction of a set of ion optics elements ("zoom lens") to couple the energy analyzer to the deceleration column as shown in Figure 5. This project formed the Senior Project of Mr. Fauzie Syies, who earned his B.S.E.P. degree in December 1991. From his results, a five element lens was chosen, with the first and last elements electrically connected to the 17th deceleration column element and the entrance element of the energy analyzer, respectively. The lens was designed to produce a parallel ion beam with a kinetic energy of 200 eV at the entrance to the analyzer. A design constraint was that the ion beam have a minimal radial diameter at the entrance of the energy analyzer in addition to being parallel. The design of this system was aided by the ion trajectory program SIMION [11], and a sample plot of ions entering the deceleration column at 50 keV is shown in Figure 6. The lens was modeled for the ion beam energies (5- to 100-keV) the accelerator is designed to produce. The zoom lens was constructed and is in the process of being coupled to the energy analyzer. This energy analyzer-zoom lens assembly is the final section of apparatus to be installed before Ion Energy-Loss Spectroscopy (IELS) measurements can be obtained. The installation in the decelerator will occur immediately after the current detachment measurements are complete. The initial operation of the ion energy analyzer is expected by the end of the spring.

Zoom Lens and Hemispherical Energy Analyzer

Figure 5.

Figure 6.

C. Atomic Hydrogen Targets

Once target inelastic processes have been measured for noble gas targets, the next step would be H^- scattering from atomic hydrogen targets. This is the fundamental negative ion - atom collisional system, so understanding the scattering processes in it is of great importance. Atomic hydrogen requires the design and fabrication of a high temperature scattering chamber as shown in Figure 7. This formed the Senior Thesis of Mr. Michael Rosendaul, and was completed in the Fall 1991. It is currently awaiting completion of the noble gas scattering experiments before installation. The target number density will not be known directly, so a normalization of the total cross sections can be made by using protons as the projectile and comparing with existing measurements. The present apparatus is capable of accelerating protons with only straightforward changes in the various potentials. If H^- scatters at large impact parameters as a structureless particle, comparisons of the various scattering processes by H^- and proton impact would be very interesting.

Figure 7.

D. Angular Differential Cross Section Measurements

The main goal for this apparatus is to obtain cross sections that are differential

in scattering angle (ADCS). The ADCS are valuable because the approximations inherent in the various calculations are more sensitive to the angular dependence than are the integrated total cross sections. Another benefit of the angular studies is the capability of measuring the "true" elastic differential cross section, as stated earlier. Work has already commenced on the design of the parts necessary for the angular capability and several of the crucial parts have already been received or constructed. The design is forming the Mechanical Engineering Senior Synthesis Project of a team of Mechanical Engineering students in collaboration with two Mechanical Engineering faculty members. The design is in its final stages, construction has already commenced, and the assembly is expected to begin prior to the beginning of summer. The major component is the undercarriage and is shown in Figure 8. It will await the completion of the total cross section measurements before actual implementation on the accelerator. To identify the relevant angular design parameters, a collaboration is underway with Constantine Theodosiou on the width and position of the predicted [12] minimum in the elastic ADCS. Preliminary results have been obtained using the Unitarized Born Approximation and formed the Master of Science Thesis of Mr. Kiu Man Ma under the direction of Prof. Theodosiou. These calculations played an important role in establishing the design criteria for the apparatus.

Figure 8.

III. Personnel

The Principal Investigator is Thomas Jay Kvale, Assistant Professor of Physics at The University of Toledo. Over 95% of his research efforts have been devoted to this project. This included 30% of his time during the academic year and 100% during the summer months. It is anticipated that these figures will not vary significantly for the upcoming year.

Dr. James Allen joined the project as a Postdoctoral Research Associate in January 1990. His doctoral research was in experimental ion-atom scattering at the University of Wisconsin - Madison. He has made numerous, very valuable contributions to this research project. Since arriving at UT, he has spent 100% of his time on the project, and will again spend 100% of his time through the current budget year on the project. After the end of this budget year, he has indicated an interest in finding a permanent position.

Mr. Xiaodong Fang is in his fourth year as a graduate student at UT. He joined the project in January 1989, and is concentrating his efforts on the single- and double-electron detachment processes. He has obtained the data for his Master of Science dissertation, and is expected to complete the M.S. degree requirements by the end of the summer.

Two undergraduate engineering physics students have made valuable contributions to the research this past year. The design, construction, and implementation of the zoom lens adapter between the deceleration column and energy analyzer formed the Senior Engineering Physics Project for Mr. Fauzie Syies. He obtained his B.S.E.P. degree in December 1991. The atomic hydrogen scattering chamber formed the Senior Engineering Physics Project of Mr. Michael Rosendaul. He is expected to graduate shortly.

The design of the angular upgrade of the accelerator is forming the Mechanical Engineering Senior Synthesis Project of a team of three Mechanical Engineering students in collaboration with two Mechanical Engineering faculty members. The design is in its final stages, and construction is beginning.

IV. Summary

The initial measurements taken on the apparatus occurred in this reporting period. These measurements have been valuable in determining the absolute values and shapes of the single- and double-detachment total cross sections in the intermediate energy region. Similar measurements of detachment cross sections will continue with neon, argon, and possibly atomic hydrogen targets into the summer. Progress toward the ion energy-loss spectroscopy has been steady, and those measurements are awaiting final installation of the remaining pieces of the energy analyzer system. It is expected that this will occur this spring. Work has already commenced on the angular upgrade, however its installation will be after the total cross section measurements are complete.

V. Acknowledgements

- * Supported by U.S.DoE. grant DE-FG05-88ER13971. Work performed in collaboration with J.S. Allen and X.D. Fang.

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