PROJECT TERMINATION

Date March 4, 1966

PROJECT TITLE: Ionization and Charge Transfer Cross Sections
PROJECT NO: B-176
PROJECT DIRECTOR: D. W. Martin
SPONSOR: U. S. Atomic Energy Commission
TERMINATION EFFECTIVE: 2-23-66
CHARGES SHOULD CLEAR ACCOUNTING BY: 3-31-66
INITIATION DATE: September 1, 1959.

COPIES TO:
Project Director
Director
Associate Director
Assistant Directors
Division Chief
Branch Head
Accounting
Engineering Design Services

General Office Services
Photographic Laboratory
Purchasing
Shop
Technical Information Section
Security
RESEARCH PROJECT INITIATION
(Revised to Include Modification No. 9 to Contract)

Project Title: Ionization and Charge Transfer Cross Section
Project No.: B-2020
Project Director: Dr. D. W. Martin
Agreement Period: From 1 March 1966 until 29 February 1968
Type Agreement: Contract No. AEC AT-(40-1)-2531
Amount: $69,973 AEC Funds (B-2020)
$17,123 GIT Contribution (B-2001)
$37,466 Total Budget

Technical Administrator
Dr. Dent C. Davis, Jr.
Technical Assistant to the Director
Research and Development Division
United States Atomic Energy Commission
Post Office Box 3
Oak Ridge, Tennessee 37830

Reports Required
Technical Progress - By 1 December 1967
Seven (7) copies to sponsor
Renewal Proposal - With Progress Report
Seven (7) copies to sponsor
Final Report - Promptly upon termination of total period of performance. Seven (7) copies to sponsor

School of Physics
Assigned to:

Library
Rich Electronic Computer Center
Photographic Laboratory
EES Machine Shop
EES Accounting Office

Filo B-2020
Mr. R. A. Martin EES
RESEARCH PROJECT INITIATION

Project Title: Ionization and Charge Transfer

Project No.: B-2006

Project Director: Dr. David W. Martin

Sponsor: Atomic Energy Commission, Oak Ridge, Tennessee

Agreement Period: From 1 March 1968 until 28 February 1969

Type Agreement: Modification No. 10 to Contract No. AT-(40-1)-2591

Amount: $32,046 AEC Funds (B-2006)
8,011 GIT Contribution (E-2008)
$40,057 Total Budget

Contract Administrator
Dr. Dent C. Davis, Jr.
Research Contracts Branch
Laboratory and University Division
United States Atomic Energy Commission
Post Office Box E
Oak Ridge, Tennessee 37830

Report Required
Progress Report - By 1 December 1968;
Seven (7) copies to sponsor

Renewal Proposal - With Progress Report; separately bound, seven (7) copies

Final Report - Promptly upon termination or expiration of the total period of performance, seven (7) copies

Assigned to: School of Physics

COPIES TO:
- Project Director
- School Director
- Dean of the College
- Administrator of Research
- Associate Controller (2)
- Security-Reports-Property Office
- Patent Coordinator
- Library
- Rich Electronic Computer Center
- Photographic Laboratory
- EES Machine Shop
- EES Accounting Office

Other

Mr. R. A. Martin EES
File B-2006
RESEARCH PROJECT INITIATION

Project Title: Ionization and Charge Transfer

Project No.: B-2012

Project Director: Dr. D. W. Martin

Sponsor: Atomic Energy Commission, Oak Ridge, Tennessee

Agreement Period: From 1 March 1969 until 28 February 1970

Type Agreement: Modification No. 11 to Contract No. AT-(40-1)-2591

Amount: $27,542 AEC Funds (B-2012)
8,775 GIT Contribution (E-2010)
$39,317 Total Budget

Contract Administrator
Dr. Dent C. Davis, Jr.
Research Contracts Branch
Laboratory and University Division
United States Atomic Energy Commission
Post Office Box E
Oak Ridge, Tennessee 37830

Reports Required
Progress Report - By 1 December 1969; Seven (7) copies to sponsor

Renewal Proposal - With Progress Report; separately bound, seven (7) copies.

Final Report - Promptly upon termination or expiration of the total period of performance, seven (7) copies.

Note: Continuation of B-2006

Assigned to: School of Physics

Copies To:
- Project Director
- School Director
- Dean of the College
- Administrator of Research
- Associate Controller (2)
- Security-Reports-Property Office
- Patent Coordinator
- Library
- Rich Electronic Computer Center
- Photographic Laboratory
- EES Machine Shop
- EES Accounting Office

Other: Mr. R. A. Martin
File B-2012
GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF RESEARCH ADMINISTRATION

RESEARCH PROJECT TERMINATION

Date: September 30, 1970

Project Title: Ionization and Charge Transfer
Project No: B-2012
Principal Investigator: Dr. D. W. Martin
Sponsor: Atomic Energy Commission
Effective Termination Date: September 15, 1970
Clearance of Accounting Charges: All charges have cleared.

This project is a continuation of B-2006.


COPIES TO:
Principal Investigator
School Director
Dean of the College
Director of Research Administration
Associate Controller (2)
Security-Reports-Property Office
Patent and Inventions Coordinator

Library, Technical Reports Section
Rich Electronic Computer Center
Photographic Laboratory
Terminated Project File No. B-2012

Other
TECHNICAL STATUS REPORT NO. 1
PROJECT NO. B-176
Covering the Period
SEPTEMBER 1, 1959, TO NOVEMBER 30, 1959

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By
E. W. McDaniel
D. W. Martin
J. W. Hooper
D. S. Harmer

CONTRACT No. AT-(40-1)-2591

U. S. ATOMIC ENERGY COMMISSION
OAK RIDGE, TENNESSEE

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia
TECHNICAL STATUS REPORT NO. 1

Project No. B-176

Covering the Period

September 1, 1959, to November 30, 1959

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By

E. W. McDaniel
D. W. Martin
J. W. Hooper
D. S. Harmer

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee
I. Title  
Ionization and Charge Transfer Cross Sections  

II. Objective and Method  
The objective of the research performed under Contract AT-(40-1)-2591 is the measurement of the cross sections for various ionization and charge transfer reactions of hydrogen atoms and ions incident on targets of hydrogen and helium gas. The energy of the incident particles will range from 0.15 to 1.10 Mev. The bulk of the previous work in this area has been confined to incident-particle energies below about 0.04 Mev, while a few charge transfer measurements have extended as far as 1.0 Mev. Thus the present investigation represents an extension into a region that is as yet largely unexplored. Theoretical interpretation of the results will be carried out as far as possible.

The source of energetic particles is a 1-Mev Van de Graaff positive ion accelerator, which is equipped with a beam analyzing and stabilizing system. For experiments with incident hydrogen ions, the analyzed proton beam is used directly. For experiments with incident hydrogen atoms, the proton beam will be passed through a cell containing hydrogen gas, in which a fraction of the incident particles will be neutralized by charge transfer processes. The emerging particles which have not been neutralized will be swept out with an electrostatic field, leaving a pure neutral atomic beam.

The beam will be passed through a collision chamber containing the target gas. The dimensions and gas pressure in this chamber are in every case such that the target is "thin," in the sense that the probability that a given incident particle will undergo any reaction is small. Under these
conditions, multiple reactions by one incident particle are negligible. Electrodes in the collision chamber will collect and measure the slow charged particles left behind when a reaction occurs, while the incident particle passes on out of the collision volume to a detector. In the first phases of the present work detection is based simply on measurement of the electrical current collected. In later phases discrete particle detection will be accomplished with electron multipliers or scintillation detectors, and e/m analysis of both slow and fast particles will be made when required.

The reactions which can occur when fast particles are incident on a gas can conveniently be grouped into two classes, either "ionization" or "charge transfer." In the first class of events, the incident particle emerges unchanged, while the struck molecule is either simply ionized or, in the case of a molecular gas, may be both ionized and dissociated. Either or both of the dissociation fragments may be charged. In the "charge transfer" class are grouped all events in which the incident particle emerges with only a small decrease in its energy and with essentially its original direction of motion, but with its charge changed. The class may again include several different individual kinds of events, in that the struck molecule may only be ionized, or may be dissociated with one or more of the fragments ionized.

Ionization events, as defined above, may be detected only by observing the slow charged particles left behind. These observations require the use of a thin target so that confusion cannot arise because of multiple reactions suffered by a given incident particle. Previous observations have
been made only at energies up to about 0.04 Mev. Charge transfer events can be studied by a different technique, in which observations are made only on the emerging beam of fast particles. The cross sections obtained from such measurements represent, however, only the sums of the cross sections for all of the individual processes that can lead to a given change in the charge of the incident particle. Measurements of this kind have been made previously* for hydrogen ions and atoms incident on hydrogen gas, at energies up to 1 Mev. The present work will serve as an independent check of these results, and will in addition attempt to evaluate the cross sections for each of the several individual reactions that contribute to the total cross section for each charge-changing process.

III. Present Status of the Experimental Work

The first cross section being studied in this investigation is the ionization cross section for protons incident on hydrogen. There are actually four individual processes in this group:

\[ \text{H}^+ + \text{H}_2 \rightarrow \text{H}^+ + \text{H}_2^+ + e \]
\[ \text{H}^+ + \text{H}^+ + \text{H}_2^0 + e \]
\[ \text{H}^+ + \text{H}^+ + \text{H}^+ + 2e \]
\[ \text{H}^+ + \text{H}^+ + \text{H}^- . \]

Of these reactions, the last two represent more complex events than the others, and it is expected that their cross sections will be small. It - - - -

is then possible to measure the sums of the cross sections for the first two reactions simply by collecting the electrons. There is in principle interference from the charge transfer reaction:

\[ \text{H}^+ + \text{H}_2^0 \rightarrow \text{H}^0 + \text{H}^+ + \text{H}^+ + \text{e}^- . \]

However, experiment has shown * that its contribution should be negligible in comparison with that of ionization reactions in the present case.

Apparatus for this measurement is now being constructed. A large collision chamber is fitted with collector plates on either side of and parallel to the incident beam. One will be charged positive to collect the electrons, and the other negative to collect the positive ions. The currents to both electrodes will be measured separately with sensitive electrometers. The electrodes are segmented into seven sections each along the beam direction, so that the effective collision volume from which charges produced by the beam will be measured can be varied. This is done to eliminate end effects. The two rows of electrodes are guarded by other electrodes above and below, to define the top and bottom of the collision volume, and to guard against secondaries from the top and bottom surfaces of the collision chamber. Fine wire grids of high transparency in front of each row of electrodes will suppress the emission of secondary electrons from the collectors themselves. After leaving the collision volume, the incident beam will pass into a Faraday cup to be measured.

Construction of the collision chamber and vacuum system has been essentially completed, and we will be ready to proceed with leak checking as

* Ibid.
soon as we receive some special fittings, which are expected momentarily. A general view of the external features is shown in Fig. 1. The large cylindrical vessel is the main vacuum manifold. The incident beam comes through the port in the wall from the magnet room of the Van de Graaff beyond. All pumps, gauges, and electrometers that will be required for the initial experiment are now on hand. Construction of the internal electrode system will be completed within about one week, and overall testing of the entire apparatus is expected to be started immediately thereafter.

Essentially all of the apparatus that has been constructed for the first experiments will also be used in the later experiments. As may be seen in Fig. 1, the collision chamber is provided with a fitting at the rear end along the beam axis, to which a beam deflector will be attached for charge analysis of the emerging beam. The collision chamber has been made large enough to contain the necessary components, to be added later, for e/m analysis of slow reaction products. The vacuum system has been arranged to provide for maximum flexibility so that it will be compatible with all projected requirements.

IV. Travel and Publications during the Report Period

E. W. McDaniel has traveled to Oak Ridge National Laboratory on two occasions to confer with C. F. Barnett on various aspects of cross section measurement. Much helpful advice has come from these meetings. No project funds have been expended for this travel.

There have been no publications in this report period.

Approved by: Respectfully submitted,

Vernon Crawford E. W. McDaniel
Head, Physics Branch Project Director
Physical Sciences Division
Figure 1. External View of Collision Chamber and Vacuum System.
TECHNICAL STATUS REPORT NO. 2
PROJECT NO. B-176
Covering the Period
DECEMBER 1, 1959, TO FEBRUARY 29, 1960

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By
E. W. McDaniel
D. W. Martin
J. W. Hooper
D. S. Harmer

CONTRACT NO. AT-(40-1)-2591

U. S. ATOMIC ENERGY COMMISSION
OAK RIDGE, TENNESSEE

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia
TECHNICAL STATUS REPORT NO. 2

Project No. B-176

Covering the Period

December 1, 1959, to February 29, 1960

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By

E. W. McDaniel

D. W. Martin

J. W. Hooper

D. S. Harmer

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee
I. Title

Ionization and Charge Transfer Cross Sections

II. Objective and Method

The objective of the research performed under Contract AT-(40-1)-2591 is the measurement of the cross sections for various ionization and charge transfer reactions of hydrogen atoms and ions incident on targets of hydrogen and helium gas. The energy of the incident particles will range from 0.15 to 1.10 Mev. The bulk of the previous work in this area has been confined to incident-particle energies below about 0.04 Mev, while a few charge transfer measurements have extended as far as 1.0 Mev. Thus the present investigation represents an extension into a region that is as yet largely unexplored. Theoretical interpretation of the results will be carried out as far as possible.

The source of energetic particles is a 1-Mev Van de Graaff positive ion accelerator, which is equipped with a beam analyzing and stabilizing system. For experiments with incident hydrogen ions, the analyzed proton beam is used directly. For experiments with incident hydrogen atoms, the proton beam will be passed through a cell containing hydrogen gas, in which a fraction of the incident particles will be neutralized by charge transfer processes. The emerging particles which have not been neutralized will be swept out with an electrostatic field, leaving a pure neutral atomic beam.

The beam will be passed through a collision chamber containing the target gas. The dimensions and gas pressure in this chamber are in every case such that the target is "thin," in the sense that the probability that a given incident particle will undergo any reaction is small. Under these
conditions, multiple reactions by one incident particle are negligible. Electrodes in the collision chamber will collect and measure the slow charged particles left behind when a reaction occurs, while the incident particle passes on out of the collision volume to a detector. In the first phases of the present work detection is based simply on measurement of the electrical current collected. In later phases discrete particle detection will be accomplished with electron multipliers or scintillation detectors, and e/m analysis of both slow and fast particles will be made when required.

III. Present Status of the Experimental Work

The first cross section that is to be measured in this investigation is the total ionization cross section for protons incident on hydrogen gas. The only two reactions that will contribute significantly to this cross section in the present energy range are the following:

\[ \text{H}^+ + \text{H}_2 \rightarrow \text{H}^+ + \text{H}_2 + e \]
\[ \rightarrow \text{H}^+ + \text{H}^+ + \text{H}_2^0 + e \]

The measurement is accomplished by collecting with a transverse electric field the slow ions and electrons that are formed and measuring the currents collected by means of electrometers.

The collecting electrodes must be carefully guarded to prevent spurious contributions to the currents from secondary electrons, and means must be provided to determine the effective target volume from which the charges will reach the collectors. Our concept of an electrode system designed to meet these two requirements has been described previously (Technical Status Report...
Construction of the electrodes is now completed, and a view of one of the two main assemblies is shown in Figure 1. The brass electrode segments are rigidly mounted to a heavy slab of teflon to maintain accurate spacing and alignment. The suppressor grid in front of the assembly is made of .004" stainless steel wires laced around a frame of brass. All the wires lie in the same plane, and are spaced 0.1" apart. The nominal transparency of the grid is 96%.

In operation, all the segments in one assembly are at the same potential, including the two guard strips at the top and bottom. However, separate leads come outside the vacuum system from each of the five center segments of the strip of seven, so that the number of them that are included in the electrometer circuit can be changed externally. In this way, the effective collision volume can be varied to eliminate end effects.

The two electrodes assemblies are identical, and they are mounted facing each other on either side of the beam path. In Figure 2 they can be seen in position inside the collision chamber. The electrode potentials, which establish the sweeping field on the collision volume, will be provided by means of shielded battery packs. Since the electrometers must each be "floated" at the potential of one of the electrodes, it is felt that only batteries can provide a sufficiently stable and quiet potential source. It is expected that the electrode potentials used will be in the range from 1 to 4 kilovolts, depending on how much difficulty is experienced with leakage currents. The batteries for the packs are now on order.

Assembly and testing of the vacuum system has been completed since the writing of the previous report. In the initial tests a number of leaks were
discovered, and some of the welds in the system had to be partially reworked. An additional 4" diffusion pump has been added, which may be seen at the left of Figure 2. At present, it is attached to the collision chamber at the port where the beam analyzer will be located for later charge-transfer experiments. This pump is equipped with a throttling valve arrangement, actuated by the rod projecting through the top of the assembly above the pump, to provide a control over the pressure in the collision chamber. The 2" pumping line from the collision chamber to the main vacuum manifold has also been provided with a valve arrangement that has only fully open or fully closed positions. Neither of these valves is actually vacuum-tight, since their only function is to permit the pressure in the collision chamber to be raised to at least \(10^{-3}\) mm Hg.

At present, the system will pump to a pressure of about \(4 \times 10^{-6}\) mm Hg, as measured by an ion gauge located on the collision chamber. Arrangements to provide for moderate heating of the collision chamber to further improve this performance are under discussion. A possibility considered is to provide internal heaters to warm the electrodes directly by radiation.

In operation, the pressure in the collision chamber is to be in the range \(10^{-3}\) to \(10^{-4}\) mm Hg. To prevent accumulation of background gas, a continuous flow of fresh target gas will be maintained. The possibility that this might produce significant pressure gradients across the target volume has been investigated. Two ion gauges were connected to the chamber at locations several inches apart, and their readings were compared as a function of the purging rate for mean chamber pressures throughout the range of interest. A small difference in reading was evident for high purge rates at the higher
pressures, but a satisfactory working range has been determined in which there was no noticeable difference. A setting of the outlet throttle valves has been found that permits adjustment of the chamber pressure through the entire working range by varying only the gas input rate. With this setting, the background pressure is $8 \times 10^{-6}$ mm Hg when the gas inlet is closed.

Our glass McLeod gauge for making absolute measurements of the target gas pressure has been cleaned and is ready to be installed. The glass connection line, cold trap, and isolation valve are under construction.

IV. Program for the Immediate Future

The apparatus is now being aligned with the beam tube of the Van de Graaff accelerator. The next step will be measurement of the beam current that can be passed through the collision chamber with the present entrance slit arrangement, to determine whether any changes in slit dimensions are indicated. The electrometers must be mounted suitably to be floated at the collector potentials, and any difficulties encountered with electrical leakage must be dealt with. A Faraday cup must be mounted at the collision chamber exit to monitor the beam. We will then be ready to begin the initial measurements.

Detailed discussions are underway concerning the later charge-transfer measurements. A large electromagnet that may be suitable for use as the beam analyzer has been made available to us by the School of Electrical Engineering at Georgia Tech. It has 8" diameter pole faces, a gap width of 3-1/2", and can produce a mean field of about 10 kilogauss. Our original plan had been to construct an electrostatic analyzer, and a final decision as to whether we will do this or use the magnet has not yet been made.
V. Travel and Publications during the Report Period

E. W. McDaniel has traveled to Oak Ridge several times for consultations with C. F. Barnett and others in connection with similar work being conducted there. These consultations are proving to be of great value to our effort at Georgia Tech. No project funds have been expended for this travel.

There have been no publications in this report period.

Respectfully submitted,

E. W. McDaniel  
Project Director

Approved by:

Vernon Crawford  
Head, Physics Branch  
Physical Sciences Division
Figure 1. Single Electrode Structure.
Figure 2. Interior View of the Collision Chamber.
TECHNICAL STATUS REPORT NO. 3

PROJECT NO. B-176

Covering the Period

MARCH 1, 1960 TO MAY 31, 1960

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By

E. W. McDaniel
D. W. Martin
J. W. Hooper
D. S. Harmer

CONTRACT NO. AT-(40-1)-2591

U. S. ATOMIC ENERGY COMMISSION
OAK RIDGE, TENNESSEE

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia
TECHNICAL STATUS REPORT NO. 3

Project No. B-176

Covering the Period

March 1, 1960 to May 31, 1960

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By

E. W. McDaniel
D. W. Martin
J. W. Hooper
D. S. Harmer

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee
I. Title

Ionization and Charge Transfer Cross Sections

II. Objective and Method

The objective of the research performed under Contract AT-(40-1)-2591 is the measurement of the cross sections for various ionization and charge transfer reactions of hydrogen atoms and ions incident on targets of hydrogen and helium gas. The energy of the incident particles is in the range from 0.15 to 1.10 Mev. The bulk of the previous work in this area has been confined to incident-particle energies below about 0.04 Mev, while a few charge transfer measurements have extended as high as 1.0 Mev. Thus the present investigation represents an extension into a region that is as yet largely unexplored. Theoretical interpretation of the results will be carried out as far as possible.

The source of energetic particles is a 1-Mev Van de Graaff positive ion accelerator, which is equipped with a beam analyzing and stabilizing system. For experiments with incident hydrogen ions, the analyzed proton beam is used directly. For experiments with incident hydrogen atoms, the proton beam will be passed through a cell containing hydrogen gas, in which a fraction of the incident particles will be neutralized by charge transfer processes. The emerging particles which have not been neutralized will be swept out of the beam with an electrostatic field.

The beam is passed through a collision chamber containing the target gas. The dimensions and gas pressure in this chamber are such that the target is "thin," in the sense that the probability that a given incident particle will undergo any reaction is small. Under these conditions, multiple reactions by one incident particle are negligible. Electrodes in the collision chamber
collect and measure the currents of slow charged particles produced when a reaction occurs, while the incident particle passes on out of the collision volume to a detector. In the first phases of the present work detection is based simply on measurement of the electrical current collected. In later phases discrete particle detection will be accomplished with electron multipliers or scintillation detectors, and e/m analysis of both slow and fast particles will be made when required.

III. Present Status of the Experimental Work

The first cross section that is being measured in this investigation is the total ionization cross section for protons incident on hydrogen gas. The only two reactions that will contribute significantly to this cross section in the present energy range are the following:

\[ \text{H}^+ + \text{H}_2^0 \rightarrow \text{H}^+ + \text{H}_2^+ + e \]
\[ \rightarrow \text{H}^+ + \text{H}_2^+ + \text{H}_2^0 + e \]

The measurement is accomplished by collecting with a transverse electric field the slow ions and electrons that are formed and measuring the currents collected by means of electrometers.

A. New Construction

The electrometers have been mounted isolated from ground on lucite blocks and are provided with AC power through isolation transformers, so they can be floated at the high potentials of the collector electrodes. A grounded screen cage completely encloses both instruments, as well as the battery packs that provide the high potentials. Performance of the electrometers has been tested with polarizing potentials up to 2100 volts. Although the noise in the
output was somewhat greater than when the instrument is grounded, it is found to be several orders of magnitude less than the ionization currents to be measured.

The segmented construction of the collector electrode assemblies, with their guard electrodes and suppressor grids, has been described in a previous report (Technical Status Report No. 2). Separate leads from each of the ten segments, the two guard assemblies, and the two grids pass out of the collision chamber through Kovar-glass seals, and proceed to the electrometer cage through double-shielded cables. The outer shield of each cable is grounded, while the inner shield is held at the same potential as the enclosed current lead, to guard against the introduction of leakage currents into the measuring circuit. The interconnections that determine how many of the electrode segments are included in the electrometer circuit are made on a patch board inside the electrometer cage, so the arrangement may be changed without entering the collision chamber.

The Kovar-glass seals used in the chamber wall are not of a double concentric type that would permit the same guard arrangement in the seals as in the cables. It is found that appreciable leakage currents are introduced at this point when the high potentials are applied. Tests have shown that the currents are ohmic up to at least 1800 volts, are reproducible over a period of hours, and in any case are less than 5% of the smallest ionization currents to be measured. We feel that they present no problem, at least for the present.

A Pyrex flask has been suspended in the main pumping outlet of the collision chamber, to serve as a cold trap. Filling this flask with liquid nitrogen improves the ultimate vacuum in the chamber by a factor of two.

A Faraday cup has been installed in the chamber to collect the proton beam after it has traversed the collision volume. A suppressor electrode is
located in front of the cup, having an aperture slightly smaller than the open end of the Faraday cup, but several times the diameter of the beam. Both of these components are wired to the electrometer patch board in the same fashion as the ionization current electrodes. Monitoring the current to the suppressor was invaluable in aligning the apparatus with the Van de Graaff beam.

Internal alignment of the entrance apertures, collection electrodes, and beam cup was done optically. The whole assembly has been coupled to the Van de Graaff exit port and aligned with the beam. A beam viewer was installed just ahead of the first aperture as an alignment and beam focusing aid. In addition, a vacuum-tight gate valve is installed in the connection tube. This permits us to disconnect the Van de Graaff when it is needed for other purposes, without disturbing the vacuum in this apparatus.

Installation of the McLeod gauge that is to provide absolute measurement of the collision chamber pressure has been deferred. This instrument is so bulky and fragile that accidental breakage during alignment adjustments was feared. The chamber pressure in all the preliminary observations described below was determined only with ion gauges, using the manufacturer's nominal calibration figure. Thus, the absolute values of the cross sections mentioned are regarded as uncertain by perhaps 20%. Since the positioning of the apparatus is now final, we are proceeding with installation of the McLeod gauge.

Using the maximum beam output of the Van de Graaff at 1 Mev, we have been able to collect a current of up to $0.75 \times 10^{-6}$ amp in the through-beam Faraday cup. The current has erratic short term fluctuations, but the long term stability of the average value appears to be satisfactory. As indicated
below, this beam intensity provides ionization currents to the collector electrodes more than 10 times the background currents due to background gas and leakage, and thus provides a satisfactory "signal-to-noise" ratio.

When the beam energy is reduced from 1 Mev, however, there is a reduction in the maximum current through the chamber, amounting to about 25% at 0.6 Mev. This unexpected effect is presumably the result of beam defocusing due to mutual repulsion. (The flight distance from the magnet, through the shielding wall, to the first of the entrance apertures is some seven feet.) The adverse effects of this phenomenon are partly compensated by the fact that all the cross sections of interest increase as the energy decreases. However, it may prove necessary to provide additional focusing if we are to get satisfactory results at energies down to 0.15 Mev.

Until recently, the beam analyzing magnet could not be operated at fields less than that corresponding to 600 kev beam energy, so the effect mentioned above has not yet been investigated below this energy. The coil connections of the magnet have now been changed to extend the operating range down to 0.15 Mev. It should be possible to determine soon whether additional focusing will be necessary.

B. **Performance Data**

The magnitude of the transverse ion collection field across the collision volume is determined by the potentials of the suppressor grids positioned in front of the collector electrodes. In all cases, the two grids are held at plus and minus potentials of equal magnitude $V_c$ with respect to ground. Both collector electrodes are held positive with respect to their respective grids by equal voltages designated $V_s$. This information is summarized in Figure 1.
Electron Collector  + $V_c + V_s$
Suppressor Grid  + $V_c$
Beam Axis  0
Suppressor Grid  - $V_c$
Positive Ion Collector  - $V_c + V_s$

Figure 1. Arrangement of electrode and grid potentials.

We have observed the variations in the electrometer currents as $V_c$ and $V_s$ were varied, while the energy and intensity of the incident beam and the gas pressure in the chamber were held constant. With $V_s$ fixed at 150 volts, the currents at first increase rapidly with $V_c$, but reach saturation when $V_c$ is about 900 volts. A slight linear increase from 900 to 1800 volts can be attributed entirely to the ohmic leakage currents that are obtained with no incident beam. Evidently, any value of $V_c$ in excess of 900 volts is sufficient to insure that sensibly all ions formed in the effective collision volume are collected. In all subsequent observations detailed below, the value $V_c = 1050$ volts was used.

It was also verified that $V_s = 150$ volts is enough to insure suppression of all secondary-electron emission from the collectors. With $V_c$ fixed at 1050 volts, both currents were constant for $V_s$ between 120 and 300 volts, although deviations were observed at 90 volts or less. The value $V_s = 150$ volts was then used in all subsequent observations.

Installation of the electrode assemblies in the collision chamber made no material difference in the vacuum performance of the system, as described in a previous report (Technical Status Report No. 2). In operation, the
collision chamber is pumped continuously while a steady flow of fresh target
gas (hydrogen) is admitted. Throttling of the pumping outlet has been adjusted
so that equilibrium chamber pressures up to $9 \times 10^{-4}$ mm Hg can be maintained
with a gas throughput that does not exceed the capabilities of the vacuum
pumps. Previous tests have verified that there are no appreciable pressure
gradients in the chamber under these conditions.

The ultimate background pressure with the inlet closed and with liquid
nitrogen in the cold trap is $4 \text{ to } 5 \times 10^{-6}$ mm Hg as indicated by the ion gauge
(using the calibration for nitrogen). When a maximum-intensity beam of 1-Mev
protons is passed through the chamber, the collector currents are just twice
the leakage currents observed with no incident beam. Thus the correction for
ionization produced in the residual gas is equal to that for ohmic leakage.
The sum of these two "background" currents was less by a factor of 12.4 than
the current collected with hydrogen admitted to the chamber to typical oper-
ating pressure of $5 \times 10^{-4}$ mm Hg, with the beam energy at 1.0 Mev. The
ratio should become even more favorable at lower energies because of the
increase in the hydrogen cross section.

This performance is judged to be satisfactory for making cross section
measurements to the desired accuracy, provided the loss of incident beam
intensity at lower energies does not prove to be too severe. Consequently,
we have not proceeded with previous plans to provide radiant heating of the
chamber interior to improve outgassing. Further experience may, of course,
indicate that this procedure will be necessary.

The ionization currents collected from hydrogen at $5 \times 10^{-4}$ mm Hg and
1.0 Mev are in the ratio of 1 to 62 to the total beam current. This
observation verifies that the target is "thin" in that only a small fraction of the incident particles suffer an ionization collision within the effective collision volume.

The ratios of the collector currents obtained when 1, 3 and 5 pairs of collector segments were included in the measurement circuit stood in the ratio 1 : 3 : 5 within the measurement precision. This verifies that the guard electrode arrangement does make the "effective" target thickness exactly equal to the total length of all segments included in the electrometer circuit.

The collector currents were also found to be closely proportional to the gas pressure in the chamber over the range from 1.0 to $9.0 \times 10^{-4}$ mm Hg. The values of the ionization cross section that were calculated, using a thin target assumption, has a total spread of about 3% in this test. Thus our determination is verified to be independent of the pressure used over at least this range.

C. Preliminary Results

A preliminary measurement of the total ionization cross section for protons on hydrogen has been made over the energy range from 0.6 to 1.0 Mev. As mentioned above, the gas pressure was measured only with an uncalibrated ion gauge, so an uncertainty of perhaps 20% in the pressure is reflected directly in the cross section values.

These results agree within 20% with the theoretical curve of Bates and Griffing.* Furthermore, the rate of change with energy is in rather close agreement.

It is noteworthy that the positive and negative ion currents collected have been equal in every case so far. This assures us that the collection

efficiencies are equal and are essentially just the transmission factor of the suppressor grids. It further verifies the assumption that there is negligible contribution from charge-transfer events.

IV. Program For The Immediate Future

Installation of the McLeod gauge will greatly reduce the uncertainty in the chamber pressure and put the absolute values of our cross sections on a much firmer basis.

We are installing a palladium leak for the hydrogen inlet, in place of the present needle valve. These devices will pass hydrogen through the body of the metal when heated, but are essentially impervious to any other molecule. Thus, high purity of the admitted hydrogen is automatically assured.

We intend to determine immediately how serious the beam defocusing at reduced energies is going to be. Possible steps to minimize the difficulty are under discussion.

Provided this problem does not introduce an unusual delay, we expect to complete the study of the ionization cross section for protons on hydrogen and helium within the coming quarterly period. Meanwhile, plans will be completed and construction begun for the later phases of the proposed effort.

V. Travel and Publications during the Report Period

E. W. McDaniel has traveled to Oak Ridge on two occasions for consultations with C. F. Barnett and others in connection with similar work being conducted there. These consultations are proving to be of great value to our effort at Georgia Tech. No project funds have been expended for this travel.

There have been no publications in this report period.
Respectfully submitted,

E. W. McDaniel  
Project Director

Approved by:

Vernon Crawford  
Head, Physics Branch  
Physical Sciences Division
TECHNICAL STATUS REPORT NO. 4
(FIRST ANNUAL REPORT)
Covering the Period
SEPTEMBER 1, 1959, TO AUGUST 31, 1960

IONIZATION CROSS SECTIONS IN THE
ENERGY RANGE 0.15 - 1.10 MEV.
PHASE I: H⁺ Ions Incident on H₂ Targets

By
E. W. McDaniel
D. W. Martin
J. W. Hooper
D. S. Harmer

CONTRACT No. AT-(40-1)-2591

U. S. ATOMIC ENERGY COMMISSION
OAK RIDGE, TENNESSEE

SEPTEMBER 1, 1960

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia
TECHNICAL STATUS REPORT NO. 4
(FIRST ANNUAL REPORT)

Project No. B-176

Covering the Period

September 1, 1959, to August 31, 1960

IONIZATION CROSS SECTIONS IN THE
ENERGY RANGE 0.15 - 1.10 MEV.
PHASE I: H+ Ions Incident on H₂ Targets

By

E. W. McDaniel
D. W. Martin
J. W. Hooper
D. S. Harmer

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee

September 1, 1960
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Figures</td>
<td>iii</td>
</tr>
<tr>
<td>Abstract</td>
<td>iv</td>
</tr>
<tr>
<td>I. Title</td>
<td>1</td>
</tr>
<tr>
<td>II. Objective And Method</td>
<td>1</td>
</tr>
<tr>
<td>III. Present Status Of The Experimental Work</td>
<td>3</td>
</tr>
<tr>
<td>IV. Experimental Results</td>
<td>22</td>
</tr>
<tr>
<td>V. Comparison With Theory</td>
<td>27</td>
</tr>
<tr>
<td>VI. Program For The Immediate Future</td>
<td>31</td>
</tr>
<tr>
<td>VII. Travel And Publication During The Past Quarter</td>
<td>32</td>
</tr>
<tr>
<td>VIII. Acknowledgements</td>
<td>32</td>
</tr>
<tr>
<td>IX. Appendix - Cross Section Calculations</td>
<td>33</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Schematic View of Apparatus for Gross Ionization Measurements</td>
<td>4</td>
</tr>
<tr>
<td>2.</td>
<td>Interior View of the Collision Chamber</td>
<td>7</td>
</tr>
<tr>
<td>3.</td>
<td>Incident Beam Collected in Faraday Cup vs. Suppression Voltage</td>
<td>11</td>
</tr>
<tr>
<td>4.</td>
<td>Single Electrode Structure</td>
<td>13</td>
</tr>
<tr>
<td>5.</td>
<td>Apparent Ion Currents vs. Suppressor Grid Voltage for Constant Collection Field</td>
<td>16</td>
</tr>
<tr>
<td>6.</td>
<td>Observed Ionization Cross Section for Various Collection Field Strengths</td>
<td>17</td>
</tr>
<tr>
<td>7.</td>
<td>Leakage Currents vs. Collection Voltage</td>
<td>20</td>
</tr>
<tr>
<td>8.</td>
<td>Impurity Contribution for Protons Incident on Background Gas</td>
<td>24</td>
</tr>
<tr>
<td>9.</td>
<td>Computed Ionization Cross Section for Varying Target Gas Pressure</td>
<td>25</td>
</tr>
<tr>
<td>10.</td>
<td>Gross Ionization Cross Section for Protons Incident on Molecular Hydrogen</td>
<td>28</td>
</tr>
</tbody>
</table>
ABSTRACT

Measurements have been made of the ionization cross section for protons incident on hydrogen gas in the energy range 0.15-1.10 Mev. The experimental cross section in this region can be represented by

\[ \sigma_1 = 3.45 \times E^{-0.870} \times 10^{-17} \text{ cm}^2/\text{molecule}, \]

where \( E \) is the incident proton energy in Mev. The experimental results are in excellent agreement with a Born approximation calculation, which is discussed.
I. Title

Ionization Cross Sections in the Energy Range 0.15-1.10 Mev.*

Phase I: \( \text{H}^+ \) Ions Incident on \( \text{H}_2 \) Targets.

II. Objective and Method

The objective of the research performed under Contract AT-(40-1)-2591 is the measurement of the ionization cross section for protons incident on targets of hydrogen and other gases. The energy of the incident particles ranges from 0.15 to 1.10 Mev. Previous work in this area has been confined to incident-particle energies below 0.18 Mev. Thus the present work represents an extension into a region that is largely unexplored. Correlation of the experimental results is carried out with the available theory.

The source of energetic protons is a 1-Mev Van de Graaff positive ion accelerator, which is equipped with a beam analyzing and stabilizing system. The beam is passed through collimating apertures and into a collision chamber containing the target gas. The chamber dimensions and gas pressure are such that the target is "thin," in the sense that only a small fraction of the incident particles undergo any collisions at all. Electrodes parallel to the beam axis in the collision chamber collect the slow charged particles produced in ionizing collisions, while the original incident particles pass through the collision volume and into a Faraday cup. Detection of both the slow and fast particles is accomplished by electrometer measurements of the electron and ion currents.

*Formerly entitled "Ionization and Charge Transfer Cross Sections."
The originally stated objectives included measurements of the charge transfer cross sections for hydrogen ions and atoms incident on hydrogen. A recent decision was made to defer these measurements in favor of more extensive ionization cross section measurements than were proposed originally.
The atomic and molecular reactions that can occur when fast atoms or atomic ions collide with the molecules of a target gas may be conveniently classed as either "ionization" or "change-transfer" events. In either case the incident particle almost always suffers only a small loss of energy and emerges with only a slight deviation from its original direction of motion. There is no general agreement on the exact definition of these two types of events. We choose to define them as follows: In an "ionization" event, the fast particle ionizes the struck molecule but emerges with no change in its own charge state, while in a "charge transfer" event the fast particle either gains or loses one or more electrons in the collision. For a given projectile on a given target, each class of event in general includes several distinct kinds of reactions differing in the array of slow residual particles that are produced. The energies of the latter are usually low, although a small fraction of them may have energies as high as a few hundred electron volts.

In charge transfer studies, the sum of the cross sections for all types of events that produce a given change in the charge state of the fast particle may be measured by observing the distribution of charge states in the emerging fast beam. Such measurements have been made previously for hydrogen atoms and ions incident on hydrogen gas with energies up to 1.0 Mev. (1) The observed cross sections indicate that in our energy range charge transfer events should not make a significant contribution to the gross ion production. (In Section III-d, it is shown that our experimental results bear out this expectation.)

---

To study ionization events one must collect and observe the slow charged particles produced by the collision, since the emerging fast beam contains no information about the occurrence of these events. To avoid confusion due to multiple reactions by a single incident particle, the target must be "thin" in the sense that most of the incident particles will traverse the target with no collisions at all. One previous study of protons on hydrogen has been made for energies up to 0.18 Mev, (2) but the bulk of other previous work has been confined to energies of less than 0.04 Mev. (3)

III. Present Status of the Experimental Work

Apparatus for measurement of gross total ionization cross sections has been constructed, and a variety of tests of its performance have been completed. Satisfactory operating ranges for each of the several experimental parameters have been determined. The cross section for protons incident on hydrogen gas has been measured in detail over the range of incident particle energies from 0.15 to 1.10 Mev. The results are now regarded as final and are presented in Section IV of this report.

A schematic drawing of the apparatus is given in Figure 1, which includes a number of the most relevant dimensions. Following is a point by point discussion of the more important features of the apparatus, some of which is a repetition of material contained in our previous quarterly reports (Technical Status Reports Nos. 1, 2, and 3).

(2) V. V. Afrosimov, R. N. Il'in and N. Fedorenko, Sov. Phys. JETP 34, 968 (1958).

Figure 1. Schematic View of Apparatus for Gross Ionization Measurements.
(a) The Incident Beam Source

Before entering the apparatus at the right side of Figure 1, the beam from the Van de Graaff accelerator is first deflected through 90° in an analyzing magnet, which assures that it consist essentially only of protons. The proton energy is stabilized by electronic regulation of the accelerator voltage to maintain equal currents on the two slit edges at "a", which amounts to demanding a constant deflection in the regulated magnetic field. (This is the standard stabilizing system provided by the accelerator manufacturer, the High Voltage Engineering Corporation. The nominal energy spread is ± 2 kev at 1 Mev.) Thus the particle energy is determined by the value of the magnetic field and is measured by measuring that field. For this purpose we use a Harvey Wells model G-501 nuclear magnetic resonance precision gaussmeter, which, as used in our experiments, has relative and absolute accuracies of one part in 10^3. The deflection geometry has been calibrated empirically by measuring the magnetic field corresponding to the 1.019-Mev threshold of the nuclear reaction H^3(p,n)He^3, using a tritium-zirconium target.

Referring again to Figure 1, the round, knife-edged apertures "b" and "c" are machined through 1/2-inch thick brass plates which, except for the apertures, are vacuum-tight closures of the beam tube. With this arrangement, there is no noticeable rise of pressure in the accelerator vacuum system when the collision chamber is filled with hydrogen to our highest working pressures (10^-3 mm Hg).

Collimation of the 1/16-inch diameter beam emerging from aperture "c" into the collision chamber is determined by that aperture and by the 0.10-inch analyzer exit slit at "a". (The beam width perpendicular to the page
at "a", observed visually with a fluorescent "viewer" target, is also of the order of 0.10 inch.) The maximum angular divergence from the axis which an emerging particle may have is only about 4 minutes, unless it has been scattered. The knife-edged design of apertures "b" and "c" minimizes scattering from their edges, and the geometry will permit very few particles that have been scattered by residual gas in the beam tube to pass both "b" and "c". All components to the left from "b" were aligned with one another optically, and the entire assembly was oriented with respect to the analyzing magnet so as to maximize the current delivered to the Faraday cup at the left.

Because of the large distance between "a" and "b" (the analyzing magnet is in a different room from the rest of the apparatus), the beam impinging on aperture plate "b" remains diffuse even with optimum adjustment of the accelerator focus controls. As a result, at 1.0 Mev, the beam emerging from "c" contains at best only about 0.8 microamperes of the 30 microamperes incident on "b". As the energy is reduced from 1.0 Mev, the beam becomes even more diffuse and the transmitted intensity correspondingly lower. However, in the present hydrogen measurements, the accompanying increase in the cross section compensates to the extent that uncertainties directly attributable to low intensity are not significant.

(b) The Collision Chamber

A photograph of the open collision chamber is shown in Figure 2. The collimated beam entering from the right passes between the two identical electrode assemblies and into a Faraday cup located in the pump-out arm to the left. Electrical connections from the electrodes pass to the outside through 16 kovar-glass seals in the rear wall of the chamber. The chamber
Figure 2. Interior View of the Collision Chamber.
may be evacuated by the four-inch baffled oil diffusion pump at the left. In the photograph, the cylinder at left above the pump contained a throttle valve arrangement actuated by the rod extending from the top of the assembly. This has been replaced by the small pyrex flask shown in Figure 1, which serves as a liquid nitrogen cold trap. Additional pumping can be provided by a 2-inch connection from the large hole at the top of the back wall into the large vacuum manifold in the background. This connection is normally closed off by a rotating valve arrangement (visible in the hole) which can be rotated to the open position by external manipulation with a hand magnet. Two ionization vacuum gauges are attached at holes visible in the lower part of the chamber, and a cold-trapped McLeod gauge is connected to a hole, hidden by the electrode assemblies, that looks directly into the space between the assemblies. The target gas is admitted through a leak attached to one of the holes at the upper right.

The effective pumping aperture to the main pump on the left has deliberately been severely constricted by the placement of the Faraday cup in the pump-out arm. The pump is operated continuously, even during a run when the target gas is in the chamber at the working pressure. The constriction has been adjusted so that the resulting throughput of gas does not exceed the capabilities of the associated forepump. Working pressure is maintained by a continuous input of fresh target gas and may be varied throughout our working range from $10^{-4}$ to $10^{-3}$ mm Hg simply by adjusting the input rate. The object of this constant pumping arrangement is to keep the impurity level in the chamber essentially constant, independent of the working gas pressure. Thus, the ionization currents due to impurities, which are measured with no target gas input, can be subtracted directly
from all the readings with target gas present. In the hydrogen measurements this "background gas" correction ordinarily amounted to only about 5 per cent. The ultimate pressure in the chamber, obtained by closing the inlet, was too small to be read meaningfully with the McLeod gauge. It is measured by the ionization gauges, using the manufacturer's nominal calibration for nitrogen, and has an average value of about $6 \times 10^{-6}$ mm Hg.

Detailed comparison of the readings of the two ion gauges with various gas input rates shows no significant pressure gradient between the two gauge locations for any setting that provides an equilibrium pressure within our working range.

(c) Measurement of the Incident Beam Intensity, $I_1$

The Faraday cup which collects the incident protons after they have traversed the collision volume is a bottle-shaped copper cup whose diameter is smallest at the open neck. The 1/2-inch inside diameter of the neck subtends an angle of $2^\circ$ at the entrance aperture, "c", and about twice that angle at a point on the beam axis at the center of the effective collision volume. Both theoretical and experimental evidence indicates that fast incident protons will scatter more than $1^\circ$ in less than one per cent of all collisions. With the "thin target" gas density used in these experiments, fewer than 2 per cent of the incident protons undergo any sort of ion-producing collisions, and the number undergoing large-angle elastic scattering collisions should be negligible. It was expected that far less than one per cent of all incident particles would fail to enter the collection cup. To check this experimentally, a larger cup having a one-inch square opening was tried, and this gave values for the cross sections identical to those from the smaller round cup within all the other experimental uncertainties.
A disc-shaped "shadow" electrode with a sharp-edged circular aperture just smaller than the inside diameter of the mouth of the cup is located immediately in front of the cup and intercepts those few particles which have scattered through an angle so large that they would not have entered the cup. If not stopped, such particles might strike the outside of the cup and release secondary electrons, resulting in a false increase in the apparent collected current. This "shadow" electrode is held at a negative potential with respect to the Faraday cup to suppress the escape of secondary electrons from the interior of the cup. In Figure 3 the collected current for constant incident beam intensity is plotted as a function of this suppression voltage. The lower curve applies to the bottle-shaped cup and shows that the apparent current is too high by over 10% when there is no suppression, despite the deep design of the cup. The current assumes a constant asymptotic value for suppression voltages exceeding about 30 volts. The convenient value of 67-1/2 volts was subsequently used throughout our measurements.

The upper curve in Figure 3 was obtained with the second Faraday cup mentioned previously, which is a box one-inch square and 7/8-inch deep. There is no "shadow" electrode in this case, but one side wall of the box is held negative to provide suppression. As expected, with the more open design of this cup, a larger suppression voltage is required to reduce the current to its asymptotic value. The two curves are arbitrarily scaled to approach the same asymptotic value to reflect the fact, mentioned earlier, that using either cup in the cross section measurement gives the same results within all other experimental uncertainties. The bulk of the present data was obtained with the round cup.
Figure 3. Incident Beam Collected in Faraday Cup vs. Suppression Voltage.
(d) The Collector Assemblies and Electrometers

A photograph of one of the two identical slow-ion collector assemblies is shown in Figure 4. The collector plate is in nine segments, each separately mounted to the rigid 3/8-inch thick teflon backing, with its front surface 1/4 inch in front of the backing. The five center segments are all cut to an accurate length of 1.106 ± .001 inches in the beam direction, and all segments are accurately spaced 0.010 inches apart. All nine sections are always held at the same potential, so that the field in front of the assembly is essentially the same as if it were one large continuous plate. However, only the ion (or electron) currents collected by one or more of the five central segments are ever included in the electrometer circuit for measurement. The remaining segments serve as guards to assure that the field in front of the active segments is parallel and uniform, so there will be no edge effects due to fringe fields. Thus the "effective volume" of the target gas from which the ion currents will be measured is the rectangular parallelepiped defined by the active segments of the two collector assemblies. Edge effects at one end of this volume which are due to forward momentum of the slow ions should be exactly compensated by the same effects at the other end, since the incident fast beam is not attenuated or scattered appreciably across the volume.

Each of the five central segments of each assembly has a separate lead to the outside, so that changes in the number of active segments may be made externally. The proportionality of the "effective volume" to the number of active segments has been tested experimentally. The currents collected to one, to three, and to all five segments, corrected for leakage and normalized to the same incident beam intensity, were found to lie in the
Figure 4. Single Electrode Structure.
ratio of 1:3:5 within all other experimental uncertainties. Therefore, the target thickness used in computation of the cross sections is simply the combined length of all the active segments. In the bulk of the measurements, we used only the three center segments, for which the target thickness is 3.318 inches.

Each collector assembly also has a grid, which can be seen in Figure 4. It consists of 0.004-inch diameter stainless steel wires strung 0.100 inch apart on a brass frame, and is positioned 1/4 inch in front of the collector plate surface. Each grid is held negative with respect to its collector to suppress the emission of secondary electrons. While the plate which is held positive to collect electrons and negative ions would not really appear to need a suppressor, it was our intention to make both collector assemblies as nearly identical as possible in order to achieve a high degree of symmetry. It has been verified that there is no change in our measured cross section values when the roles of the two collector assemblies are interchanged. The ion transmission of these grids is assumed to be essentially equal to their geometric transmission, which is 96 per cent.

A significant fraction of the "slow" ions produced by energetic protons may in fact have substantial energies of 100 ev and more, and their initial motion may of course be directed toward the wrong collector plate. A substantial "collection" field across the collision volume is required to assure that essentially all particles will reach the proper collector. Actually, the collection field will be determined by the potentials of the two suppressor grids. For symmetry, the two grids are maintained at potentials of equal magnitude but opposite sign with respect to the grounded
chamber. We designate this magnitude hereafter as $V_c$ (c for "collection"). Each collector plate is positive with respect to its grid by an amount we have designated $V_s$ (s for "suppression"). Thus the electron collector is at the positive potential $+(V_c + V_s)$, while the positive-ion collector is at the negative potential $-(V_c - V_s)$.

The magnitudes of $V_c$ and $V_s$ must be chosen large enough that the collected currents show saturation and do not change for any further increase of either $V_c$ or $V_s$. We designate the collected positive-ion current $I^+$, the collected electron current $I^-$, and the incident beam current collected at the Faraday cup $I_i$. The observed ratios $I^+/I_i$ and $I^-/I_i$ for constant $V_c = 750$ volts are plotted against $V_s$ in Figure 5, for two different incident beam energies. Saturation is evidently achieved for $V_s$ greater than 50 volts. The value $V_s = 150$ volts proved to be convenient and has been used in the bulk of the measurements.

It may be noted in Figure 5 that the ordinate is not in arbitrary units. The saturation values of $I^+$ and $I^-$ are equal, within our ability to read the meters, at both of the energies shown for protons incident on hydrogen. This indicates that charge-transfer reactions are not making any appreciable contribution to the observed positive-ion current. Further, the small values of the ratio $I^+/I_i$ (less than $10^{-2}$) verify the earlier assertion that the target is "thin".

In Figure 6 are plotted the values of the gross ionization cross section $\sigma_i$ at 1.0 Mev computed from measurements made with various values of $V_c$ and constant $V_s = 150$ volts. The scatter of the points reflects all of the several uncertainties which enter into this computation, and does not exceed our stated overall uncertainty (see Section IV). It is concluded
Figure 5. Apparent Ion Currents vs. Suppressor Grid Voltage for Constant Collection Field.
Figure 6. Observed Ionization Cross Section for Various Collection Field Strengths.
that saturation has already been reached at $V_c = 450$ volts, the smallest value investigated. (A statement in one of our earlier reports that saturation was not reached below about 900 volts has not been borne out by more careful investigation.) We have used the value $V_c = 1050$ volts in obtaining the bulk of the data for protons on hydrogen. Below 0.3 Mev incident proton energy, the collection voltage had to be removed while reading the incident beam current, because it was found to deflect the incident beam off the opening of the Faraday cup. Complete runs at lower $V_c$ of 750 volts and 450 volts, where this procedure was not necessary, gave identical results. The overall collection efficiencies are taken to be equal to the geometric transmission factors of the grids, or 96 per cent.

The two Keithley model 410 electrometers used for current measurements have to be floated from laboratory ground at the potentials of the collectors. They are isolated from their mounting rack by lucite blocks and are completely enclosed by a well-grounded screen cage. AC power is supplied through isolation transformers. The DC polarizing potentials are supplied by shielded battery packs which are also enclosed in the cage, because any ripple or noise in this supply is capacitively coupled into the electrometer input. Under the present conditions, the noise from this source is such as would interfere with current measurements in the $10^{-13}$ ampere range, but it is negligible for the smallest currents ($10^{-11}$ amperes) encountered in the present measurements.

The most serious source of noise in these experiments comes directly from the behavior of the incident proton beam. Although the current entering the collision chamber has satisfactory long-term stability, its
instantaneous value varies rapidly and erratically. We have added damping
time constants to the electrometer input circuits to reduce the meter
jitter. In practice, one electrometer is used to measure either $I^+$ or $I^-$,
while the second is used for simultaneous reading of the incident beam
intensity $I_i$. The two meters are in close physical proximity so that
both can be seen at the same time. The ratios $I^+/I_i$ or $I^-/I_i$ can be ob-
served to an estimated 2 per cent maximum uncertainty, including both
reading error and the inherent uncertainty of the electrometer.

A most important factor that has not yet been mentioned is that of
leakage currents. The construction of the collector assemblies is such
that the leakage paths from the active collector segments across the teflon
mounting plate to the grounded collision chamber are long and of very high
resistance, and the resulting leakage currents across the teflon are
negligible. The leads to the kovar-glass seals in the chamber wall are
stiff copper wires that do not touch any surface. Each of the leads from
the outside end of a seal to the electrometer cage is doubly-shielded,
consisting of a coaxial cable with a heavy rubber outer jacket, slipped
inside an extra braided wire sleeve. Only the outermost shields are
grounded, while the inner shields of all cables are held at the same
potentials as their central current leads. The kovar-glass seals them-
selves are however unguarded since they are not of a doubly-concentric
type that would permit the same arrangement as in the cables. (Such
seals are obtainable and can be substituted in the future if necessary.)

A typical set of leakage currents to the positive-ion collector is
shown in Figure 7 for several values of $V_c$, with $V_s = 150$ volts. While
not strictly ohmic, the currents are small and steady, and vary with
Figure 7. Leakage Currents vs. Collection Voltage.
voltage in a regular way. They reproduce well over periods of hours, although there is some day-to-day variation that is presumably related to atmospheric conditions. We read the leakage current at frequent intervals during all data runs. In most cases it constitutes a correction of less than 5 per cent to the ion current reading, and contributes a negligible uncertainty. In all of the previous discussion throughout Section III, it is implied that all ion current readings mentioned are corrected for leakage.

To clarify any possible confusion about the arrangement of the high-voltage connections, we summarize as follows:

Each of the five central segments of a collector assembly have separate leads. A sixth lead connects to all four of the outer guard segments, and a seventh to the grid. All seven leads pass out of the vacuum through separate kovar-glass seals, and through separate doubly-shielded cables to a teflon patch board inside the electrometer cage.

The high-voltage tap of the polarizing battery pack is connected directly to the electrometer frame and to the inner shields of all seven cables. The physical arrangement is such as to avoid any "loops" for pickup.

The leads from the outer guard segments and from any "inactive" inner segments are also connected directly to the battery at the patch board.

The leads from all active segments are joined at the patch board and connect only to the electrometer input. The internal feedback arrangement of the electrometer limits the potential difference between the input and the frame to a few millivolts for any value of the input current, so
that the active segments have essentially the same potential as the guards.

IV. Experimental Results

(a) Summary of experimental method.

The gross ionization cross section for protons incident on hydrogen gas has been measured for incident particle energies over the range from 0.15 to 1.10 Mev. The incident proton energy was determined by 90° deflection in a regulated magnetic field, whose value was measured with a precision gaussmeter. The ionization currents of both signs were measured simultaneously with the incident beam current by means of sensitive electrometers. The target gas pressure was measured by a liquid-nitrogen-trapped McLeod gauge and ranged from 1.0 to 12.0 x 10^{-4} mm Hg. The effective collision volume was determined by the use of guard structures around the collector electrodes. Collection potentials of plus and minus 1050 volts were used for the bulk of the measurements. Suppression potentials of 150 volts were used on both collectors throughout.

(b) Corrections

Leakage currents in the electrometer circuits were measured frequently and subtracted from all current measurements. The correction was usually less than 5 per cent. The constant pumping arrangement described in Section III was used to provide a residual background gas density that is independent of the sample gas density insofar as possible. The hydrogen target gas was admitted through a palladium leak which automatically assures high purity of the entering gas.

The pressure of the residual gas averaged about 6 x 10^{-6} mm Hg as indicated by ionization gauges, using the nitrogen calibration. The actual value is uncertain since the composition is unknown. A typical
run of the ionization currents produced in the residual gas is shown in Figure 8. The slope of the line is almost the same as that obtained with hydrogen in the chamber, and was not found to vary from day to day. The impurity currents at several energies were read daily before the hydrogen was admitted, and again at the end of a day's run. The impurity ionization current for each energy inferred from these data was subtracted directly from each hydrogen ionization current reading. Except for the lowest hydrogen pressures, this amounted to a correction of less than 5 per cent.

In a given run the incident particle energy was varied over the entire range while the hydrogen gas pressure was held nominally constant. Usually the setting of the palladium leak heater power was left fixed for at least one hour before readings were begun, to allow pressure equilibrium to be reached. Even so, the McLeod gauge was read frequently during the run.

Complete runs were made for hydrogen pressures throughout the range from 1.0 to 12.0 x 10^{-4} mm Hg. The residual gas pressure was not subtracted from the indicated total pressure since it was not really well known; however, if it were really of the order of 6 x 10^{-6} mm Hg as the ionization gauges indicate, it would represent a correction of less than 5 per cent for all hydrogen pressures above 1.2 x 10^{-4} mm Hg. In computing the molecular density of the target gas, its temperature was taken to be that of the room.

A set of values obtained for the gross ionization cross section at one energy from a series of runs at different pressures is shown in Figure 9, plotted to a relative scale. The fall-off at pressures below 2.5 x 10^{-4} mm Hg can be identified with the above failure to take account of the residual gas in computing the target gas density. Similarly, the
Figure 8. Impurity Contribution for Protons Incident on Background Gas.
Figure 9. Computed Ionization Cross Section for Varying Target Gas Pressure.

EACH POINT IS AN AVERAGE OF MANY RUNS
indication of rising values for pressures above $10 \times 10^{-4}$ mm Hg can be identified with multiple collisions and failure of the "thin target" assumptions. The existence of a definite plateau between these regions lends confidence that all the important assumptions are valid there. All of the data used in compiling the final results have been taken from runs lying within this plateau.

(c) Results

Our final values* for the absolute gross ionization cross section for protons incident on hydrogen gas with energies from 0.15 to 1.10 Mev are plotted in Figure 10. The data give an excellent fit to a straight line in this log-log plot throughout the energy range. The line drawn in Figure 10 corresponds to the expression:

$$
\sigma_i = 3.45 \times 10^{-0.870} \times 10^{-17} \text{ cm}^2/\text{molecule},
$$

in which $E$ is the incident proton kinetic energy in Mev. In terms of the proton velocity, $v$, this becomes:

$$
\sigma_i = K v^{-1.74},
$$

in which $K$ is a constant.

(d) Errors

It has been indicated in Section III that the uncertainties in the ratios of the corrected ionization currents to the incident beam current should not exceed about $\pm 2$ per cent. The target gas temperature is not directly measured and may be uncertain by perhaps $\pm 1$ per cent. By far the largest uncertainty is in the measurement of the target gas pressure. Our McLeod gauge scale extends only to $10^{-5}$ mm Hg, and the instrument has not been absolutely calibrated. We believe we can read its scale to less than 5 per cent in the range around $5 \times 10^{-4}$ mm Hg, but must admit a

* See Appendix
probable error of about ±5 per cent in the absolute reading.

Combining these errors leads to an estimated probable error of about ±6 per cent in the constant 3.45 in the expression for \( \sigma_1 \) above, and this is the vertical error indicated by the brackets on the points in Figure 10.

The slope of the line is less uncertain, however. The proton energy has a nominal uncertainty of only ±0.2 per cent at 1 Mev, and we believe the uncertainty is not over ±0.5 per cent at 0.15 Mev. Since individual runs were made at constant nominal pressure, the slopes obtained depend only on the relative scale-reading accuracy rather than on the absolute accuracy of the McLeod gauge. Further, self-consistency of the slopes from many individual runs gives us confidence that the ratios of the cross sections at the extreme energies are known to ±2 per cent or better. Therefore the final result may be stated:

\[
\sigma_1 = (3.45 \pm 0.20) \times 10^{-17} \text{ cm}^2/\text{molecule},
\]

where \( E \) is the proton energy in Mev.

V. Comparison with Theory

In the present case of protons incident on molecular hydrogen, the gross ionization measurements described here yield in principle the sum of the cross sections for the following four distinct kinds of ionization events:

1. \( \text{H}^+ + \text{H}_2 \rightarrow \text{H}^+ + \text{H}_2^+ + e \)
2. \( \text{H}^+ + \text{H}^+ + \text{H}^0 + e \)
3. \( \text{H}^+ + \text{H}^+ + \text{H}^+ + 2e \)
4. \( \text{H}^+ + \text{H}^+ + \text{H}^- \)
Figure 10. Gross Ionization Cross Section for Protons Incident on Molecular Hydrogen.
plus the three kinds of charge-transfer events:

\begin{align*}
(5) \quad & \text{H}^+ + \text{H}_2 \rightarrow \text{H}^0 + \text{H}_2^+ \\
(6) \quad & \text{H}^0 + \text{H}^+ + \text{H}^0 \\
(7) \quad & \text{H}^0 + \text{H}^+ + \text{H}^+ + e
\end{align*}

Among the first four, reactions (3) and (4) represent more complex events than do (1) and (2), and it seems quite likely that they will be correspondingly improbable and contribute in a minor fashion to the total ionization. The sum of the cross sections for (5), (6), and (7) is the gross charge transfer cross section \( \sigma_{10} \) which has been measured previously\(^1\). This cross section is found to be of such magnitude that charge transfer should make a barely significant contribution of about 2 per cent at 0.15 Mev, but be negligible above 0.2 Mev. In verification of this assertion is the fact that the collected electron currents observed were always equal to the positive ion currents within our reading accuracy of \( \pm 2 \) per cent. Any significant amount of charge transfer would lead to an excess of positive ion current over electron current. Therefore, the present gross ionization measurements yield essentially the sum of the cross sections for processes (1) and (2).

Theoretical cross section calculations using the Born approximation have been made\(^4\) for the atomic process:

\begin{align*}
(8) \quad & \text{H}^+ + \text{H}^0 \rightarrow \text{H}^+ + \text{H}^+ + e
\end{align*}

A method of obtaining an approximate theoretical treatment for the present molecular processes has been indicated in reference \(^4\). Although the

results calculated for reaction (8) were not given in explicit analytic form, the following generalization is made:

If a fast proton collides with a nucleus of atomic number $Z_p$, to which one electron is bound in the 1s state, then the cross section for removal of that electron takes the general form (Equation 21 of Reference (4)):

$$
\sigma^+ = \left( \frac{Z_p}{\Delta E} \right)^2 f \left( \frac{M \Delta E}{E} \right)
$$

in which:

- $\Delta E$ is the ionization energy for removal of the electron,
- $M$ is the reduced mass of the colliding system,
- $E$ is the kinetic energy of the relative motion,
- $f$ is a function of unspecified analytic form.

This formula permits scaling of the graphical results given for reaction (8) to any other reaction that meets the above description.

It has often been assumed that a hydrogen molecule is simply equivalent in an energetic collision process to two independent hydrogen atoms, so that the molecular cross section would be expected to be simply twice the atomic cross section. However, in the formula above there is an explicit dependence on the ionization energy $\Delta E$ of the electron to be removed. The vertical ionization energy of one electron in the hydrogen molecule is appreciably different from the atomic ionization energy, being, in fact, greater by the factor 1.2.

The procedure followed is this: The molecule is considered to be equivalent to two free neutral atoms in every respect except that account is taken of the fact that the ionization energy is 1.2 times the normal
atomic value. Ignored are the effects of the second atom on the reduced mass of the system consisting of the projectile and the first atom, on the ratio of the incident particle energy to the relative motion energy, and of course on the form of the electronic wave function that was used in the calculation of the atomic cross section. To this approximation, a theoretical cross section for the removal of one electron from the molecule by the impact of an incident proton of energy \( E \) will be twice the given atomic cross section for the incident proton energy \( \frac{E}{1.2} \), divided by \((1.2)^2\). This cross section should actually correspond to the sum of the cross sections for all of the several kinds of molecular ionization events, since the theoretical assumptions made no assertion as to the final state of the molecule. Therefore this cross section should correspond to our measured gross ionization cross section.

The dashed line in Figure 10 is the extrapolation from the theory of Bates and Griffing as described. Knowledge of the proper location of the line is limited by our ability to read the rather small graphs in the published paper. There is essentially perfect agreement within our stated experimental uncertainties.

The triangle points in Figure 10 are the Russian results\(^{(2)}\), which extend upward in energy only to 0.18 Mev. The agreement in the overlap region is quite satisfactory.

VI. Program For The Immediate Future

Similar measurements over the same energy range of the gross ionization cross section for protons incident on helium are already under way. When these are completed the measurements will be extended to other gases. Present plans call for the use of Ne, A, \( N_2 \), and CO targets.
VII. Travel And Publication During The Past Quarter

Periodic visits to the Oak Ridge National Laboratory by E. W. McDaniel, for consultation with C. F. Barnett and others, have continued. E. W. McDaniel and D. W. Martin attended the meeting of the American Physical Society held in Montreal in June. E. W. McDaniel also attended the conference on Thermonuclear Plasmas held in Gatlinburg, Tennessee on August 22-26.

There have been no publications during this quarter. A manuscript describing the work covered by this report has been prepared for submission to the Physical Review.

VIII. Acknowledgements

It is a pleasure to acknowledge the many helpful suggestions made by members of the Oak Ridge Cross Section Group, particularly C. F. Barnett and Herman Postma. We also wish to acknowledge the expert assistance of Robert Langley in the performance of this work.

Respectfully submitted,

E. W. McDaniel
Project Director

Approved by:

Vernon Crawford
Head, Physics Branch
Physical Sciences Division
APPENDIX

The results of the present work, presented in Figure 10, were computed from the relationship

\[ \sigma_i = \frac{I^+}{I_1} \left( \frac{1}{n_i} \right) \text{ cm}^2/\text{molecule} \]

where:  
- \( I \) = corrected transverse positive ion current  
- \( I_1 \) = incident proton current  
- \( \lambda \) = effective length of the collision volume  
- \( n \) = number density of the target gas molecules
TECHNICAL STATUS REPORT NO. 5

PROJECT NO. B-176

Covering the Period

SEPTEMBER 1, 1960 to NOVEMBER 30, 1960

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By

E. W. McDaniel
D. W. Martin
J. W. Hooper

CONTRACT NO. AT-(40-1)-2591

U. S. ATOMIC ENERGY COMMISSION
OAK RIDGE, TENNESSEE

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia
TECHNICAL STATUS REPORT NO. 5

Project No. B-176

Covering the Period

SEPTEMBER 1, 1960 to NOVEMBER 30, 1960

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By

E. W. McDaniel
D. W. Martin
J. W. Hooper

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee
I. Title

Ionization and Charge Transfer Cross Sections

Phase I: The Gross Ionization Cross Section for Protons Incident on Various Gases

II. Objective and Method

The objective of the research currently being performed under Contract AT-(40-1)-2591 is the measurement of the gross cross section for ionization of various gases by fast protons. The energy of the incident particles is variable throughout the range 0.15-1.1 Mev. The bulk of the previous work in this area has been confined to incident-particle energies below 0.04 Mev. Thus the present investigation represents an extension into a region which is largely unexplored.

The source of energetic protons is a 1-Mev Van de Graaff positive ion accelerator, which is equipped with a beam analyzing and stabilizing system. The beam is passed through differentially pumped collimating apertures into a collision chamber containing the target gas. The chamber dimensions and the gas pressure are such that the target is "thin", in that only about one percent of the incident protons will engage in even one ion-producing collision, and a negligible fraction will be involved in two or more such collisions. Those protons which do collide will almost always lose only a small fraction of their energy, and suffer only a small change in the direction of their motion. After they have traversed the active collision volume, the protons are collected in a Faraday cup, and the measured current to this cup is taken to be a measure of the total intensity of the incident beam.
In the present phase of the research we are measuring what we have called the "gross ionization" cross section. Polarized electrodes within the collision volume collect essentially all of the charged particles of both signs formed in the gas by the passage of the proton beam. Most of these residual charged particles have quite low energies, although a few have energies as high as several hundred electron volts. The currents collected are measured by means of electrometers. Suppression of secondary electron emission has been provided, and an arrangement of guard electrodes serves to define the effective target thickness in such a way that no end corrections are required. Complete details of the existing apparatus may be found in our First Annual Report (Technical Status Report No. 4, August 31, 1960).

Cross section values computed from the positive ion current will in principle include contributions from charge transfer events, in which the incident proton captures an electron from the struck molecule and emerges as a neutral atom, leaving behind only a slow positive ion, rather than an ion pair. Any appreciable contribution from such events will be manifested by an excess of the positive ion current over the collected electron current. Previous independent measurements of the charge transfer cross sections for fast protons incident on a number of the gases of interest here have been made by a different method, in which the intensity of the emerging beam of fast neutral hydrogen atoms was observed (1). It will in most cases be possible to show that the contribution from charge transfer is negligible in the present energy range.

---

Detailed measurements of the gross ionization cross section for protons incident on hydrogen were completed several months ago, and the results were presented in our First Annual Report. There was a slight error in the analytic expression representing the experimental data that was given there. The equation which appears in the middle of page 27 should read:

\[ \sigma_1 = (3.45 \pm 0.20)E^{-0.874 \pm 0.010} \times 10^{-17} \text{ cm}^2/\text{molecule} \]

where \( E \) is the incident proton energy in Mev.

III. Present Status of the Experimental Work

Measurements of the gross ionization cross section for protons incident on helium were begun early in the present reporting period, using the same apparatus and the values of the operating parameters found to be satisfactory for hydrogen. Almost immediately we began to have serious difficulties with electrical discharges inside the collision chamber. Once started, the discharge problems persisted even when the voltages of all the chamber electrodes were reduced to minimum values. When the chamber was flushed and filled with hydrogen, we found that we were unable to reproduce the earlier hydrogen data. It appeared that the discharges had activated some of the electrode and lead wire surfaces so that breakdown could occur much more readily than before.

The chamber was then partially dismantled and cleaned. The electrical leads were shortened, rearranged, and covered with tygon plastic tubing to inhibit arcing. Since the earlier tests with hydrogen had
shown that the guard electrode arrangement provides a well-defined effective target thickness, it is no longer necessary to provide for variation of this quantity by changing the number of electrode segments in the electrometer circuit. The three center segments of each collector assembly were connected together internally with only a single lead brought out to the electrometer. The remaining two inner segments were connected internally to the guard assembly and thus made a part of it. The reduction of the number of leads passing to the outside through kovar-glass seals to the electrometer has materially reduced the observed leakage currents, as expected.

After these changes, the apparatus was checked by repeating some of the hydrogen measurements. Cross section values calculated from the positive ion currents collected were found to check with the earlier results; however, it was found that the electron current collected at the opposite plate now exceeded the positive ion current, whereas in the previous work these currents had always been equal as expected. The magnitude of the difference varied with the intensity of the incident beam, but was roughly independent of the target gas pressure, and therefore with the absolute magnitudes of the separate currents, for constant beam intensity. It was further found to decrease rapidly with decreasing energy of the incident beam. From these and other considerations, it was believed that the extra electrons were probably photoelectrons ejected from the suppressor grids by ultraviolet or x-ray photons generated by the impact of the fast protons in the Faraday cup. Accordingly, the cup was rebuilt deeper than before and was installed farther down the beam axis from the collector
plates. These measures reduced the anomalous electron current, which tends to confirm our hypothesis concerning its origin. The effect has not been eliminated at the present time, however, and an electron excess of about 5 percent remains at 1 Mev with an average target gas pressure. At the lower end of our energy range the excess current becomes negligible.

Since this excess electron current had not been observed in the earlier hydrogen work, we now believe that the discharges encountered with helium must have sensitized the surface of the suppressor-grid wires in some way. The possible remedy could involve cleaning the grids with a strong acid bath, or even rewinding with new wire. We intend first to try further redesign of the Faraday cup, including perhaps the insertion of baffles between it and the collision volume that will shadow the grids from the beam impact point.

In the meantime, our ability to reproduce the hydrogen results by relying on the collected positive-ion current has enabled us to proceed with cross section measurements on other gases. The cross section values are calculated from the observed positive ion currents, which are not affected by the anomalous excess electrons. At the lower energies, where charge transfer events could conceivably make an observable contribution to the positive ion current, the anomalous electron current has disappeared. In this region the observed equality of the collected currents of both signs still provides a check on the extent of the charge transfer contribution.

IV. New Experimental Results

Measurements of the gross ionization cross section for protons incident on nitrogen gas from 0.15 Mev to 1.10 Mev have been completed. The
results are shown in the figure. As was the case with hydrogen, the data follow a straight line in a log-log plot throughout the energy range. The line drawn in the figure is represented by the expression:

\[ \sigma_{1} = (1.42 \pm 0.09)E^{-0.711 \pm 0.011} \times 10^{-16} \text{ cm}^2/\text{molecule}, \]

where \( E \) is the kinetic energy of the incident proton in Mev.

The earlier independent measurement of the charge transfer cross section \( \sigma_{10} \) for protons on nitrogen indicates that this process could make a barely significant contribution of as much as two percent only in the region below 0.2 Mev. This cross section decreases rapidly with energy, and amounts to only about \( 10^{-4} \) of our result at 1.0 Mev. Observed equality of the collected positive ion and electron currents (except for the anomalous electron currents at the higher energies discussed above) is consistent with this conclusion. Thus the situation regarding charge transfer in nitrogen is similar to that previously found for hydrogen.

V. Program for the Immediate Future

The problem of the anomalous electron current at high energies will be investigated further, and we expect to take some or all of the steps indicated above to attempt to eliminate the effect.

We plan to press ahead with measurements of the gross ionization cross section for protons incident on argon, carbon monoxide, neon, and helium. We expect to complete these measurements within the coming period.

VI. Travel and Publications During the Report Period

A manuscript presenting in detail our measurements of the gross ionization cross section for protons incident on hydrogen has been accepted
for publication in The Physical Review. This article contains essentially the same information presented in our First Annual Report (Technical Status Report No. 4, August 31, 1960).

D. W. Martin and J. W. Hooper attended the 1960 Thanksgiving meeting of the American Physical Society, November 25-26, in Chicago. A contributed paper on the hydrogen results was presented. The nitrogen results were also described.

E. W. McDaniel has continued his periodic visits to Oak Ridge National Laboratory for consultations relevant to the present work with C. F. Barnett and others. No project funds have been expended for these visits.

Respectfully submitted,

E. W. McDaniel
Project Director

Approved by:

Vernon Crawford
Head, Physics Branch
Physical Sciences Division
GROSS IONIZATION CROSS SECTION FOR PROTONS INCIDENT ON MOLECULAR NITROGEN.
TECHNICAL STATUS REPORT NO. 6
PROJECT NO. B-176
Covering the Period
DECEMBER 1, 1960 to FEBRUARY 28, 1961

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By
E. W. McDaniel
D. W. Martin
J. W. Hooper
D. S. Harmer

CONTRACT NO. AT-(40-1)-2591

U. S. ATOMIC ENERGY COMMISSION
OAK RIDGE, TENNESSEE

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia
TECHNICAL STATUS REPORT NO. 6

Project No. B-176

Covering the Period

DECEMBER 1, 1960 to FEBRUARY 28, 1961

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By

E. W. McDaniel

D. W. Martin

J. W. Hooper

D. S. Harmer

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee
I. Title

Ionization and Charge Transfer Cross Sections

Phase I: The Gross Ionization Cross Section for Protons Incident on Various Gases

II. Objective and Method

The objective of the research currently being performed under Contract AT-(40-1)-2591 is the measurement of the gross cross section for ionization of various gases by fast protons. The energy of the incident particles is variable throughout the range 0.15-1.1 Mev. The bulk of the previous work in this area has been confined to incident-particle energies below 0.04 Mev. Thus the present investigation represents an extension into a region which is largely unexplored.

The source of energetic protons is a 1-Mev Van de Graaff positive ion accelerator, which is equipped with a beam analyzing and stabilizing system. The beam is passed through differentially pumped collimating apertures into a collision chamber containing the target gas. The chamber dimensions and the gas pressure are such that the target is "thin", in that only about one percent of the incident protons will engage in even one ion-producing collision, and a negligible fraction will be involved in two or more such collisions. Those protons which do collide will almost always lose only a small fraction of their energy, and suffer only a small change in the direction of their motion. After they have traversed the active collision volume, the protons are collected in a Faraday cup, and the measured current to this cup is taken to be a measure of the total intensity of the incident beam.
In the present phase of the research we are measuring what we have called the "gross ionization" cross section. Polarized electrodes within the collision volume collect essentially all of the charged particles of both signs formed in the gas by the passage of the proton beam. Most of these residual charged particles have quite low energies, although a few have energies as high as several hundred electron volts. The currents collected are measured by means of electrometers. Suppression of secondary electron emission has been provided, and an arrangement of guard electrodes serves to define the effective target thickness in such a way that no end corrections are required. Complete details of the existing apparatus may be found in our First Annual Report (Technical Status Report No. 4, August 31, 1960).

Cross section values computed from the positive ion current will in principle include contributions from charge transfer events, in which the incident proton captures an electron from the struck molecule and emerges as a neutral atom, leaving behind only a slow positive ion, rather than an ion pair. Any appreciable contribution from such events will be manifested by an excess of the positive ion current over the collected electron current. Previous independent measurements of the charge transfer cross sections for fast protons incident on a number of the gases of interest here have been made by a different method, in which the intensity of the emerging beam of fast neutral hydrogen atoms was observed\(^{(1)}\). It will in most cases be possible to show that the contribution from charge transfer is negligible in the present energy range.


-2-
III. Present Status of the Experimental Work

Measurements of the gross ionization cross section for protons incident on hydrogen and nitrogen, with energies from 0.15 to 1.10 Mev, were completed in previous reporting periods. The results have been presented in Technical Status Reports Nos. 4 and 5. In the present period, similar measurements have been completed for protons incident on argon, neon, and carbon monoxide. Measurements for helium have also been completed for incident proton energies below 0.85 Mev. These data are presented in Figures 1 through 4.

Completion of the helium data above 0.85 Mev has been delayed by recent deterioration of the performance of our Van de Graaff accelerator at these energies. After a substantial loss of running time had been incurred in attempts to rectify this situation, it was finally determined that the accelerating tube of the machine had come to the end of its useful life. A replacement has been procured (at no cost to this project) and will be installed within the first week of the coming period. Presuming that the accelerator will thereby be restored to its normal performance, it is expected that the helium data will be completed in a few days.

A situation was described in our last previous report (No. 5) in which, following extensive electrical discharges in the collision chamber during the early helium measurements, anomalous excess electron current was observed at the positive collector plate. It was our belief that this current was due to photoelectrons from the suppressor grids, whose surfaces must have become activated in some fashion by the discharges. It is consistent with this interpretation that the effect has diminished steadily with the passage of time. At present, the difference between the
collected electron and positive-ion currents is appreciable only when the
gas pressure in the collision chamber is very low, as when the "background"
ionization of the residual chamber contaminants is being observed. With
target gas present in the chamber at normal pressures, the relative
difference is always less than 2% and is not significant.

Although this effect, no longer represents a possible perturbation
on the results of the present measurements, the apparent presence of appreciable
soft X-ray or ultraviolet radiation in the chamber is believed to require
further investigation. A supply of ultraviolet-sensitive photographic
plates has been obtained, with which a rough survey for such radiation in
the chamber will be made.

The difficulties with electrical discharges that were encountered in
our first attempts to make measurements in helium have not reappeared. We
attribute this to the steps that were previously taken (see Report No. 5)
to shorten and shield the leads from the collectors, and to the fact that
somewhat lower collection potentials of plus and minus 600 volts are now
being used.

With the single exception of carbon monoxide (see Fig. 3), for each
of the gases so far studied our experimental cross section values appear
to lie on a straight line, when plotted against the incident-proton energy
on a log-log plot, throughout the entire energy range covered. This implies
that the cross section is simply proportional to a power of the proton
energy. For hydrogen and nitrogen, values of both the proportionality
constant and the exponent have been given, in report No. 5, that were
determined from straight lines drawn through the data points by eye.
A program is being set up for the Georgia Tech Burroughs 220 computer to
determine the best possible straight-line fit according to the criterion
of least squares. A tentative computation has been carried out for the
hydrogen data, and indicates a need for a small adjustment in the previously
reported values of these parameters. It is of interest that the probable
errors in these values, as indicated by only the variance of the data from
the fitted line, are only 0.2%. Nevertheless, it is believed that the
previously stated probable errors (6% for the proportionality constant and
2% for the value of the exponent) are realistic because of the possibility
of systematic errors in the target gas pressure and in the proton energy.

It is a well known general feature of theoretical calculations, in
the Born approximation, that the cross section predicted for a given process
with incident protons is equal to that for incident electrons of the same
velocity, in the limit of large velocities. Comparisons of our data with
electron data tabulated in Massey and Burhop\(^{(2)}\) show substantial agreement
above 0.5-Mev proton energy (260-ev electron energy) for several of the
gases studied, but show systematic differences for others. Since some of
the electron data cited appears to be quite old, a literature search has
been initiated to locate more recent results. The present tentative
comparisons will not be quoted in detail here.

Previous measurements\(^{(1)}\) of charge transfer cross sections for protons
incident on helium have indicated that, for this case, these processes
should contribute to the gross ionization at 0.15 MeV to the extent of

\(^{(2)}\) H. S. W. Massey and E. H. S. Burhop, "Electronic and Ionic Impact
about 10% of our observed value. The resulting excess of the collected positive-ion current over the electron current at this energy, which should be easily discernible, has not been observed. Further, the fact that our lowest-energy points lie right on the straight line from the higher-energy points seems to argue against the existence of significant contributions from an additional process there. No explanations of this discrepancy can be offered at present.

IV. Program for the Immediate Future

The measurements for protons incident on helium with energies above 0.85 Mev will be completed as soon as the Van de Graaff has been restored to normal operation at these energies. It has been decided that measurement of the gross ionization cross section for incident protons should be extended to oxygen, and it is not anticipated that these measurements will present any special difficulties.

Our measurements of ionization in helium by incident protons will be compared in detail with the theoretical calculations of Mapleton\(^{(3)}\). Detailed comparisons of our data with the best incident-electron results that can be located will also be made.

Preliminary investigations will be made concerning the probable presence of ultraviolet radiation or soft X-rays in our collision chamber, as was indicated above. Present plans call for a survey of the chamber using ultraviolet-sensitive photographic plates, simply to verify the presence of the radiation and to locate its source. Any further plans will be contingent on the outcome of these studies.

Components for a dual gas supply system for the Van de Graaff ion source have been ordered, and will be installed within the coming period. Our projected program of measurements of gross ionization in several gases by incident helium ions, both singly and doubly charged, will then be started. The dual gas system is required so that proton and deuteron beams will still be available when needed in certain instructional courses which share the accelerator with this project. It will also facilitate rapid checks of the helium-ion measurements against the existing incident proton measurements whenever this seems to be desirable.

V. Travel and Publications During the Reporting Period

The article describing this experiment in detail and presenting the results for protons incident on hydrogen, which was referred to in the previous report, appeared in the Feb. 15 issue of *The Physical Review*. The reference is *Phys. Rev.* 121, 1123 (1961).

E. W. McDaniel has continued to make periodic visits to Oak Ridge National Laboratory for consultations relevant to the present work with C. F. Barnett and others.

Respectfully submitted,

E. W. McDaniel
Project Director

Approved by:

Vernon Crawford
Head, Physics Branch
Physical Sciences Division
Figure 1. Gross Ionization Cross Section for Protons Incident on Argon.
Figure 2. Gross Ionization Cross Section for Protons Incident on Neon.
Figure 3. Gross Ionization Cross Section for Protons Incident on Carbon Monoxide.
Figure 4. Gross Ionization Cross Section for Protons on Helium.
TECHNICAL STATUS REPORT NO. 7

Project No. B-176

Covering the Period

March 1, 1961 to May 31, 1961

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

Phases I and II: H⁺ Ions Incident on He, Ne, Ar, H₂, N₂, O₂, and CO Targets

By

E. W. McDaniel
J. W. Hooper
D. W. Martin
D. S. Harmer

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee

June 1, 1961

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia
IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

Phases I and II: \( H^+ \) Ions Incident on He, Ne, Ar, \( H_2 \), \( N_2 \), \( O_2 \), and CO Targets

By

E. W. McDaniel

J. W. Hooper

D. W. Martin

D. S. Harmer

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee

June 1, 1961
# TABLE OF CONTENTS

| LIST OF TABLES                                      | iii  |
| LIST OF ILLUSTRATIONS                              | iv   |
| SUMMARY                                           | vi   |

## CHAPTER

### I. INTRODUCTION

### II. PHENOMENA RELATED TO THE PASSAGE OF A HOMOGENEOUS BEAM OF IONS THROUGH A GAS: COLLISION CROSS SECTIONS

### III. EXPERIMENTAL EQUIPMENT AND METHOD

- The Incident Beam Source
- The Collision Chamber
- Measurement of the Incident Beam Intensity \( I_i \)
- The Collector Assemblies and Electrometers

### IV. EXPERIMENTAL RESULTS

- Summary of Experimental Method
- Data Corrections
- Results
- Discussion of Errors

### V. COMPARISON WITH AVAILABLE THEORY

- Protons Incident on Molecular Hydrogen
- Protons Incident on Helium
- Comparison of Experimental Cross Sections Obtained for Incident Protons and Electrons of Equal Velocity

### VI. CONCLUSIONS

### VII. ACKNOWLEDGEMENTS

## APPENDIX

- THE CONCEPT OF THE COLLISION CROSS SECTION

## BIBLIOGRAPHY
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Calculated Values for the Equation $\sigma_x = A \times E^C$ cm$^2$/molecule</td>
<td>46</td>
</tr>
</tbody>
</table>
# LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Schematic View of Apparatus for Gross Ionization Measurements</td>
<td>14</td>
</tr>
<tr>
<td>2.</td>
<td>Interior View of the Collision Chamber</td>
<td>17</td>
</tr>
<tr>
<td>3.</td>
<td>Incident Beam Collected in Faraday Cup versus Suppression Voltage</td>
<td>21</td>
</tr>
<tr>
<td>4.</td>
<td>Single Electrode Structure</td>
<td>23</td>
</tr>
<tr>
<td>5.</td>
<td>Apparent Ion Currents versus Suppressor Grid Voltage for Constant Collection Field</td>
<td>26</td>
</tr>
<tr>
<td>6.</td>
<td>Observed Ionization Cross Section for Various Collection Field Strengths</td>
<td>28</td>
</tr>
<tr>
<td>7.</td>
<td>Leakage Currents versus Collection Voltage</td>
<td>31</td>
</tr>
<tr>
<td>8.</td>
<td>Impurity Contributions for Protons Incident on Background Gas</td>
<td>35</td>
</tr>
<tr>
<td>9.</td>
<td>Computed Ionization Cross Section for Varying Target Gas Pressure</td>
<td>37</td>
</tr>
<tr>
<td>10.</td>
<td>Gross Ionization Cross Section for Protons Incident on Helium</td>
<td>38</td>
</tr>
<tr>
<td>11.</td>
<td>Gross Ionization Cross Section for Protons Incident on Neon</td>
<td>39</td>
</tr>
<tr>
<td>12.</td>
<td>Gross Ionization Cross Section for Protons Incident on Argon</td>
<td>40</td>
</tr>
<tr>
<td>13.</td>
<td>Gross Ionization Cross Section for Protons Incident on Molecular Hydrogen</td>
<td>41</td>
</tr>
<tr>
<td>14.</td>
<td>Gross Ionization Cross Section for Protons Incident on Molecular Nitrogen</td>
<td>42</td>
</tr>
<tr>
<td>15.</td>
<td>Gross Ionization Cross Section for Protons Incident on Molecular Oxygen</td>
<td>43</td>
</tr>
<tr>
<td>16.</td>
<td>Gross Ionization Cross Section for Protons Incident on Carbon Monoxide</td>
<td>44</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>17.</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>18.</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>19.</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>20.</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>21.</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>22.</td>
<td>59</td>
<td></td>
</tr>
<tr>
<td>23.</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>24.</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>25.</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>26.</td>
<td>66</td>
<td></td>
</tr>
</tbody>
</table>
SUMMARY

The gross ionization cross sections for protons incident on helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide have been measured for incident particle energies over the range 0.15 to 1.10 Mev. These results represent a portion of a more comprehensive program of ionization and charge transfer measurements for various projectile/target combinations.

The source of energetic protons was a 1-Mev Van de Graaff positive ion accelerator, which was equipped with a beam analyzing and stabilizing system. The chamber dimensions and gas pressure were such that the target was "thin," in the sense that only a small fraction of the incident particles underwent any collisions at all. Electrodes parallel to the beam axis in the collision chamber collected the slow charged residual particles produced in ionizing collisions, while the original incident particles passed through the collision volume and into a Faraday cup. Detection of both the slow and fast particles was accomplished by electrometer measurements of the electron and ion currents.

Values for the absolute gross ionization cross sections are presented along with the data of other investigators which are available in the energy range below 0.18 Mev. 

It is shown that there

*This report is based on a thesis submitted by one of us (JWH) in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the School of Electrical Engineering at the Georgia Institute of Technology.
is considerable disagreement in the low energy range among some of the results; however, the values of Afrosimov, et al., for protons in hydrogen, and Fedorenko, et al., for protons in neon and helium agree with the present results quite satisfactorily in the region between 0.15 and 0.18 Mev that overlaps the present results.

The results gave an excellent fit to a straight line on a log-log plot throughout the energy range for all cases examined except carbon monoxide. The carbon monoxide data also fit a straight line for energies greater than approximately 0.1 Mev. The data therefore correspond, with the noted exception, to an expression of the form:

\[
\sigma_i = A \times E^{-C} \text{cm}^2/\text{molecule}
\]

where \(E\) represents the incident particle energy. A Burroughs 220 electronic computer was programmed to compute the values \(A\) and \(C\) which corresponded to a least-squares fit to the average cross sections obtained from many individual runs, and to compute the probable errors in these constants that are indicated by the scatter of the data. The resulting values are presented in Table 1, Chapter IV.

The present experimental result for protons incident on molecular hydrogen is in excellent agreement with an approximate extension to the molecular case of a Born approximation calculation of the cross section for the atomic process \(H^+ + H^0 \rightarrow H^+ + H^+ + e\). Theoretical calculations in the Born approximation of the cross sections for ionization and simultaneous ionization and excitation of helium by protons have been made by Mapleton. There is essentially perfect agreement within the
experimental uncertainties between the theoretical calculation and the present experimental result in the energy range above approximately 400 kev.

It has been pointed out by Mott and Massey, Bates and Griffing, Mapleton, and others that if the velocities of relative motion are the same, and are sufficiently high, the ionization cross sections for electron-atom and proton-atom collisions calculated in the Born approximation are the same. The velocity of relative motion is the same in both the laboratory and the center-of-mass coordinate systems. It is possible therefore to translate the electron cross section data by multiplying the electron energy scale by the ratio of the proton to the electron mass.

It is demonstrated that there is excellent agreement between the cross sections obtained with incident electrons and with incident protons of the same velocity for the target gases helium, neon, argon, nitrogen, oxygen, and carbon monoxide. Excellent agreement is also obtained for the molecular hydrogen case if only the data of Tate and Smith, Bleakney, and Tozer and Craggs are considered.

Further investigations for helium ions incident on helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide are underway at the present time.
CHAPTER I

INTRODUCTION

The ionization produced by the passage of ions and atoms through gases has been the subject of many investigations, but practically all of the experimental work done to date in this field has been confined to energies below 180 kev. The work reported here therefore represents an extension into a region that is largely unexplored.

The phenomenon of ionization of gases by fast particles is of basic theoretical interest and has considerable importance from the practical standpoint as well. In the field of controlled thermonuclear reactions there are several fusion devices which utilize high energy injection, and knowledge of the ionization cross sections for various projectiles moving at high velocities through various target gases should prove of real value. Not only are hydrogen and helium targets of interest in this connection--heavier gases, such as carbon monoxide, may also be important since they are present in fusion devices as contaminants.

Detection of fast charged particles in gas-filled counters and cloud chambers depends directly on the ionization produced by the primary particles, and the detection of neutrons in $BF_3$ and proton-recoil counters and in fission chambers involves the production of ion-pairs following a nuclear reaction in the target material. Another problem of interest in nuclear physics which involves the production of ion-pairs in gases is that of the design of high current ion sources for use in accelerators.
Ionization cross sections at high energies enter into consideration in a number of astrophysical and upper atmospheric phenomena related to communications. The use of ion guns for space propulsion is also under consideration.

Comparison between experimental and theoretical cross sections for high-energy ionization is desirable. Such comparison can provide checks on the various approximations to which recourse must be made in the application of atomic collision theory to the ionization problem. At the present time theoretical results are available for atomic hydrogen$^1$, helium$^2$, and lithium$^3$ and it seems certain that other cases will be investigated within the next few years.

The atomic and molecular reactions that can occur when fast atoms or atomic ions collide with the molecules of a target gas may be conveniently classed as either "ionization" or "charge transfer" events. There is no general agreement on the exact definition of these terms--here it is chosen to define them as follows: in an "ionization" event, the fast particle ionizes the struck molecule but emerges with no change in its own charge state, while in a "charge transfer" event the fast particle either gains one or more electrons from, or loses one or more electrons to, the target particle. For a given projectile on a given target, each class of events in general includes several distinct kinds of reactions differing in the array of slow residual particles that are produced. The energies of the latter are usually low, although a small fraction of them may have energies as high as a few hundred electron volts. In either ionization or charge transfer, the incident particle almost always suffers only a small loss of energy and emerges with only a slight deviation from its original direction of motion.
In charge transfer studies, the sum of the cross sections for all types of events that produce a given change in the charge state of the fast particle may be measured by observing the distribution of charge states in the emerging fast beam. Such measurements have been made previously for hydrogen atoms and ions incident on helium, argon, hydrogen, and nitrogen gases with energies up to 1.0 Mev. The observed cross sections indicated that in the energy range of this research charge transfer should not make a significant contribution. Experimental results bore out this expectation.

To study ionization events one must collect and observe the slow charged particles produced by the collisions, since the emerging fast beam contains no information about the occurrence of these events. To avoid confusion due to multiple reactions by a single incident particle, the target must be "thin" in the sense that most of the incident particles will traverse the target with no collisions at all.

The experimental work done on ionization by fast ions and atoms prior to 1951 has been thoroughly surveyed by Massey and Burhop. Most of the experiments, both before and since 1951, have been confined to energies below 40 kev. Some recent Russian work and the work reported herein are exceptions to this statement: Afrosimov, et al., have measured the cross section for ionization produced by protons in hydrogen from 0.005-0.18 Mev. Fedorenko, et al., have performed similar measurements for protons in helium, neon, and argon. The cross sections for ionization of helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide in the energy range 0.15-1.10 Mev were the subject of this research.
The most recent reviews of the charge transfer field appear to be those of Allison.\textsuperscript{8,9} Allison's articles concentrate on investigations of charge-changing collisions of hydrogen and helium ions and atoms at kinetic energies above 0.2 kev. He discusses all of the previous charge-changing work which has an important bearing on this research. Hasted\textsuperscript{10} has reviewed the experimental techniques applied to the study of inelastic collisions between atomic systems and presents some limited results. He makes a comparison of experiment and theory wherever possible.
CHAPTER II

PHENOMENA RELATED TO THE PASSAGE OF A HOMOGENEOUS BEAM OF IONS THROUGH A GAS: THE CONCEPT OF COLLISION CROSS SECTION

The passage of a homogeneous beam of fast ions or atoms through a gas leads to both elastic and inelastic collisions between the incident and target particles. An elastic collision may be defined as one in which there is no change in the energies of the internal motions of the target particle or the incident projectile and in which the kinetic energy of the system is conserved. A transfer of kinetic energy usually does occur. The inelastic collision, on the other hand, results in a transformation of kinetic energy into internal energy, or vice versa, of either the struck particle or the projectile or both. This transfer of energy results in the excitation of internal motion in the particle receiving the energy or in an increase in its kinetic energy. The concept of inelastic collisions may be expanded to include the radiative effects due to Bremsstrahlung. An inelastic collision of a type sometimes referred to as "superelastic" arises from a collision between an excited structure and an incident projectile leading to de-excitation of the structure without radiation.

One possible subdivision of inelastic collisions would be as follows:

(a) radiation  (d) charge transfer
(b) excitation  (e) dissociation
(c) ionization
Radiation results from an inelastic collision in which some of the kinetic energy of the incident projectile enters the radiation field rather than entering into a change in the internal motion of either the projectile or target particle. This radiation, which is frequently called Bremsstrahlung, may be classically considered to arise from the acceleration of the charged particle in the atomic field of the target atoms. The effect, whose magnitude is inversely proportional to the square of the mass of the projectile, is essentially negligible when dealing with heavy particles such as ions in the energy range of this research.

Excitation may be considered as a change in atomic state of one or more of the electrons associated with the particle receiving the potential energy, or in a change in the vibrational or rotational states of the system. A change in the potential energy sufficient to lead to the ejection of one or more electrons is excluded from the excitation classification but instead is considered to be ionization. The transfer of one or more electrons between the struck particle and the projectile is classified as charge transfer. Dissociation results as a consequence of the formation of unstable molecular structures. It is possible to have combinations of any of the preceding events.

To illustrate the multiplicity of possible reactions, a list of the possible reactions for the case of fast protons incident on molecular hydrogen is presented below. The first symbol appearing on the right-hand side of each equation denotes the projectile particle after the collision. This particle may or may not have experienced a change in its charge state as the result of the reaction, but in any event theory and experiment show that it retains essentially all of its initial energy and its original direction of motion.
Reactions (1-4) are charge transfer events whereas reactions (5-8) represent ionization. Dissociation also occurs in several of these events. Reaction (9) which yields two slow hydrogen atoms is unobservable in any experiment involving the collection of charged particles and is therefore omitted from the following discussion. As an example of the interpretation of the preceding equations consider reaction (1) in which a fast \( \text{H}^+ \) ion is incident on an \( \text{H}_2\text{O} \) gas molecule. Two electrons are transferred to the incident particle and the resulting \( \text{H}_2\text{O}^{++} \) gas ion, which is unstable since it consists of two positively charged particles, dissociates into two slow \( \text{H}^+ \) ions.

Ionization and charge transfer measurements pertaining to reactions of the type listed above may be divided into two major categories. These are:
(a) The "thick" target approach in which the incident particle beam passes through a sufficient quantity of target material to attain a statistical charge-state equilibrium. This method has been utilized by Allison, Stier and Barnett, and many others.

(b) The "thin" target approach, in which the probability of multiple collisions by a single incident ion or atom is negligible. This method has been described by Keene, Hasted and his collaborators, and by Barnett and Reynolds.

Method (b) lends itself to a further subdivision on the basis of particle measurement techniques. It is possible to perform an analysis of the beam constituents after passage through the target gas as done in the thick target approach. It is further possible to analyze the products of collision by applying a transverse collection field to the collision chamber. In some cases this added source of information provides the means for the subdivision of the results of the gross measurements into results pertaining to individual reactions.

It is well known that in microscopic physics, theory will not in general predict certainties but instead will yield only probabilities. This is true for collision processes of all kinds. It is therefore necessary to develop a means of expressing the probability that some particular event will occur. The concept of collision cross section, which is developed mathematically in Appendix I, is frequently used when quantitatively discussing such probabilities. This concept permits the assignment of a hypothetical size, which is related to the probability of
occurrence of a specific event, to the target particles. It is important to note that this "size" has no direct relation to the physical dimensions of the atoms or ions under consideration.

Reaction equations (1-9) illustrate the multiplicity of events which may result from the passage of a beam of ions through a gas. Slow secondary ions in the target gas are seen to result from charge exchange, from ionization of the hydrogen molecules without dissociation, and from dissociation of the molecules after ionization or charge transfer has occurred. This same information can be presented in terms of cross sections in the following manner. Let \( \sigma_{ab}^{mn} \) represent the cross section for a reaction of unspecified type. Adopting an expanded version of Hasted's notation \(^{10}\) we let the subscripts \( a \) and \( b \), which precede the cross section symbol, represent the initial charge states of the incident projectile and target molecule, respectively. \( m \) represents the final charge state of the incident projectile and \( n \) denotes the net positive charge associated with the residual gas ions. The net number of electrons and/or negative ions present in the gas can be obtained from a consideration of net charge equality prior to and after the collision. The superscript \( c \), \( i \), or \( d \) indicates reference to the specific case of charge transfer, ionization, or dissociation, respectively. Compound superscripts are provided to account for reactions in which several of the basic processes occur simultaneously. The multiple reactions may now be represented by the cross sections of equations (1'-9').

\[
\begin{align*}
\sigma_{12}^{cd} & = 10^{-12} \\
\sigma_{01}^{c} & = 10^{-01}
\end{align*}
\]
Let $\sigma_1^+$ represent the total cross section for the production of slow positive ions and $\sigma_1^-$ represent the total cross section for the production of free electrons and negative ions. In a "thin" target experiment these cross sections are calculated from the relations

$$\sigma_1^+ = \left(\frac{I^+}{I_i}\right)\left(\frac{1}{n\ell}\right) \text{ cm}^2/\text{molecule}$$

$$\sigma_1^- = \left(\frac{I^-}{I_i}\right)\left(\frac{1}{n\ell}\right) \text{ cm}^2/\text{molecule}$$

where $I^+$ and $I^-$ are the positive and negative currents collected from a collision region of length $\ell$ by transverse electric fields, $n$ is the number density of gas molecules in the collision chamber, and $I_i$ is the incident ion current. These expressions are developed in Appendix I.

It is evident that $\sigma_1^+$ and $\sigma_1^-$ can be represented in terms of the individual cross sections ($1'$-$9'$) as follows:
These expressions clearly demonstrate that a measurement involving the collection of only the gross positive and negative charges arising in the collision volume will lead to an unequal weighting of individual events. Further information must be obtained if separation of the individual cross sections is to be realized.

Some insight into the significance of this unequal weighting can be obtained by considering the difference in $\sigma_1^+$ and $\sigma_1^-$. $\sigma_1^+ - \sigma_1^- = \left[ 10^0_{02} \sigma_{cd}^{cid} + 10^0_{01} \sigma_{c}^c + 10^0_{01} \sigma_{cd}^{cd} \right] + 2 \left[ 10^0_{12} \sigma_{cd}^{id} \right]$ (14)

The cross section $10^0_{12} \sigma_{cd}^{ccd}$ has been shown to be very small at energies above 0.04 Mev. For the gases studied in the present research the positive and negative currents measured at the collection plates were equal, within the limits of experimental error, for normal operation throughout the energy range 0.15-1.10 Mev. This implies that the sum of the cross sections $10^0_{02} \sigma_{cd}^{cid}$, $10^0_{01} \sigma_{c}^c$, and $10^0_{01} \sigma_{cd}^{cd}$ is negligible in equation (12). Therefore a measurement of the gross positive ion current for incident proton energies greater than 0.15 Mev yields in effect the cross section
\[ \sigma_1 = 10^{\sigma_{11}} + 10^{\sigma_{1d}} + 10^{\sigma_{1dc}} + 2(10^{\sigma_{112}}) \]  \hspace{1cm} (15)

where

\[ \sigma_1 = \sigma_1^+ \approx \sigma_1^- \]

There is reason to believe that \(10^{\sigma_{1dc}}\) is negligible due to the relative complexity of the event, however, this fact has not been definitely established.

Experimental values for \(\sigma_1\) for protons in the energy range 0.15-1.10 Mev incident on helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide gases are presented in Chapter IV.
CHAPTER III

EXPERIMENTAL EQUIPMENT AND METHOD

The objective of this research was the measurement of the ionization cross section for protons incident on helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide. The energy of the incident particles ranged from 0.15-1.10 Mev.

The source of the energetic protons was a 1-Mev Van de Graaff positive ion accelerator, which was equipped with a beam analyzing and stabilizing system. The beam was passed through collimating apertures and into a collision chamber containing the target gas. The chamber dimensions and gas pressure were such that the target was "thin," in the sense that only a small fraction of the incident particles underwent any collisions at all. Electrodes parallel to the beam axis in the collision chamber collected the slow charged particles produced in ionizing collisions, while the original incident particles passed through the collision volume and into a Faraday cup. Detection of both the slow and fast particles was accomplished by electrometer measurements of the electron and ion currents.

A schematic drawing of the apparatus is given in Figure 1, which includes a number of the most relevant dimensions. Following is a point by point discussion of the more important features of the apparatus, considered in sequence from the ion source to the electrometer circuits.

The Incident Beam Source.--Prior to entering the apparatus at the right side of Figure 1, the beam from the Van de Graaff was first deflected
Figure 1. Schematic View of Apparatus for Gross Ionization Measurements.
through 90° in an analyzing magnet, which assured that it consisted essentially only of protons. The proton energy was stabilized by electronic regulation of the accelerator voltage to maintain equal currents on the two slit edges at "a," which amounted to demanding a constant deflection in the regulated magnetic field. (This was the standard stabilizing system provided by the accelerator manufacturer, the High Voltage Engineering Corporation. The nominal energy spread was ± 2 kev at 1 Mev.) Thus the particle energy was determined by the value of the magnetic field and was measured by measuring that field. Employed for this purpose was a Harvey Wells model G-501 nuclear magnetic resonance gaussmeter, which as used had relative and absolute accuracies of one part in $10^3$. The deflection geometry was calibrated empirically by measuring the magnetic field corresponding to the 1.019-Mev threshold of the nuclear reaction $^3\text{H}(p,n)^3\text{He}$, using a tritium-zirconium target.

Referring again to Figure 1, the round, knife-edged apertures "b" and "c" were machined through 1/2-inch thick brass plates which, except for the apertures, were vacuum-tight closures of the beam tube. With this arrangement, there was no noticeable rise of pressure in the accelerator vacuum system when the collision chamber was filled with hydrogen to its highest working pressure of $10^{-3}$ mm Hg.

Collimation of the 1/16-inch diameter beam emerging from aperture "c" into the collision chamber was determined by that aperture and by the 0.10-inch analyzer exit slit at "a." (The beam width perpendicular to the page at "a," observed visually with a fluorescent "viewer" target, was also of the order of 0.10 inch.) The maximum angular divergence from the axis which an emerging particle could have was only about 4 minutes,
unless it had been scattered. The knife-edged design of apertures "b" and "c" minimized scattering from their edges, and the geometry permitted very few particles that had been scattered by residual gas in the beam tube to pass both "b" and "c". All components to the left from "b" were aligned with one another optically, and the entire assembly was oriented with respect to the analyzing magnet so as to maximize the current delivered to the Faraday cup at the left.

Because of the large distance between "a" and "b" (the analyzing magnet was in a different room from the rest of the apparatus), the beam impinging on aperture plate "b" remained diffuse even with optimum adjustment of the accelerator focus controls. As a result the beam emerging from "c", at 1.0 Mev, contained at best only about 0.8 microamperes of the 30 microamperes incident at "b". As the energy was reduced from 1.0 Mev, the beam became more diffuse and the transmitted intensity correspondingly lower. However, in all cases considered, the accompanying increase in the cross section compensated to the extent that uncertainties directly attributable to low intensity were not significant.

The Collision Chamber.--A photograph of the open collision chamber is shown in Figure 2. The collimated beam entered from the right and passed between the two identical electrode assemblies and into a Faraday cup located in the pump-out arm to the left. Electrical connections from the electrodes passed to the outside through 16 kovar-glass seals in the rear wall of the chamber. The chamber was evacuated by the four-inch baffled oil diffusion pump at the left. In the photograph, the cylinder at left above the pump initially contained a throttle valve arrangement
Figure 2. Interior View of the Collision Chamber.
actuated by the rod extending from the top of the assembly. This throttling valve was used during tests which were made to insure that no pressure gradients existed in the chamber at operating pressures. The valve was later replaced by the small pyrex flask shown in Figure 1, which served as a liquid nitrogen cold trap. Additional pumping was provided by a 2-inch connection from the large hole at the top of the back wall into the large vacuum manifold in the background. This connection was normally partially or completely closed off by a rotating valve arrangement (visible in the hole) which could be rotated to the open position by manipulation with an external hand magnet. Two ionization vacuum gauges were attached at holes visible in the lower part of the chamber, and a cold-trapped McLeod gauge was connected to a hole, hidden by the electrode assemblies, that looked directly into the space between the assemblies. The McLeod gauge was read with a cathetometer. Hydrogen gas was admitted through a palladium leak attached to one of the holes at the upper right. Other target gases were admitted through a mechanical leak after being passed through a cold trap.

The effective pumping aperture to the main pump on the left was deliberately severely constricted by the placement of the Faraday cup in the pump-out arm. The pump was operated continuously, even during a run when the target gas was in the chamber at the working pressure. The constriction was adjusted so that the resulting throughput of gas did not exceed the capabilities of the associated forepump. Working pressure was maintained by a continuous input of fresh target gas and was varied throughout the working range from $10^{-4}$ to $10^{-3}$ mm Hg simply by adjusting the input rate. The object of this constant pumping was to keep the
impurity level in the chamber essentially constant, independent of the working gas pressure. Thus, the ionization currents due to impurities arising from outgassing of interior surfaces and back-diffusion of pump oil vapor, which were measured with no target gas input, could be subtracted directly from all the readings with target gas present. In the course of all the measurements this "background gas" correction ordinarily amounted to only 2 to 5 per cent. The ultimate pressure in the chamber, obtained by closing the gas inlet, was too small to be read meaningfully with the McLeod gauge. It was measured by the ionization gauges to have an average value of almost $6 \times 10^{-6}$ mm Hg, using the gauge manufacturer's nominal calibration for nitrogen. This was assumed to give only the general order of magnitude, however, since the composition of the background gas was unknown.

Detailed comparison of the readings of the two ion gauges with various gas throughput rates showed no significant pressure gradient between the two gauge locations for any gas input setting that provided an equilibrium pressure within the working range.

**Measurement of the Incident Beam Intensity $I_i$** --The Faraday cup which collected the incident protons after they had traversed the collision volume was a bottle-shaped copper cup whose diameter was smallest at the open neck. The 1/2 inch inside diameter of the neck subtended an angle of 2° at the entrance aperture, "c", and about twice that angle at a point on the beam axis at the center of the effective collision volume. Both theoretical and experimental evidence indicated that fast incident protons would scatter more than 1° in far less than one per cent of all collisions. With the "thin target" gas density used in these experiments,
fewer than 2 per cent of the incident protons underwent any sort of ionproducing collisions, and the number undergoing large angle elastic scattering collisions should have been negligible. It was expected that far less than one per cent of all incident particles would fail to enter the collection cup. To check this experimentally, a larger cup having a one-inch square opening was tried, and this gave values for the cross sections identical to those from the smaller round cup within all the other experimental uncertainties.

A disk-shaped "shadow" electrode with a sharp-edged circular aperture just smaller than the inside diameter of the mouth of the cup was located immediately in front of the cup and intercepted those few particles which had scattered through an angle so large that they would not have entered the cup. If not stopped, such particles might have struck the outside of the cup and released secondary electrons, resulting in a false increase in the apparent collected current. This "shadow" electrode was held at a negative potential with respect to the Faraday cup to suppress the escape of secondary electrons from the interior of the cup. In Figure 3 the collected current for constant incident beam intensity is plotted as a function of the suppression voltage. The lower curve applies to the bottle-shaped cup and shows that the apparent current was too high by over 10 per cent when there was no suppression, despite the deep design of the cup. The current assumed a constant asymptotic value for suppression voltages exceeding about 30 volts. The convenient value of $67\frac{1}{2}$ volts was subsequently used throughout the measurements.
Figure 3. Incident Beam Collected in Faraday Cup Versus Suppression Voltage.
The upper curve in Figure 3 was obtained with the second Faraday cup mentioned previously, which was a box one-inch square and 7/8-inch deep. There was no "shadow" electrode in this case, but one side wall of the box was held negative to provide suppression. As expected, with the more open design of this cup, a larger suppression voltage was required to reduce the current to its asymptotic value. The two curves are arbitrarily scaled to approach the same asymptotic value to reflect the fact, mentioned earlier, that using either cup in the cross section measurement gave the same result within all other experimental uncertainties. The bulk of the data presented in the results was obtained with the round cup.

The Collector Assemblies and Electrometers.--A photograph of one of the two identical slow-particle collector assemblies is shown in Figure 4. The collector plate had nine segments, each separately mounted to the rigid 3/8-inch teflon backing, with its front surface 1/4-inch in front of the backing. The five center segments were all cut to an accurate length of 1.106 ± .001 inches in the beam direction, and all segments were accurately spaced 0.010 inches apart. All nine sections were always held at the same potential, so that the field in front of the assembly was essentially the same as if it had been one large continuous plate. However, only the ion (or electron) currents collected by one or more of the five central segments were ever included in the electrometer circuit for measurement. The remaining segments served as guards to assure that the field in front of the active segments was parallel and uniform, so there would be no edge effects due to fringe fields. Thus the "effective volume"
Figure 4. Single Electrode Structure.
of the target gas from which the ions were drawn was the rectangular parallelepiped defined by the active segments of the two collector assemblies. Edge effects at one end of this volume which were due to forward momentum of the slow ions should have been exactly compensated by the same effects at the other end, since the incident fast beam was not attenuated or scattered appreciably across the volume.

Each of the five central segments of each assembly had a separate lead to the outside, so that changes in the number of active segments could be made externally. The proportionality of the "effective volume" to the number of active segments was tested experimentally. The currents collected to one, to three, and to all five segments, corrected for leakage and normalized to the same incident beam intensity, were found to lie in the ratio of 1:3:5 within all other experimental uncertainties. Therefore, the target thickness used in computation of the cross sections was simply the combined length of all the active segments. In the bulk of the measurements only the three center segments were used, for which the target thickness was 3.318 inches.

Each collector assembly also had a grid, which can be seen in Figure 4. It consisted of 0.004-inch diameter stainless steel wires strung 0.100 inch apart on a brass frame, and was positioned 1/4 inch in front of the collector plate surface. Each grid was held negative with respect to its collector to suppress the emission of secondary electrons. While the plate which was held positive to collect electrons and negative ions would not really appear to need a suppressor, it was intended to make both collector assemblies as nearly identical as possible in order to achieve a high degree of symmetry. It was verified that there was no
change in the measured cross section values when the roles of the two collector assemblies were interchanged. The ion transmission of these grids was assumed to be essentially equal to their geometric transmission, which was 96 per cent.

A significant fraction of the "slow" ions produced by energetic protons might in fact have had substantial energies of 100 ev and more, and their initial motion might of course be directed toward the wrong collector plate. A substantial "collection" field across the collision volume was required to assure that essentially all particles would reach the proper collector. Actually, the collection field was determined by the potentials of the two suppressor grids. For symmetry, the two grids were maintained at potentials of equal magnitude but opposite sign with respect to the grounded chamber. This magnitude will hereafter be designated as \( V_c \) (c for "collection"). Each collector plate was positive with respect to its grid by an amount designated as \( V_s \) (s for "suppression"). Thus the electron collector was at the positive potential \( (V_c + V_s) \), while the positive-ion collector was at the negative potential \( -(V_c - V_s) \).

The magnitudes of \( V_c \) and \( V_s \) had to be chosen large enough that the collected currents would show saturation in that they would not change for any further increase of either \( V_c \) or \( V_s \). The collected positive-ion current is designated \( I^+ \), the collected electron current \( I^- \), and the incident beam current collected at the Faraday cup \( I_i \). The observed ratios \( I^+/I_i \) and \( I^-/I_i \) for constant \( V_c = 750 \) volts are plotted against \( V_s \) in Figure 5, for two different incident beam energies. Saturation was evidently achieved by \( V_s \) greater than 50 volts. The values \( V_s = 150 \) and \( V_s = 100 \) volts proved to be convenient and were used in the bulk of the measurements.
Figure 5. Apparent Ion Currents Versus Suppressor Grid Voltage for Constant Collection Field.
It will be noted in Figure 5 that the ordinate is not in arbitrary units. The saturation values of $I^+$ and $I^-$ were equal for all data runs, within the ability to read the meters, at both energies shown for protons incident on the target gases investigated. An anomalous case with higher electron than positive ion current arose following discharges in helium. The excess electron current apparently arose from the release of electrons from the grids by photon emission arising from the bombardment of the Faraday cup by the incident beam. This apparent grid surface sensitivity disappeared with time. A further discussion of this topic appears in Chapter VI. The current equality existing during data runs indicated that charge-transfer reactions were not making any appreciable contribution to the observed positive-ion current. Further, the small values of the ratio $I^+/I_1$ (less than $10^{-2}$) verified the earlier assertion that the target was "thin."

In Figure 6 are plotted the values of the gross ionization cross section $\sigma_1$ at 1.0 Mev computed from measurements made with various values of $V_c$ and constant $V_s = 150$ volts. The scatter of the points reflects all of the several uncertainties which entered into this computation, and does not exceed the overall uncertainty to be discussed subsequently. It was concluded that saturation had already been reached at $V_c = 450$ volts, the smallest value investigated. The values $V_c = 900$ and 1050 volts were used in obtaining the bulk of the data for protons on argon, hydrogen, nitrogen, and carbon monoxide. The lower value $V_c = 600$ volts was used for protons on helium, neon, and oxygen to alleviate a discharge condition which occurred in these gases. In some cases below 0.3 Mev incident proton energy, the collection voltage had to be removed while reading the
Figure 6. Observed Ionization Cross Section for Various Collection Field Strengths.

\[ E = 1.0 \text{ MEV.} \]
\[ V_s = 150 \text{ VOLTS} \]
\[ P_m = 3.7 \times 10^{-4} \text{ mm Hg} \]
incident beam current, because it was found to deflect the incident beam off the opening of the Faraday cup. Complete runs at lower $V_c$ of 750 and 450 volts, where this procedure was not necessary, gave identical results. The overall collection efficiencies were taken to be equal to the geometric transmission factors of the grids, or 96 per cent.

The two Keithley model 410 electrometers used for current measurements had to be floated from laboratory ground at the potentials of the collectors. They were isolated from their mounting rack by lucite blocks and were completely enclosed by a well-grounded screen cage. AC power was supplied through isolation transformers. The DC polarizing potentials were supplied by shielded battery packs which were also enclosed in the cage, because any ripple or noise in this supply was capacitively coupled into the electrometer input. Under these conditions, the noise in the electrometers with no input current was such as would have interfered with current measurements in the $10^{-13}$ ampere range, but it was negligible for the smallest currents ($2 \times 10^{-12}$ amperes) encountered in the measurements described.

The most serious source of noise in these experiments came directly from the behavior of the incident proton beam. Although the current entering the collision chamber had satisfactory long-term stability, its instantaneous value varied rapidly and erratically. Damping time constants provided by high quality shunting capacitors in the electrometer input circuits were added to reduce the meter jitter. In practice, one electrometer was used to measure either $I^+$ or $I^-$, while the second was used for simultaneous reading of the incident beam intensity $I_i$. The two meters were in close physical proximity so that both could be seen at the
same time. The ratios $I^+ / I_1$ and $I^- / I_1$ could be observed to an estimated 2 per cent maximum uncertainty, including both reading error and the inherent uncertainty of the electrometers.

A most important factor that has not yet been mentioned is that of leakage currents. The construction of the collector assemblies was such that the leakage paths from the active collector segments across the teflon mounting plate to the grounded collision chamber were long and of very high resistance, and the resulting leakage currents across the teflon were negligible. The leads to the kovar-glass seals in the chamber wall were stiff copper wires that did not touch any surface. Each of the leads from the outside end of a seal to the electrometer cage was doubly shielded by the use of a coaxial cable with a heavy rubber outer jacket, slipped inside an extra braided wire sleeve. Only the outermost shields were grounded, while the inner shields of all cables were held at the same potentials as their central current leads. The kovar-glass seals themselves were, however, unguarded since they were not of a doubly concentric type that would permit the same arrangement as in the cables.

A typical set of leakage currents to the positive-ion collector is shown in Figure 7 for several values of $V_c$, with $V_s = 150$ volts. While not strictly ohmic, the currents were small and steady, and varied with voltage in a regular way. They reproduced well over periods of hours, although there was some day-to-day variation that was presumably related to atmospheric conditions. The leakage current was read at frequent intervals during all data runs. In the case of hydrogen it constituted a correction of less than 5 per cent to the ion current reading, and contributed a negligible uncertainty. Following the occurrence of
Figure 7. Leakage Currents Versus Collection Voltage.
discharges in helium, the internal leads in the chamber were consoli-
dated with the result that leakage current corrections were negligible
for all later runs. In all of the previous discussion all ion current
readings mentioned had been corrected for leakage.

The arrangement of the high-voltage connections may be summarized
as follows:

Each of the five central segments of a collector assembly had
separate leads. A sixth lead was connected to all four of the outer
guard segments, and a seventh to the grid. All seven leads passed out
of the vacuum through separate Kovar-glass seals, and through separate
doubly shielded cables to a teflon patch board inside the electrometer
cage.

The high-voltage tap of the polarizing battery pack was connected
directly to the electrometer frame and to the inner shields of all seven
cables. The physical arrangement was such as to avoid any "loops" for
pickup.

The leads from the outer guard segments and from any "inactive"
inner segments were also connected directly to the battery at the patch
board.

The leads from all active segments were joined at the patch board
and connected only to the electrometer input. The internal feedback
arrangement of the electrometer limited the potential difference between
the input and the frame to a few millivolts for any value of the input
current, so that the active segments had essentially the same potential
as the guards.
CHAPTER IV

EXPERIMENTAL RESULTS

Summary of Experimental Method.--The gross ionization cross sections for protons incident on helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide were measured for incident particle energies over the range from 0.15 to 1.10 Mev. The incident proton energy was determined by 90° deflection in a regulated magnetic field, whose value was measured with a precision gaussmeter. The ionization currents of both signs were measured simultaneously with the incident beam current by means of sensitive electrometers. The target gas pressure was measured by a liquid-nitrogen-trapped McLeod gauge and ranged from 1.0 to 12.0 x 10^{-4} mm Hg. The effective collision volume was determined by the use of guard structures around the collector electrodes. Collection potentials of plus and minus 1050 and 600 volts were used for the bulk of the measurements. Suppression potentials of 100 and 150 volts were used on the collectors.

Data Corrections.--Leakage currents in the electrometer circuits were measured frequently and subtracted from all current measurements for which they had a significant value. The correction was usually less than 5 per cent. The constant pumping arrangement described in Chapter III was used to provide a residual background gas density that was independent of the sample gas density insofar as possible. In the case of hydrogen the target gas was admitted through a palladium leak which automatically
assured high purity of the entering gas. Other gases were admitted through a mechanical leak subsequent to liquid nitrogen or dry ice and acetone trapping.

The pressure of the residual gas averaged about \(6 \times 10^{-6}\) mm Hg as indicated by ionization gauges, using the nitrogen calibration. The actual value was uncertain since the composition was unknown. A typical run of the ionization currents produced in the residual gas is shown in Figure 8. The slope of the line is almost the same as that obtained with target gas in the chamber, and was not found to vary significantly from day to day. The impurity currents at several energies were read daily before the target gas was admitted, and again in most instances at the end of a day's run. The impurity ionization current for each energy inferred from these data was subtracted directly from each target gas ionization reading. Except for the lowest gas pressures, this amounted to a correction of less than 5 per cent.

In a given run the incident particle energy was varied over the entire range while the target gas pressure was held nominally constant. For the case of hydrogen, the setting of the palladium leak heater power was left fixed for at least one hour before readings were begun, to allow pressure equilibrium to be attained. This long equilibration time was not required when the mechanical leak was used. In all cases the McLeod gauge was read frequently during the run.

Complete runs were made for target gas pressures throughout the range from 1.0 to \(12.0 \times 10^{-4}\) mm Hg. The residual gas pressure was not subtracted from the indicated total pressure since it was not really well known; however, if it was really of the order of \(6 \times 10^{-6}\) mm Hg as the
Figure 8. Impurity Contribution for Protons Incident on Background Gas.
ionization gauges indicated, it represented a correction of less than 5 per cent for all total gas pressures above $1.2 \times 10^{-4}$ mm Hg. In computing the molecular density of the target gas, its temperature was taken to be that of the room.

A set of values obtained for the gross ionization cross section at one energy from a series of runs at different pressures of hydrogen gas is shown in Figure 9, plotted to a relative scale. The apparent fall-off at pressures below $2.5 \times 10^{-4}$ mm Hg was identified with the above mentioned neglect of the contribution of the residual gas in computing the target gas density. Similarly, the indication of rising values for pressures above $10 \times 10^{-4}$ mm Hg was identified with multiple collisions and failure of the "thin target" assumptions. The existence of a definite plateau between these regions lent confidence that all the important assumptions were valid there. All of the data used in compiling the final results were taken from runs lying within this plateau.

Results.--The final values for the absolute gross ionization cross sections for protons incident on helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide are plotted in Figures 10 through 16. The data give an excellent fit to a straight line on a log-log plot throughout the energy range for all cases examined except carbon monoxide. The carbon monoxide data also fit a straight line for energies greater than approximately 0.400 Mev. The data therefore correspond, with the noted exception, to an expression of the form:

$$\sigma_i = A \times E^{-C} \text{ cm}^2/\text{molecule}$$

(16)

where E represents the incident particle energy.
Figure 9. Computed Ionization Cross Section for Varying Target Gas Pressure.

Each point is an average of many runs.
Figure 10. Cross Ionization Cross Section for Protons Incident on Helium.
Figure 11. Gross Ionization Cross Section for Protons Incident on Neon.
Figure 12. Gross Ionization Cross Section for Protons Incident on Argon.
Figure 13. Gross Ionization Cross Section for Protons Incident on Molecular Hydrogen.
Figure 14. Gross Ionization Cross Section for Protons Incident on Molecular Nitrogen.
Figure 15. Gross Ionization Cross Section for Protons Incident on Molecular Oxygen.
Figure 16. Cross Ionization Cross Section for Protons Incident on Carbon Monoxide.
An expression of this form has been fitted to the experimental data by a least squares method using a Burroughs 220 electronic computer. Values of the normalizing coefficient $A$ and the exponent $C$ obtained for the several gases studied are presented in Table 1 in the next section, together with the range of uncertainty of each that is indicated by the scatter of the data. The straight lines drawn in Figures 10-16 correspond to these computed values. Discussion of the possible error brackets shown on the curves is contained in the next section.

**Discussion of Errors.**--It was indicated in Chapter III that the uncertainty in a single reading of the ratio of the uncorrected ionization current to the incident beam current should not have exceeded about $\pm 2$ per cent. The target gas temperature was not directly measured and may have been uncertain by perhaps $\pm 1$ per cent. By far the largest uncertainty in these experiments lay in the measurement of the target gas pressure. Use of the cathetometer was believed to permit a relative reading accuracy of the McLeod gauge of less than 1 per cent in the range around $5 \times 10^{-4}$ mm Hg. This gauge had not been absolutely calibrated, however, so that a possible error of about $\pm 5$ per cent must be admitted in the absolute reading. This led to proportionate possible systematic error in the absolute magnitude of the cross sections, i.e., in the value of the normalization constant $A$ in equation (16).

The slope of the curves is less uncertain than the cross section magnitudes. The proton energy had a nominal uncertainty of only $\pm 0.2$ per cent at 1 Mev, and the uncertainty was believed to be not only $\pm 0.5$ per cent at 0.15 Mev. Individual data runs were made at constant nominal
pressure, so the slopes obtained depended only on the relative scale-reading accuracy rather than on the absolute accuracy of the McLeod gauge. Any error in calibration of the energy due to uncertainty of the onset of the $^3H(p,n)^3He$ reaction would likewise lead to a shifting of the curves without affecting their slopes.

A Burroughs 220 electronic computer was programmed to compute the values of $A$ and $C$ of equation (16) which corresponded to a least-squares fit to the average cross sections obtained from many individual runs, and to compute the probable errors in these constants that are indicated by the scatter of the data. The resulting values are given in Table 1 below.

Table 1. Calculated Values for the Equation $\sigma_1 = A \times e^{-C}$

<table>
<thead>
<tr>
<th>Gas</th>
<th>$A \times 10^{-17} \text{ cm}^2/\text{molecule}$</th>
<th>$C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>$2.073 \pm 0.005$</td>
<td>$0.755 \pm 0.003$</td>
</tr>
<tr>
<td>Ne</td>
<td>$5.883 \pm 0.013$</td>
<td>$0.687 \pm 0.003$</td>
</tr>
<tr>
<td>Ar</td>
<td>$15.59 \pm 0.03$</td>
<td>$0.712 \pm 0.003$</td>
</tr>
<tr>
<td>$H_2$</td>
<td>$3.433 \pm 0.009$</td>
<td>$0.864 \pm 0.004$</td>
</tr>
<tr>
<td>$N_2$</td>
<td>$14.20 \pm 0.03$</td>
<td>$0.704 \pm 0.003$</td>
</tr>
<tr>
<td>$O_2$</td>
<td>$15.26 \pm 0.11$</td>
<td>$0.747 \pm 0.007$</td>
</tr>
<tr>
<td>CO*</td>
<td>$15.47 \pm 0.05$</td>
<td>$0.733 \pm 0.009$</td>
</tr>
</tbody>
</table>

* As explained in Chapter IV, the straight line relationship holds only above $.400 \text{ Mev}$ for this case.
The probable error of the normalization constant $A$ that is computed from the scatter of the data can be seen to be less than 1 per cent in all cases. The previously mentioned possible error of about $\pm 5$ per cent caused by uncertainty in the target gas pressure does not appear in these computed values since such an error is systematic. It is concluded that a possible error of $\pm 6$ per cent must be admitted in the absolute normalization of the cross section curves and the flags shown on Figures 10-16 are of this magnitude.

It is emphasized that the relative values of the cross sections at various energies are not subject to this systematic error, and hence the uncertainties in the slopes of the lines are as indicated by the probable errors of the constant $C$ in Table 1 above. Furthermore, the relative magnitudes of the cross sections for the various gases at a given energy are uncertain by no more than about $\pm 2$ per cent.

The experimental results of other investigators $^{6,7,12,14,15,16}$ which are available in the lower energy ranges are included in Figures 10 through 16 for completeness. It is apparent that there is considerable disagreement in the low energy range among some of the results; however, the values of Afrosimov, et al. $^{6}$, for protons in hydrogen, and Fedorenko, et al. $^{7}$, for protons in neon and helium agree with the present results quite satisfactorily in the region between 0.15 and 0.18 Mev that overlaps the present results.
CHAPTER V

COMPARISON WITH AVAILABLE THEORY

Protons Incident on Molecular Hydrogen.--For the case of protons incident on molecular hydrogen, the gross ionization measurements yield in principle, as shown in Chapter II, the sum of the contributions from the following four distinct kinds of ionization events:

\[ H^+ + H_2 \rightarrow H^+ + H_2^+ + e \]  \hspace{1cm} (5)

\[ H^+ + H^+ + H^0 + e \]  \hspace{1cm} (6)

\[ H^+ + H^+ + H^+ + 2e \]  \hspace{1cm} (7)

\[ H^+ + H^+ + H^- \]  \hspace{1cm} (8)

plus the three kinds of charge-transfer events:

\[ H^+ + H_2 \rightarrow H^0 + H_2^+ \]  \hspace{1cm} (2)

\[ H^0 + H^+ + H^+ + e \]  \hspace{1cm} (3)

\[ H^0 + H^+ + H^0 \]  \hspace{1cm} (4)

Reactions (7) and (8) represent more complex events than do (5) and (6), and it seems quite likely that they are correspondingly improbable and contribute in a minor fashion to the total ionization. The sum of the cross sections for (2), (3), and (4) is the gross charge transfer cross section which has been measured previously\(^4\). This cross section is
found to be of such a magnitude that charge transfer should make a barely significant contribution of about 2 per cent at 0.15 Mev, but be negligible above 0.2 Mev. In verification of this assertion is the fact that the collected electron currents observed were always equal to the positive ion currents within the reading accuracy of ± 2 per cent. Any significant amount of charge transfer would have led to an excess of positive ion current over electron current. Any secondary electron emission produced by positive-ion impact on the grid shielding the slow-ion collector would have had the opposite effect. The data presented in Figure 5, Chapter III, indicate that this latter mechanism increased the electron current by less than 2 per cent. Therefore the gross ionization measurements yielded essentially the sum of the cross sections for processes (5) and (6).

Theoretical cross section calculations using the Born approximation have been made\(^1\) for the atomic process:

\[
H^+ + H^0 \rightarrow H^+ + H^+ + e
\]  

(17)

A method of obtaining an approximate theoretical treatment for the molecular processes has been indicated in reference 1. Although the results calculated for reaction (16) were not given in explicit analytic form, the following generalization was made:

If a fast proton collides with a nucleus of atomic number \(Z_b\), to which one electron is bound in the \(1s\) state, then the cross section for removal of that electron takes the general form (Equation 21 of Reference 11):

\[
\sigma^+ = \left(\frac{Z_b}{\Delta E}\right)^2 \frac{f(M\Delta E)}{E}
\]
in which:

\[ \Delta E \] is the ionization energy for removal of the electron,

\[ M \] is the reduced mass of the colliding system,

\[ E \] is the kinetic energy of the relative motion,

\[ f \] is a function of unspecified analytic form.

This formula permits scaling of the graphical results given for reaction (17) to any other reaction that meets the above description.

It has often been assumed that a hydrogen molecule is simply equivalent in an energetic collision process to two independent hydrogen atoms, so that the molecular cross section would be expected to be simply twice the atomic cross section. However, in the formula above there is an explicit dependence on the ionization energy \( \Delta E \) of the electron to be removed. The *vertical* ionization energy of one electron in the hydrogen molecule is appreciably different from the atomic ionization energy, being, in fact, greater by the factor 1.2.

The scaling procedure followed was this: The molecule was considered to be equivalent to two free neutral atoms in every respect except that account was taken of the fact that the ionization energy is 1.2 times the normal atomic value. Ignored were the effects of the second atom on the reduced mass of the system consisting of the projectile and the first atom, on the ratio of the incident particle energy to the relative motion energy, and of course on the form of the electronic wave function that was used in the calculation of the atomic cross section. To this approximation, a theoretical cross section for the removal of one electron from the molecule by the impact of an incident proton of energy \( E \) will be twice the given atomic cross section for the
incident proton energy $E/1.2$, divided by $(1.2)^2$. This cross section should actually correspond to the sum of the cross sections for all of the several kinds of molecular ionization events, since the theoretical treatment made no restrictions on the final state of the molecule, and so the result should include all possible final states. Therefore, this cross section should correspond to the measured gross ionization cross section.

The dashed line in Figure 17 is the extrapolation from the theory of Bates and Griffing as described. Precision in plotting the line was limited by the accuracy with which the rather small graphs of the published paper could be read. There is essentially perfect agreement within the stated experimental uncertainties for high energies.

Protons Incident on Helium.--Theoretical calculations in the Born approximation of the cross sections for ionization and simultaneous ionization and excitation of helium by protons have been made by Mapleton.\(^2\) He assumed that the helium wave functions may be approximated by products of normalized hydrogen wave functions in which the helium nucleus had an effective charge $Z_1$ of 1.6875 for the ground state. He examined three cases corresponding to various choices for $Z_2$ the effective charge associated with the Coulomb field acting on the final state bound electron, and $Z_3$ the effective charge associated with the Coulomb field acting on the final state positive energy electron. These cases were:

Case I: $Z_2 = 2, \quad Z_3 = 1$

Case II: $Z_2 = 2, \quad Z_3 = Z_1$
Figure 17. Comparison of the Experimental and Theoretical Gross Ionization Cross Sections for Protons Incident on Molecular Hydrogen.
Case III: \( Z_3 = Z_1 \) for the \( l = 0 \) term of the wave function of the final state positive energy electron

\( Z_3 = 1 \) for the \( l > 0 \) terms of the wave functions of the final state positive energy electron.

Mapleton has pointed out that the cross sections determined from calculations based on the assumptions of Case III would be expected to be the most realistic. The dashed line in Figure 18 represents Mapleton's Case III result, plotted with rather poor precision because of difficulty in reading the small graphs of his published paper. There is essentially perfect agreement within the stated experimental uncertainties between the theoretical calculation and the experimental results in the energy range above approximately 400 kev.

Ionization cross sections for \( \alpha \)-particle impact and electron impact on helium have been calculated by Erskine\(^{17}\) through an application of the Born approximation. Mapleton has demonstrated that it is possible to scale the \( \alpha \)-particle results to those for protons if particles with equal velocities of relative motion are considered. Translation of Erskine's results to the proton case leads to close agreement with Mapleton's Case III. It is also significant to note that Erskine's results for electron impact on helium are in close agreement with the experimental cross sections determined from the data of Smith\(^{18}\). This cross-correlation leads to added confidence in the experimental results for protons incident on helium obtained in this research.
Figure 18. Comparison of Experimental and Theoretical Gross Ionization Cross Sections for Protons Incident on Helium.
Comparison of Experimental Cross Sections Obtained for Incident Protons and Electrons of Equal Velocity. -- It has been pointed out by Mott and Massey\textsuperscript{19}, Bates and Griffing\textsuperscript{1}, Mapleton\textsuperscript{2}, and others that if the velocities of relative motion are the same, and are sufficiently high, the ionization cross sections for electron-atom and proton-atom collisions calculated in the Born approximation are the same. The velocity of relative motion is the same in both the laboratory and center-of-mass coordinate systems. It is possible to translate the electron cross section data by multiplying the electron energy scale by the ratio of the proton to the electron mass.

The known electron data corresponding to an energy range which is sufficiently high to be of interest in this comparison is limited in quantity and was obtained, for the most part, several decades ago. There appears to be reason to believe, however, that the bulk of the data is reliable. As an aid in evaluating the electron-molecule and proton-molecule comparisons some electron-molecule results in the energy range below the supposed lower limit of validity of the Born approximation are included. Data from the following sources appear, along with the proton-molecule cross sections obtained in this research, in Figures 19 through 25.

<table>
<thead>
<tr>
<th>Investigators</th>
<th>Gases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smith\textsuperscript{18}</td>
<td>He, Ne, A</td>
</tr>
<tr>
<td>Tate and Smith\textsuperscript{20}</td>
<td>N\textsubscript{2}, H\textsubscript{2}, O\textsubscript{2}, CO</td>
</tr>
<tr>
<td>Harrison\textsuperscript{21}</td>
<td>H\textsubscript{2}, He</td>
</tr>
<tr>
<td>Tozer and Craggs\textsuperscript{22}</td>
<td>A, Ne, He</td>
</tr>
<tr>
<td>Bleakney\textsuperscript{23,24}</td>
<td>Ne, A, H\textsubscript{2}</td>
</tr>
<tr>
<td>Compton and Van Voorhis\textsuperscript{25}</td>
<td>H\textsubscript{2}, H\textsubscript{c}</td>
</tr>
<tr>
<td>Lampe, Franklin, and Field\textsuperscript{26}</td>
<td>He, Ne, A, H\textsubscript{2}, N\textsubscript{2}, CO, O\textsubscript{2}</td>
</tr>
</tbody>
</table>
Figure 19. Comparison of Experimental Gross Ionization Cross Sections for Protons and Electrons of Equal Velocity Incident on Helium.
PRESENT RESULTS ($H^+ + N_e$)
REFERENCE 18
REFERENCE 22
REFERENCE 24
REFERENCE 26

Figure 20. Comparison of Experimental Gross Ionization Cross Sections for Protons and Electrons of Equal Velocity Incident on Neon.
Figure 21. Comparison of Experimental Gross Ionization Cross Sections for Protons and Electrons of Equal Velocity Incident on Argon.
Figure 22. Comparison of Experimental Gross Ionization Cross Sections for Protons and Electrons of Equal Velocity Incident on Molecular Hydrogen.
Figure 23. Comparison of Experimental Gross Ionization Cross Sections for Protons and Electrons of Equal Velocity Incident of Molecular Nitrogen.
<table>
<thead>
<tr>
<th>INCIDENT ELECTRON ENERGY (ev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
</tr>
<tr>
<td>I</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INCIDENT PROTON ENERGY (Mev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
</tr>
<tr>
<td>I</td>
</tr>
</tbody>
</table>

Figure 24. Comparison of Experimental Gross Ionization Cross Sections for Protons and Electrons of Equal Velocity Incident on Molecular Oxygen.
Figure 25. Comparison of Experimental Gross Ionization Cross Sections for Protons and Electrons of Equal Velocity Incident on Carbon Monoxide.
There is excellent agreement between the cross sections obtained with incident electrons and with incident protons of the same velocity for the target gases helium, neon, argon, nitrogen, oxygen, and carbon monoxide. There is also good agreement for the molecular hydrogen case if only the data of Tate and Smith\(^\text{20}\), Bleakney\(^\text{23}\), and Tozer and Craggs\(^\text{22}\) are considered. The cross sections obtained by Harrison\(^\text{21}\), and by Compton and Van Voorhis\(^\text{25}\) lie somewhat above the result obtained with incident protons. Harrison\(^\text{21}\) has pointed out that the pressure measurements for his experiments were obtained with an ionization gauge whose calibration constant was 2.41. A constant of 3.20 would have led to results essentially identical to those of Tate and Smith.\(^\text{20}\) Harrison’s recalibration of his gauge yielded a constant of 2.50. The discrepancies therefore remain unresolved, however, the evidence seems to be in favor of the results of Tate and Smith.

An additional feature of comparison which is not apparent from Figures 23 and 25 is that according to the data of Tate and Smith the electron cross sections for nitrogen and carbon monoxide are equal at high energy whereas the proton results were found to be unequal by about 12 per cent. However, the electron results lie between the proton results for the two gases and are within the limits of the stated experimental uncertainties for the proton measurements on both gases. It does not seem likely that the proton experimental errors could be such as to lead to the observed displacement of the curves since, as it was pointed out in Chapter IV, the ± 6 per cent possible experimental error is believed to be largely systematic and attributable to inaccuracy in the McLeod gauge calibration.
The composite results indicate that it is justifiable to scale electron cross sections to proton cross sections for the gases investigated under the assumed high velocity conditions.
CHAPTER VI

CONCLUSIONS

The experimental values of the ionization cross sections for protons incident on helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide are presented for comparison in Figure 26. The energy of the incident particles ranged from 0.15-1.10 Mev. Experimental points and limits-of-error flags are omitted to avoid unnecessary confusion. For all cases except carbon monoxide the results may be expressed throughout the energy range 0.15-1.10 Mev by an equation of the form \( \sigma_1 = A \times E^{-C} \) cm\(^2\)/molecule, where \( E \) is the incident proton energy in the laboratory coordinate system. Numerical values for the constants \( A \) and \( C \), and their probable errors are given in Table I, Chapter IV.

A scaling of the theoretical calculation in the Born approximation of the cross section for the ionization of atomic hydrogen to the experimentally determined molecular results has been accomplished.\(^1\) The scaled cross sections are in close agreement with experimental values at high energy. The validity of some of the assumptions made in the scaling process (e.g., that the difference between the electronic wave functions of the hydrogen molecule and those of the hydrogen atom can be neglected) is questionable; however, the results of such a scaling clearly indicate that the common practice of merely doubling the cross section for atomic cases to obtain the associated molecular results is suspect.

Born approximation calculations by Mapleton\(^12\) for protons incident on helium targets have been found to be in excellent agreement with this
Figure 26. Gross Ionization Cross Sections for Protons Incident on Helium, Neon, Argon, Molecular Hydrogen, Molecular Nitrogen, Molecular Oxygen, and Carbon Monoxide.
experiment. Further corroboration of the experimental results for incident protons comes from a comparison of the scaled cross sections for α-particles incident on helium which have been calculated by Erskine.\textsuperscript{17}

It has been established that for sufficiently high, and equal, velocities of relative motion, the ionization cross sections for electrons and for protons incident on helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide are the same within the limits of the estimated experimental error of this experiment.

CHAPTER VII

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the many helpful suggestions made by members of the Oak Ridge Cross Section Group, particularly C. F. Barnett and Herma Postma. We also wish to acknowledge the expert assistance of Mr. R. A. Langley, Mr. M. S. Spielberger, and Mr. J. W. Martin in the performance of this work.

Respectfully submitted,

E. W. McDaniel
Project Director

Approved by:

Vernon Crawford
Head, Physics Branch
Physical Sciences Division
APPENDIX

THE CONCEPT OF THE COLLISION CROSS SECTION

The various reactions which can occur when a beam of monoenergetic particles traverses a gas may be described in terms of reaction cross sections. The following development is only one of several possible presentations of the cross section concept.

Consider a monoenergetic beam of \( N_0 \) particles per second incident upon a gas whose density is \( n \) particles per cubic centimeter. Let \( N(x) \) represent the incident beam particles which have not undergone a reaction in traversing the distance \( x \) in the gas. The change in the unreacted component of the beam in traversing an infinitesimal distance \( dx \) beyond the point \( P \) located \( x \) units within the gas will be proportional to \( N(x) \), \( n \), and \( dx \). Or:

\[
- \frac{dN(x)}{dx} \sim N(x)n
\]  

(18)

where the minus sign indicates a decrease in the number of unreacted particles.

Let the constant of proportionality be represented by \( \sigma \). Then:

\[
- \frac{dN(x)}{dx} = \sigma N(x)n
\]  

(19)

Integration of equation (19) followed by evaluation of the arbitrary constant yields:
\[ N(x) = N_0 e^{-nx} \]  \hspace{1cm} (20)

A knowledge of \( N_0 \), \( N(x) \), and \( n \) leads to a determination of \( \sigma \). It will be observed that the porportionality constant \( \sigma \) has the dimensions of \((\text{centimeters})^2\). Therefore \( \sigma \) is called the total reaction cross section for the specific target-projectile combination. It is sometimes convenient to consider the cross section to be an effective projected area of the target particle for the particular reaction or reactions of interest.

If the reactions of interest are those which arise in collision processes, \( \sigma \) may be considered to be the total collision cross section. This total collision cross section may be considered to be made up of the sum of the cross sections for elastic and inelastic collisions of all possible types. Thus:

\[ \sigma = \sum \sigma_n \]  \hspace{1cm} (21)

where \( \sigma_0 \), \( \sigma_1 \), \( \sigma_2 \), \( \sigma_3 \), etc. represent the individual cross sections. In general \( \sigma \) and all of the \( \sigma_n \) are functions of the particle velocity.

To illustrate the use of the concept of collision cross section, consider the following experiment. A homogeneous ion beam is injected into a collision chamber containing target gas atoms at a pressure sufficiently low to insure that only single collisions will occur. It is evident that for ionizing collisions equal quantities of positive and negative charge will be produced in the collision region. Thus a gross ionization cross section for the production of free electrons can be determined by measurement of the ionization electron current.
To construct a model for this experiment let $n$ represent the number of target atoms per unit volume, $\sigma_1^-$ the cross section of each target structure for the production of electrons, $A$ the cross sectional area of gas presented to the incident beam, and $N_0$ the total number of incident particles per second. It follows from the earlier discussion that if we consider an element of the gas of thickness $dx$ the fraction of the target area blocked by the target particles is:

$$f = \frac{A \sigma_1^- n \, dx}{A} = \sigma_1^- n \, dx \quad (22)$$

This result is based on the assumption that the gas pressure is sufficiently low to preclude any shielding of one target atom by another.

$N_0 \sigma_1^- n \, dx$ collisions will occur in the length $dx$. If a sufficiently small number of reactions occur to insure that the incident beam is essentially unaltered in passing through the collision region, $N_0 \sigma_1^- n \, l$ collisions will occur in the total collision chamber length $l$.

The application of a transverse electric field will result in the collection of a number of electrons which is proportional to the gross electron ionization cross section $\sigma_1^-$. The total number of electrons collected per unit time under the preceding conditions will be equal to $N_0 \sigma_1^- n \, l$. The collected electrons will produce a current $I^-$ equal to $N_0 \sigma_1^- n \, l \, e$, where $e$ denotes the electron charge.

All of the incident beam current $I_i^+$ passes through the collision chamber and is collected. It follows that the ratio of the electron current to the total beam current is given by:
\[
\frac{I^-}{I_i} = \frac{N_0 \cdot e}{N_0 \cdot e} \cdot \frac{\sigma^-}{n \cdot \ell} = \sigma^- \cdot n \cdot \ell
\]  

(23)

Therefore the gross electron ionization cross section for this special case is:

\[
\sigma^- = \left( \frac{1}{n \cdot \ell} \right) \left( \frac{I^-}{I_i} \right) \text{cm}^2 / \text{target particle}
\]  

(24)

A similar analysis applied to a measurement of residual positive ions would lead to the result:

\[
\sigma^+ = \left( \frac{1}{n \cdot \ell} \right) \left( \frac{I^+}{I_i} \right) \text{cm}^2 / \text{target particle}
\]  

(25)


TECHNICAL STATUS REPORT NO. 8
Project No. B-176
Covering the Period
June 1, 1961 to August 31, 1961

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS
Phase III: Fast He$^+$ Ions Incident on He, Ne,
Ar, H$_2$, N$_2$, O$_2$, and CO

By
E. W. McDaniel
D. W. Martin
J. W. Hooper
D. S. Harmer
R. A. Langley

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee

September 1, 1961

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia
TECHNICAL STATUS REPORT NO. 8

Project No. B-176

Covering the Period

June 1, 1961 to August 31, 1961

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

Phase III: Fast He\(^+\) Ions Incident on He, Ne, Ar, H\(_2\), N\(_2\), O\(_2\), and CO

By

E. W. McDaniel
D. W. Martin
J. W. Hooper
D. S. Harmer
R. A. Langley

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee

September 1, 1961
I. Title

Ionization and Charge Transfer Cross Sections

Phase III: Fast He\(^+\) Ions Incident on He, Ne, Ar, H\(_2\), N\(_2\), O\(_2\) and CO.

II. Objective and Method

The objective of the current phase of the research under Contract AT-(40-1)-2591 is the measurement of the gross cross section for ionization of He, Ne, Ar, H\(_2\), N\(_2\), O\(_2\), and Co by fast He\(^+\) ions. The energy of the projectile ions is variable throughout the range 0.15-1.0 Mev. Since the previous work in this area has been confined to incident-particle energies below 0.20 Mev, the present investigation represents an extension into a region that is largely unexplored.

The source of energetic ions is a 1-Mev Van de Graaff positive ion accelerator, which is equipped with a beam analyzing and stabilizing system. The beam is passed through differentially pumped collimating apertures into a collision chamber containing the target gas. The chamber dimensions and the gas pressure are such that the target is "thin", in that only about one percent of the incident ions engage in even one ion-producing collision, and a negligible fraction engage in two or more such collisions. All but a negligible fraction of those ions which do collide lose only a small fraction of their energy, and suffer only a small change in their direction of motion. After they have traversed the active collision volume, the ions are collected in a Faraday cup, and the measured current to this cup is taken to be a measure of the total intensity of the incident beam.

In the present phase of the research we are measuring what we have called the "gross ionization" cross section. Polarized electrodes within the collision volume collect essentially all of the charged particles of both signs formed in the gas by the passage of the energetic ions. Most of these residual charged
particles have quite low energies, although a small fraction may have energies as great as several hundred electron volts. The currents collected are measured by means of electrometers. Suppression of secondary electron emission has been provided, and an arrangement of guard electrodes serves to define the effective target thickness in such a way that no end corrections are required. Complete details of the existing apparatus may be found in our Technical Status Report No. 7, June 1, 1961.

The ion and electron currents observed here will include any contributions from charge changing events, in which the incident He\(^+\) either gains or loses an electron and emerges as either a fast He\(^0\) neutral or a He\(^{++}\) ion. Whenever there is an appreciable contribution from such events, it will be manifested in an inequality of the positive and negative ion currents collected from the collision region. In this case our measurements provide separately the cross sections for production of positive ions and of electrons, respectively. The cross sections for capture and for loss of an electron by fast He\(^+\) ions in various gases have been measured over part of our energy range by others,\(^1\) who made observations of the composition of the fast beam emerging from the collision region, rather than observations of the residual slow particles as done here. Where such data is available, we can subtract the contributions from the charge changing events and thus obtain the cross section for the production of ion pairs, which is what we normally mean by the gross ionization cross section. A cross check between our data and any outside data so used is that the difference between our cross sections for production of positive and negative ions should agree with the difference between the electron capture and loss cross sections. In any

case, it is of course essential that we maintain our thin target conditions, as described above, to assure that the composition of the beam does not change appreciably as it crosses the collision volume.

III. Present Status of the Experimental Work

Modifications of the Van de Graaff accelerator to permit the use of either hydrogen or helium ion beams at will were completed early in the present reporting period. Subsequently, a substantial body of data was collected on the ionization of hydrogen by helium ions. In contrast to the earlier measurements with proton beams, it was found that there were substantial contributions from charge changing events. The positive ion current collected from the collision region exceeded the electron current by more than ten percent at low energies, the two currents were equal at about 0.5 to 0.6 Mev, and the electron current was the greater by a few percent at the highest energies. The difference at the low-energy end was found to agree very roughly with the values tabulated by Allison for the electron capture cross section by He⁺ in hydrogen, although our data analysis was not then complete enough to say if the agreement was quantitatively satisfactory.

Certain inconsistencies in the data caused us to question whether the beam entering the collision chamber might contain appreciable numbers of He⁰ neutrals and/or He⁰⁺ ions. The beam was being magnetically analyzed, with resolution more than adequate to assure that only He⁺ ions emerged from the analyzer exit slit. However, from this point the beam was being passed through a two-inch-diameter beam pipe for a total distance of some seven feet, through a port in the target room shielding wall, to the point where the collision chamber was located in an adjacent room. This section of the vacuum system was rather
remote from any of the vacuum pumps, and contained no gauge with which to monitor the quality of the vacuum. The possibility could not be ruled out that appreciable charge changing collisions with the residual gas might be occurring before the beam entered the collision chamber.

An additional two-inch trapped and baffled mercury diffusion pump and a cold cathode discharge gauge were therefore installed along the beam tube between the analyzing magnet exit slit and the collision chamber entrance aperture. This would permit the pressure to be lowered so that any beam contamination that might be occurring would be sharply reduced. If this reduction of pressure were found not to affect the cross section determinations in any way, this would assure that there had not been any appreciable contributions due to beam contamination in the first place.

Unfortunately, before these checks could be conducted, an accidental loss of power to one of the fore-pumps in the system, while it was unattended at night, caused a general failure of the whole vacuum system, with subsequent heavy contamination of much of it by the decomposition products of the diffusion pump fluids. A complete dismantling, cleaning, and overhauling of everything except the accelerator proper was required. We took this occasion to effect a move of the entire apparatus from its former location outside the analyzing magnet room to a place inside the room and much closer to the magnet. By this move, the former seven-foot flight path of the beam from the analyzing magnet exit slit to the first of the two collimating apertures directly in front of the collision chamber was reduced to about two feet. At the same time, a number of mechanical improvements in the chamber support structure were made, which provided for much easier and more rigidly maintained alignment. Other changes were made in the differential pumping arrangement, and an additional beam viewer
was installed behind the collision chamber as an aid both in beam alignment and in observing the lateral deflection of the beam by the ion-collection fields in the chamber. More than four weeks altogether were consumed in effecting these changes and repairs.

The reduction of the beam flight distance aids first of all in reducing beam contamination by charge changing collisions inside the beam tube. In addition, it has made it possible to obtain some increase in the beam currents into the collision chamber by reducing the beam focussing problems.

The earliest checks made with the reassembled apparatus showed at once that charge changing processes had indeed been of serious proportions under the earlier experimental conditions. The beam viewer newly installed behind the collision chamber permitted observation of the lateral deflection of the beam by the charge collecting fields in the chamber, and a second spot interpreted as He$^{++}$ was observed at twice the deflection of the main beam spot. The intensity of the contaminant was estimated visually as at least ten percent of the beam. This effect was observed despite the much reduced flight path length, at a beam energy of 1.0 Mev. At the time, the new vacuum pump mentioned above was not operating, and the observed pressure of about $3 \times 10^{-4}$ Torr in the beam tube was presumably about the same as had prevailed there under the old arrangement. When the new pump was operated, the pressure dropped to less than $10^{-6}$ Torr and the He$^{++}$ spot disappeared. Thus it appears that the new arrangement is successful in reducing the beam contamination due to charge changing collisions to a negligible value.

When the earlier ionization measurements in hydrogen were repeated, following the improvements described, the cross section values obtained were running
about 25 percent lower than before. Therefore all the data previously obtained with the helium ion beam on hydrogen has been discarded, and new measurements are in progress.

It should be emphasized that none of the above is believed to have any bearing on our earlier measurements of the ionization of gases by a proton beam. There is of course no electron loss process possible with protons, and the cross section for electron capture is much smaller than for He$^+$. However, we expect to check this by rerunning a few representative points with the proton beam.

When the present measurements for He$^+$ ions on hydrogen have been completed, we will then proceed to the measurements for He$^+$ on helium, neon, argon, nitrogen, oxygen, and carbon monoxide.

IV. Travel and Publications During the Present Reporting Period

E. W. McDaniel, J. W. Hooper, and D. W. Martin attended the Second International Conference on the Physics of Electronic and Atomic Collisions at the University of Colorado, Boulder, on June 12-15, 1961, and the D. A. S. A. Symposium on Reaction Rates at the National Bureau of Standards, Boulder, on June 16, 1961. At the conference, a paper was presented entitled "Ionization Cross Sections for Protons Incident on He, Ne, Ar, H$_2$, N$_2$, O$_2$, and CO in the Energy Range 0.15 to 1.0 Mev".

J. W. Hooper was awarded the degree of Doctor of Philosophy by the Georgia Institute of Technology at the June, 1961 Commencement, following presentation of a thesis based on the proton ionization measurements. Dr. Hooper also attended the A.E.C.-A.S.E.E. Advanced Institute on Thermonuclear Theory held at the University of Michigan during July and August, 1961.
E. W. McDaniel attended the Fifth International Conference on Ionization Phenomena in Gases, held in Munich from August 28 to September 1, and there presented a paper describing the group's work on ionization. He also will serve as a U. S. delegate at the Conference on Plasma Physics and Controlled Nuclear Fusion Research, to be held in Salzburg from September 4-9. Upon Dr. McDaniel's return, a report on these meetings will be submitted to the sponsor.

Respectfully submitted,

E. W. McDaniel
Project Director

Approved by:

A. L. Bennett, Chief
Physical Sciences Division
PROGRESS REPORT
(TECHNICAL STATUS REPORT NO. 9)

Project No. B-176

Covering the Period
September 1, 1959 to November 30, 1961

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By
E. W. McDaniel
D. W. Martin
J. W. Hooper
D. S. Harmer
R. A. Langley

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee

December 1, 1961

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia
PROGRESS REPORT

(TECHNICAL STATUS REPORT NO. 9)

Project No. B-176

Covering the Period

September 1, 1959 to November 30, 1961

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By

E. W. McDaniel
D. W. Martin
J. W. Hooper
D. S. Harmer
R. A. Langley

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee

December 1, 1961
I. **Title**

Ionization and Charge Transfer Cross Sections

II. **Period Covered by Report**

The period covered by this report is September 1, 1959 through November 30, 1961. The first 18 months of this period fell under the original contract, No. AT-(40-1)-2591, and the remaining 9 months under the 12-month extension of said contract.

III. **Scope of Research**

The initial contract (dated October 21, 1959 and effective September 1, 1959) called for the measurement of various ionization and charge transfer cross sections for incident beams of protons and hydrogen atoms on molecular hydrogen and helium targets in the energy range 0.15-1.1 Mev. Subsequent increased interest in the phenomenon of proton ionization within the thermonuclear program led us to request permission to change the scope of our work. In a letter to Dr. A. E. Ruark dated May 31, 1960, we proposed to restrict our program to studies of proton ionization, but to extend the work to include the use of neon, argon, nitrogen, and carbon monoxide as target gases. This suggested change in scope was approved in the letter of July 13, 1960 from Dent C. Davis to E. W. McDaniel. The bulk of the work within the new research program was successfully completed and has been described in publications listed in Section IV of this report. Time did not permit the performance of the magnetic analysis of the ionization products which we had hoped to make.

The contract for the extension of our research program called for measurement of the cross sections for ionization of hydrogen, nitrogen, carbon monoxide, helium, neon, and argon by He⁺ and He++ ions in the energy range
The measurements of the cross sections for He$^+$ ionization of hydrogen and helium have been completed, and we expect to finish the remaining He$^+$ experiments before the present expiration date of the contract, February 28, 1962. However, these experiments have met with certain difficulties which were not encountered in the previous proton work (see Technical Status Report No. 8, September 1, 1961), and the acquisition of reliable data has required more time than was anticipated. It is now apparent that the measurements involving He$^{++}$ projectiles will not have been completed by the end of the present contract period, and it is our intention to perform these measurements in a later phase of our program.

IV. Publications


A reprint of publication no. 2 and a preprint of publication no. 5 above are attached.
V. Incident Report

No incidents have occurred during the performance of the research under this contract.

VI. Statement of Current Expenditures

<table>
<thead>
<tr>
<th></th>
<th>Expenditures for the period September 21, 1959 through October 31, 1961</th>
<th>Estimated Expenditures for the period November 1, 1961 through February 28, 1962</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.E.C. CONTRIBUTION:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salaries and Wages</td>
<td>$27,416</td>
<td>$2,320</td>
</tr>
<tr>
<td>Overhead</td>
<td>16,080</td>
<td>1,415</td>
</tr>
<tr>
<td>Permanent Equipment</td>
<td>1,279</td>
<td>0</td>
</tr>
<tr>
<td>Materials and Supplies</td>
<td>3,649</td>
<td>635</td>
</tr>
<tr>
<td>Travel</td>
<td>1,501</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$49,925</strong></td>
<td><strong>$4,370</strong></td>
</tr>
<tr>
<td>GEORGIA TECH CONTRIBUTION:</td>
<td>$13,271</td>
<td>$1,162</td>
</tr>
<tr>
<td>(21% of Total Budget)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$63,196</strong></td>
<td><strong>$5,532</strong></td>
</tr>
</tbody>
</table>

To date, a total of $49,870 of A.E.C. funds have been allocated to this research effort. In a letter to Dent C. Davis, dated October 12, 1961, additional A.E.C. funds in the amount of $4,425 were requested to enable the present level of research activity to be continued until February 28, 1962. It is anticipated that there will be no residual funds at the present expiration date of the contract.

Respectfully submitted,

E. W. McDaniel

Approved by:

A. L. Bennett, Chief
Physical Sciences Division
ANNUAL SUMMARY REPORT
(TECHNICAL STATUS REPORT NO. 10)
Project No. B-176

Covering the Period
March 1, 1961 to February 28, 1962

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS
Phase III: Fast He\(^+\) Ions Incident on He, Ne, Ar, H\(_2\), N\(_2\), and CO

By
E. W. McDaniel
D. W. Martin
J. W. Hooper
D. S. Harmer
R. A. Langley

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee

March 1, 1962

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia
ANNUAL SUMMARY REPORT

(TECHNICAL STATUS REPORT NO. 10)

Project No. B-176

Covering the Period

March 1, 1961 to February 28, 1962

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

Phase III: Fast He⁺ Ions Incident on He, Ne, Ar, H₂, N₂, and CO

By

E. W. McDaniel
D. W. Martin
J. W. Hooper
D. S. Harmer
R. A. Langley

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee

March 1, 1962
TABLE OF CONTENTS

I. Title ............................................. 1
II. Objective and Method ............................... 1
III. Progress of the Research During the Present Contract Year .... 4
    A. Ionization by Protons: Experimental Results ............ 4
    B. Ionization by Protons: Comparison with Theory ........... 4
    C. Modifications of the Apparatus for Studies of He⁺ Ions on
       H₂, He, and Ne .................................... 10
    D. Data for He⁺ on H₂, He, and Ne ........................... 13
IV. Miniaturization of Apparatus for Studies on Ar, N₂, and CO ...... 13
V. Travel and Publications during the Contract Year ................ 22
VI. References ........................................... 24

This report contains 23 pages.
I. Title

Ionization and Charge Transfer Cross Sections.

Phase III: Fast He\(^+\) Ions Incident on He, Ne, Ar, H\(_2\), N\(_2\), and CO.

II. Objective and Method

The current research under contract AT-(40-1)-2591 involves the measurement of the cross sections for production of electrons and positive ions in He, Ne, Ar, H\(_2\), N\(_2\), and CO by fast He\(^+\) ions with energies in the range 0.15-1.0 Mev. The source of projectile ions is a Van de Graaff positive ion accelerator, which is equipped with a beam analyzing and stabilizing system. The beam energy is continuously variable throughout the range indicated above. A sketch of the apparatus arrangement as it was constituted during a part of this work is given in Fig. 1. The ion beam is passed through differentially pumped collimating apertures into a collision chamber containing the target gas. There it is passed between two parallel, identical planar arrays of collector plates, one of which is shown in Fig. 1, and finally into a Faraday cup.

Our method of measurement requires that the chamber dimensions and the gas pressure be such that the target is "thin", in that only about one per cent of the incident ions experience even one ion-producing impact, and a negligible fraction engage in two or more such collisions. Practically all of the ions which do undergo collisions lose only a small fraction of their energy and suffer only a small change in their direction of motion. Therefore essentially all of the fast ions that enter the chamber are collected in the Faraday cup, and the measured current to this cup is taken to be a measure of the total intensity of the incident beam.

All of the plates of one of the two parallel collector arrays are held at a common positive potential, and those of the opposite array at a common negative
In the chamber, the beam passes between two identical, parallel collector arrays, only one of which is shown. Slow-ion currents collected by only the three segments A are measured, with other segments serving as guards. Suppressor grid covering entire collector array not shown. Apertures "b" and "c" designed for large differential pumping impedance, but slit "a" has small pumping impedance (see text Section III-C). (In earlier proton work, distance from "a" to "b" was 84", and the pumping outlet near "a" was not present.)
potential. These potentials are made great enough that essentially all of the slow charged particles of both signs formed in the gas by the energetic ions are collected. Most of these residual particles have energies of less than 50 ev, although a small fraction may have energies as great as several hundred ev.

The currents of slow residual particles collected by the three "active" central segments of each collector array, designated "A" in Fig. 1, are measured by electrometers. Suppression of secondary electrons from the collectors has been provided by screening each array with a suitably biased grid (not shown in Fig. 1). The inactive sectors constitute a guard arrangement which defines the effective target thickness in such a way that no end corrections are required.

The measurements provide separately the cross sections for production of positive ions and of electrons. The slow-ion and electron currents include contributions from what are designated "ionizing events", in which the charge of the projectiles does not change, and also contributions from "charge-changing" events in which the projectile either gains or loses electrons. Whenever the difference between the number of electron-capture and electron-loss collisions is appreciable compared to the number of ionizing events, this situation is manifested in an inequality of the currents of positive and negative charges drawn from the collision volume. The cross sections for capture and for loss of electrons by fast He$^+$ ions in various gases have been measured previously by others over a part of our energy range, by a method that involved observation of the composition of the fast beam emerging from a "thick" target, in contrast to our observations of the slow residual particles produced in a thin target. Wherever such data are available, we can subtract the contributions of the charge-changing events from our data and obtain the apparent or gross ionization cross section. A cross check between our data and any other data so used
is that the difference between our cross sections for production of positive and of negative ions should agree with the difference between the electron capture and the electron loss cross sections. In any case, it is most essential that we maintain "thin" target conditions, to ensure that the composition of the beam does not change appreciably as it crosses the collision volume.

III. Progress of the Research during the Present Contract Year

A. Ionization by Protons: Experimental Results

The work on proton ionization of Phases I and II of this research was completed early in the present contract year. The apparatus used throughout the proton work was as shown in Fig. 1, except that the distance between the magnetic analyzer exit slit "a" and the first collimator aperture "b" was about 84 inches, and the pumping outlet shown near "a" in Fig. 1 was not present. A detailed and cumulative account of all the proton experimental work has been given previously in our Technical Status Report No. 7, and has also been published.\(^2,3\) Included there were comparisons with the experimental results of several other investigators, most of which are at lower energies.

B. Ionization by Protons: Comparison with Theory

For all but one of the gases investigated it was found that a plot of the log of the experimental gross ionization cross section for protons against the log of the proton energy, \(E\), gave a straight line of negative slope throughout the energy range 0.15 to 1.10 Mev. For the one exceptional case of CO, the plot was straight only above 0.4 Mev. An expression of the form \(\sigma = A \cdot E^{-C}\) was fitted to these data by a least squares procedure (see below). The empirical values obtained for the coefficients A and C, together with their probable errors
as indicated by the fit, have been presented in Table I of Technical Status Report No. 7. In general, the fits obtained were extremely good.

It is well known that all these cross sections must eventually reach a maximum and then decrease as the energy decreases. In the one case of CO, our cross sections fell below the straight line for energies below about 0.4 Mev, indicating a possible approach to the maximum. However, in all the other cases the straight line fit continued to be excellent down to our lowest energy, 0.15 Mev, giving no indication of approach to the maximum.

Detailed theoretical computations in the Born approximation have been given by Bates and Griffing\textsuperscript{4} for protons on atomic hydrogen, which could be generalized approximately to the case of molecular hydrogen. Computations for protons on He have been given by Mapleton.\textsuperscript{5} A comparison of their results with our data was also presented in Technical Status Report No. 7. In both cases the theoretical curves were found to be in good agreement with our data for proton energies above about 0.3 Mev, but fell below our fitted straight lines toward lower energies.

Comparisons of our data with the available measurements of the cross sections for ionization by electrons were also presented in Technical Status Report No. 7. Rather general theoretical considerations predict that the cross sections for electrons should become equal to those for protons of the same velocity at high velocities. It was found that generally good agreement obtains above about 300 ev electron energy, corresponding to about 0.55 Mev proton energy. In every case the electron data curves sharply below our proton data toward lower energies. In several cases the electron cross section has its maximum above 80 ev, whereas, as noted, our proton cross sections continue to follow the $E^{-C}$ energy dependence down to the corresponding proton energy of 0.15 Mev.
A general theoretical treatment of the high-energy ionization process has been given by Bethe who used the Born approximation and hydrogen-like electron wave functions. Bethe showed that for high impact velocity \(v\), the cross section for removal of one electron from the \(n\ell\) shell of the target atom by an incident ion of charge \(Z'\) is:

\[
Q^1_{n\ell} = \frac{2\pi e^4 Z'^2}{mv^2} \log_e \left( \frac{2mv^2}{c_{n\ell} E_{n\ell}} \right)
\]

where \(e\) is the electronic charge, \(m\) is the electronic mass, \(Z_{n\ell}\) is the number of electrons in the \(n\ell\) shell, \(E_{n\ell}\) is the ionization energy of that shell, and \(C_{n\ell}\) is an energy of the order of the energy of an electron in the \(n\ell\) shell. \(c_{n\ell}\) is a dimensionless reduced electron matrix element of order unity. Theoretical values of \(C_{n\ell}\) and \(c_{n\ell}\) were computed by Bethe only for the case of atomic hydrogen.

In principle, the total ionization is the sum of contributions from the several \(n\ell\) shells. However, it is known that the predominant contribution comes from the outermost shell, so that the observed total ionization should correspond to Eq. 1 for that shell.

Our experimental proton ionization data have been fitted by a least-squares procedure to the expression:

\[
\sigma = A \log_e (BE)
\]

in which \(A\) and \(B\) are constants, and \(E\) is the proton energy. Since this function is not linear in both \(A\) and \(B\), the method used is a generalization of the usual method for linear functions (this is the same method previously used in fitting the data to the expression \(\sigma = A E^{-C}\)). The function is expanded in a Taylor's series in \(A\) and \(B\) about the mean "best" trial values of these coefficients.
In this form, the function can be properly weighted according to the experimental variance of each of the data points. Only the first two terms of the expansion need be used if one has good initial estimates of A and B. The equations are solved by a simple least-squares procedure using these estimates as trial values. Then in an iterative procedure the results are used as new trial values, and the equations are solved again. This iteration is repeated until the values of the coefficients are unchanged for the desired number of significant figures. The method was programmed for the Burroughs 220 computer of the Rich Electronic Computer Center of the Georgia Institute of Technology. The experimental value for the cross section at each energy used in the computation was an average of many individual measurements, so that a reliable estimate of its variance had been obtained. The values that were obtained for the coefficients A and B for each of the several target gases are presented in Table I, and the error estimates given there reflect the true random errors in the measurements.

Table I

Values of the constants A and B in the equation \( \sigma_1 = \frac{A}{E} \log_e (BE) \) for the gross proton ionization cross section from the best fit to experimental data for incident proton energies in the range from 0.15 to 1.10 Mev. E is in units of Mev and \( \sigma_1 \) in units of \( 10^{-17} \text{ cm}^2/\text{molecule} \).

<table>
<thead>
<tr>
<th>Gas</th>
<th>A ( \times 10^{-17} \text{ cm}^2/\text{MeV} \text{ molecule}^{-1} )</th>
<th>( \log_e B )</th>
<th>B ( \frac{1}{\text{MeV}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>0.4132 ± 0.008</td>
<td>4.974 ± 0.09</td>
<td>144.6 ± 13</td>
</tr>
<tr>
<td>Ne</td>
<td>1.470 ± 0.008</td>
<td>4.017 ± 0.02</td>
<td>55.6 ± 1.1</td>
</tr>
<tr>
<td>Ar</td>
<td>3.616 ± 0.08</td>
<td>4.261 ± 0.08</td>
<td>70.9 ± 6.0</td>
</tr>
<tr>
<td>H₂</td>
<td>0.4191 ± 0.01</td>
<td>8.160 ± 0.19</td>
<td>3500 ± 667</td>
</tr>
<tr>
<td>N₂</td>
<td>3.257 ± 0.07</td>
<td>4.287 ± 0.08</td>
<td>72.8 ± 5.8</td>
</tr>
<tr>
<td>O₂</td>
<td>3.006 ± 0.10</td>
<td>4.993 ± 0.14</td>
<td>147.4 ± 21</td>
</tr>
<tr>
<td>CO</td>
<td>4.040 ± 0.04</td>
<td>3.844 ± 0.03</td>
<td>46.7 ± 1.4</td>
</tr>
</tbody>
</table>
From the empirical values of A and B in Table I, values can be computed for the quantities in Eq. 1:

\[ C_n \ell = \frac{4 m/M}{B} \times 10^6 = \frac{2.18 \times 10^3}{B} \text{ electron volts} \]

\[ \frac{E_n \ell}{C_n \ell Z \ell} = \frac{4 \pi^2 Z^2}{m/M} \times \frac{1}{A} = \frac{11.97}{A} \text{ electron volts} \]

The values obtained are given in Table II. Numerical values computed from theory are not presently available for comparison except for the case of hydrogen, for which there is excellent agreement (see below). For the other gases our values are clearly of the proper order of magnitude.

Table II

Values for the parameters appearing in Bethe's theory, as derived from a least-squares fit of experimental proton ionization data to the theoretical expression. \( E_0 \) is the observed threshold for electron ionization, and all energies are in electron volts.

<table>
<thead>
<tr>
<th></th>
<th>He</th>
<th>Ne</th>
<th>A</th>
<th>H(_2)</th>
<th>N(_2)</th>
<th>O(_2)</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_n \ell )</td>
<td>15.0</td>
<td>39.0</td>
<td>30.6</td>
<td>0.62</td>
<td>29.8</td>
<td>14.7</td>
<td>46.4</td>
</tr>
<tr>
<td>( E_n \ell / C_n \ell Z \ell )</td>
<td>29.0</td>
<td>8.1</td>
<td>3.3</td>
<td>28.6</td>
<td>3.7</td>
<td>4.0</td>
<td>3.0</td>
</tr>
<tr>
<td>( E_0 )</td>
<td>24.5</td>
<td>21.5</td>
<td>15.7</td>
<td>15.6</td>
<td>15.5</td>
<td>12.5</td>
<td>14.1</td>
</tr>
</tbody>
</table>

Bethe\(^6\) has calculated theoretical values of \( C_n \ell \) and \( C_n \ell Z \ell \) for the case of atomic hydrogen. On inserting them into Eq. 1, he obtained for this case

\[ Q^i = (2 \pi e^4 / 0.285/|E_0|E') \log (2E'/0.048|E_0|) \text{ Eq. 2} \]

in which \( E' = 2Em/M \), \( E \) and \( M \) being the incident proton energy and mass, respectively, and \( E_0 \) is the ionization energy. For comparison of this result with molecular
hydrogen ionization, it is assumed that the hydrogen molecule is equivalent in high energy collisions to two hydrogen atoms, except that the ionization potential $E_0$, must be taken to be that of the molecule. Thus two electrons are available for ionization ($Z_{\text{nuc}} = 2$ for the molecule). On comparing our empirical values of $A$ and $B$ from the least-squares fit with the corresponding coefficients in Eq. 2, the implied values of $E_0$ may be obtained. From the linear factor, $E_0$ is $16.3 \pm 0.4$ ev, and from the log factor, $E_0$ is $13.0 \pm 2.5$ ev, in surprisingly good agreement with the measured electron ionization threshold of 15.6 ev. The larger uncertainty in the value of $E_0$ derived from the log factor arises from the uncertainty in the least-squares fit of the more slowly varying factor over a limited range of change of the independent variable, $E$.

In summary, our results appear to be in essential agreement with Bethe's treatment throughout the energy range 0.15-1.10 Mev. Our empirical values of the coefficients $A$ and $B$ provide a uniformly good fit of the function $(A/E)\log_e(BE)$ to the data throughout the range; as noted above, the empirical coefficients are in good explicit agreement with the theory for hydrogen, and look entirely reasonable for the other cases. In contrast, the electron data (see Technical Status Report No. 7), although in good agreement with the proton data at the high end of the energy range, fall sharply away from it toward the lower end of the range. An attempt to fit the function $(A/E)\log_e(BE)$ to the electron data over the entire corresponding energy range would require radically different values of $A$ and $B$ that would not be at all "reasonable". Thus it can be asserted that the proton cross sections agree with Bethe's treatment to lower incident velocities than do electron cross sections. This is not unexpected, since the physical assumptions in Bethe's treatment should hold to lower velocities for protons than for electrons.

A manuscript describing all of the curve fitting and electron comparison results given in this section has been accepted for publication in The Physical Review, and is scheduled to appear in the March 15 issue (Vol. 125, No. 6, 1962).
C. Modifications of the Apparatus for Studies of He$^+$ Ions on H$_2$, He, and Ne

Following the completion of the proton experimental work, the Van de Graaff accelerator was modified to provide a He$^+$ beam for the present Phase III of this research. Originally the rest of the apparatus was left unchanged, and a substantial body of data was collected on the ionization of H$_2$ by He$^+$. In contrast to the earlier findings with proton beams, it was found that there were substantial contributions from charge-changing events. The positive ion current collected from the collision region exceeded the electron current by more than ten percent at low energies, while the electron current was the greater by a few percent at the higher energies. The difference at the low energies was found to be in very rough agreement with the values tabulated by Allison$^1$ for the difference between the cross sections for electron capture and for electron loss by He$^+$ on H$_2$.

However certain inconsistencies in the data raised the question of whether the beam entering the collision chamber might contain appreciable fractions of He$^0$ neutrals and/or He$^{++}$ ions. The beam from the Van de Graaff was being analyzed magnetically with resolution more than adequate to assure that only He$^+$ ions emerged from the analyzer exit slit. However, at that time the collision chamber was located outside the shielded magnet room because of biological hazards from the neutron background that had been present during the proton work. (The hydrogen gas used in the Van de Graaff ion source had been about 50 percent deuterium, in order to provide a deuteron beam for occasional use in other work.) The beam was passed from the magnet exit slit ("a" in Fig. 1) to the first collimator aperture ("b" in Fig. 1) a distance of some seven feet. This section of the vacuum system consisted of a 2-inch diameter pipe passing through a port in the magnet room wall. Recalling that the pumping outlet shown near "a" in Fig. 1 was not present at that time, it is seen that this beam pipe
was quite remote from any vacuum pump. Further, it contained no gauge with which to monitor the vacuum. The possibility existed that appreciable charge-changing collisions could have been occurring with the residual gas in the pipe.

Therefore a two-inch mercury diffusion pump with a baffle and cold trap and a cold cathode discharge gauge were installed at the pumping outlet shown near "a" in Fig. 1. (The slit "a" consists of a pair of round cartridge assemblies that project into the beam tube so as to form a horizontal slit only 0.1-inch high at the center of the pipe, but which leave about a third of the pipe cross section unobstructed at the sides. Therefore slit "a" does not constitute a large pumping impedance between the new pump and the beam pipe.)

Since there was no neutron hazard present when using the helium beam, we also moved the collision chamber into the magnet room. This step permitted a reduction of the distance from "a" to "b" (Fig. 1) from 84 inches to about 23 inches. In addition to minimizing the problem of charge-changing collisions in the pipe, this change was intended to reduce the difficulty of obtaining optimum beam alignment and to provide some increase of beam intensity in the chamber. At the same time, a number of mechanical improvements were made in the chamber support structure to provide for easier and more rigidly maintained alignment. Other improvements were made in the differential pumping arrangement. In addition, a fluorescent beam "viewer" was installed "behind" the collision chamber, in the pumpout pipe at the left of Fig. 1. On removing the Faraday cup temporarily, the beam could be made to strike this viewer after traversing the collision chamber. This was done to provide a further aid in beam alignment, and to permit observation of the lateral deflection of the beam by the ion-collection fields in the chamber.
It was immediately ascertained that charge-changing processes in the beam tube had indeed been of serious proportions, under the earlier experimental conditions, with incident He\(^+\) beams. When the new pump near "a" (Fig. 1) was valved off, the pressure in this section of the vacuum system was observed to be about \(3 \times 10^{-4}\) Torr. A 1-Mev helium ion beam was passed through the chamber to the viewer under these conditions. On the application of voltage to the collector plates in the chamber, the beam spot was observed to split into two spots, one of which was deflected twice as much as the other. This clearly showed a He\(^{++}\) contamination, which was visually estimated to constitute at least 10 percent of the total intensity. Under the former conditions the pressure in the pipe had probably been even higher, so that with the longer flight path the effect must have been even more serious. When the new vacuum pump was brought into action, the indicated pressure in this region fell below \(10^{-6}\) Torr, and the He\(^{++}\) spot in the viewer disappeared. The Faraday cup was then replaced, and new measurements of the cross sections for He\(^+\) in H\(_2\) were made. The results were found to run about 25 percent lower than before, and therefore all of the data previously accumulated for the He\(^+\) beam had to be discarded.

Subsequently, careful tests were made of the sensitivity of the apparent cross sections in H\(_2\), at three widely spaced energies in our usual range, to the indicated pressure in the beam tube. The apparent cross sections were found to rise sharply when the pressure was raised to around \(10^{-4}\) Torr. However, in every case, they were found to be constant for pressures from at least \(2 \times 10^{-5}\) Torr down to the pressure of less than \(10^{-6}\) Torr that is obtained with the pump in full operation. It is therefore demonstrated that the steps taken have reduced charge-changing collisions within the beam pipe to a negligible effect.
It should be emphasized that none of the above is believed to have any bearing on our earlier measurements of the ionization of gases by protons. There is, of course, no electron-loss process possible with protons, and the cross section for electron capture is much smaller for protons than for He$^+$. A few measurements were made, with the revised apparatus for proton beams on hydrogen in order to obtain an experimental check on this point. The cross sections which were obtained were the same, within experimental error, as those previously reported in Technical Status Report No. 7.

D. Data for He$^+$ on H$_2$, He, and Ne

The cross sections obtained for He$^+$ on H$_2$, He, and Ne with the revised apparatus of Fig. 1 are displayed in Figs. 2, 3, and 4. It is believed that these data are correct, but they should be regarded as preliminary until rechecked with the miniaturized apparatus described in Section IV.

The data of Figs. 2, 3, and 4 were obtained with target gas pressures in the range 0.5 to 1.0 x 10$^{-4}$ Torr. There was no dependence of the measured cross section on the pressure in this range, and the slow-ion currents collected were always less than one percent of the incident beam current. At higher pressures there was obvious breakdown of the thin target conditions, and the apparent cross sections measured were too large. At such pressures there are multiple collisions within the target volume, and in addition, charge-changing collisions in the target gas between the last collimating aperture and the effective target region gave an impure beam.

IV. Miniaturization of Apparatus for Studies of Ar, N$_2$, and CO

While the apparatus of Figure 1 is believed to have been satisfactory for the light target gases H$_2$, He, and Ne, preliminary tests with N$_2$ indicated that
Figure 2. Cross Sections for the Gross Production of Positive Ions and Free Electrons by He\(^+\) Incident on H\(_2\).
Figure 3. Cross Sections for the Gross Production of Positive Ions and Free Electrons by H$^+$ Incident on He.
Figure 4. Cross Sections for the Gross Production of Positive Ions and Free Electrons by He$^+$ Incident on Ne.
it was not satisfactory for the heavier gases. The essential reason for this is simply that a number of the He$^+$ cross sections are so very large for these cases. With the apparatus dimensions as in Figure 1 it was not found to be possible to maintain satisfactory "thin target" conditions without resorting to impractically low target gas pressures. The practical lower limit on the working pressure, determined by the partial pressure of residual impurities in the chamber and by the sensitivity of the McLeod gauge used to measure pressures, is about $0.5 \times 10^{-4}$ Torr.

As an alternative to the complete reconstruction of the vacuum system that would have been necessary to work at lower pressures, it was decided that the apparatus should be miniaturized in order to reduce the length of the flight paths of the projectiles in the gas. In particular, it was desired that the part of the path that was not part of the effective target thickness be reduced as much as possible. The reason is that computations based on existing knowledge of the charge-changing collision cross sections, as well as the results of preliminary tests in nitrogen, indicated that change of the beam composition due to such collisions would become a significant perturbation at lower gas pressures than would the occurrence of multiple ion-producing collisions within the effective volume.

Accordingly, the system of differentially pumped collimating apertures and the electrode assembly have been rebuilt. Fig. 5 is a schematic sketch showing the relevant dimensions, and Fig. 6 a photograph of the new assembly in place in the collision chamber. For reference in the following discussion the several apertures are designated by the letters with which they are labeled in Fig. 5. Aperture sizes and pumping speeds have been designed so that the greatest part of the pressure drop from the target region will occur at "d".
Figure 5. Schematic View of Apparatus as Modified for Studies of He$^+$ on N$_2$, Ar, and CO.

In the chamber, the beam passes between two identical, parallel collector arrays, only one of which is shown. Slow-ion currents collected by only the segment A are measured, with other segments serving as guards. Suppressor grid covering entire collected array not shown. The slit "a" and the aperture "c" are designed for small pumping impedance, while the apertures "b" and "d" are designed for large differential pumping impedance. The incident beam is collimated by "b" and "c".
Figure 6. View of Apparatus as Modified for Studies of He\(^+\) on \(\text{N}_2\), Ar, and CO.

The collector assembly is rotated 90° about the beam axis from the position shown for clarity in schematic Figure 5. Entire collector and collimator subassemblies installed as units after rigid external assembly.
so that the effective beginning of the flight path in the gas is at "d". The total path length from there to the entrance of the Faraday cup has been reduced from about 13.7 inches (Fig. 1) to about 5 inches (Fig. 5). The effective target thickness itself has also been reduced by a factor of 3 from 3.348 to 1.126 inches.

In addition to the overall miniaturization, two separate apertures ("c" and "d" in Fig. 5) are now utilized to perform separately the beam collimating and differential pumping functions that had been combined in a single final aperture in the old design (see Fig. 1). This has been done to minimize the entry into the target region of energetic secondary electrons produced at slit edges. It is known that some secondaries with energies up to 2 kev are produced by impact of 1-Mev protons on a metal surface. We had noted that, at very low target gas pressures, the collected electron current invariably exceeded the positive-ion current for incident He\(^+\) ions at the higher energies. Further, the amount of the excess depended sensitively on the overall alignment of the collimator system with the incident beam, and with the magnitude of the potential difference between the two collector assemblies. It appeared that a few fast secondaries produced at the last slit were reaching the effective target region despite the extensive guard arrangement.

In the new arrangement of Fig. 5 apertures "b" and "c" each have circular knife-edged openings 1/16-inch in diameter, and the minimum opening in "d" is a knife edge slightly over 3/32-inch in diameter. Thus the collimation of the beam is defined by "b" and "c", and only a few scattered particles will impinge on "d". The opening in "d" presents a small solid angle to the secondaries produced at "c", and very few should pass through. However "d" is designed to have a relatively large pumping impedance, while the thin plate containing "c" is perforated with three large off-center holes to present a small impedance.
Thus the greatest part of the pressure drop that defines the beginning of the gas target is at "d", despite the larger diameter of its opening.

As is indicated in Fig. 5 the portion of the apparatus that contains the three apertures "b", "c", and "d" can be rigidly assembled before insertion into the collision chamber, so that all three apertures can be accurately aligned optically. Further, the entire electrode and Faraday cup subassembly is now mechanically supported by a snug-fitting collar over the end of the collimator subassembly, whereas previously it was independently mounted to the wall of the collision chamber. This feature permitted assembly of the entire system outside the chamber to facilitate optical alignment. The collector and collimator subassemblies were separated at the collar for installation in the chamber, but the mechanical arrangement is such that their relative position was reproduced accurately on reassembly.

Installation of the new arrangement has been completed. Fig. 6 is a photograph of the complete assembly. Results obtained in early tests indicate that the redesign has apparently accomplished its objectives. First, the entry of fast secondary electrons into the effective target region appears to have been eliminated. When 1-Mev He$^+$ ions are incident on the residual background gas present in the chamber, the collected electron current still exceeds the positive-ion current by some 25%, but the amount of the excess is now reproducible and not sensitive to the alignment of the incident beam with the collimator. Therefore the excess electron current can be attributed to electron loss collisions in the residual gas only. In a recheck of the earlier measurements for He$^+$ incident on He, it was found that proper thin target conditions were maintained for target gas pressures as great as $5 \times 10^{-4}$ Torr, an improvement of about a factor of three as expected.
The data for He\(^+\) on H\(_2\), He, and Ne shown in Figs. 2, 3, and 4 are being rechecked with the miniaturized apparatus. If the existing results are found to be reproduced satisfactorily, it is expected that the remaining He\(^+\) measurements on Ar, N\(_2\), and CO can be disposed of in the first weeks of the coming period.

V. Travel and Publications During the Contract Year


J. W. Hooper was awarded the degree of Doctor of Philosophy by the Georgia Institute of Technology at the June, 1961 Commencement, following presentation of a thesis based on the proton ionization measurements.


E. W. McDaniel served on the Thermonuclear Panel at the Nuclear Engineering Education Conference held at the Argonne National Laboratory, Jan. 29-30, 1962.

A paper entitled "Comparison of Electron and Proton Ionization Data with the Born Approximation Predictions" has been accepted for publication by The Physical Review, and is scheduled to appear in the March 15 issue (Vol. 125, No. 6, 1962).

Respectfully submitted,

E. W. McDaniel
Project Director

Approved by:

A. L. Bennett, Chief
Physical Sciences Division
VI. References


TECHNICAL STATUS REPORT NO. 11
Project No. B-176
Covering the Period
March 1, 1962 to May 31, 1962

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By
D. W. Martin
J. W. Hooper
D. S. Harmer
R. A. Langley

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee

June 1, 1962

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia
TECHNICAL STATUS REPORT NO. 11

Project No. B-176

Covering the Period

March 1, 1962 to May 31, 1962

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By

D. W. Martin
J. W. Hooper
D. S. Harmer
R. A. Langley

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee

June 1, 1962
I. Title

Ionization and Charge Transfer Cross Sections

II. Objective and Method

The objective of the research being performed under Contract AT-(40-1)2591 is the measurement of the cross sections for the production of slow positive ions and free electrons in gaseous targets by fast hydrogen and helium ions and atoms with energies in the range 0.15-1.10 MeV. A thin target method is used, involving electrostatic collection of the slow products formed in the gas, with absolute measurements of the collected currents and of the incident beam.

The beam of energetic particles, which is obtained from a 1-Mev Van de Graaff positive ion accelerator, is analyzed and is passed through differentially pumped collimating apertures into the collision chamber containing the target gas. The chamber dimensions and the gas pressure are such that only about one percent of the incident particles engage in even one ion-producing collision, and a negligible fraction engage in two or more such collisions. All but a negligible fraction of those particles which do collide lose only a small fraction of their energy, and suffer only a small change in their direction of motion. After they have traversed the active collision volume, the particles are collected, and the measured intensity at this point is taken to be a measure of the intensity of the incident beam. For the present cases where the fast beam particles are ions, the collector is simply a Faraday cup, the total current to which is measured.

Polarized electrodes within the collision volume collect essentially all of the charged particles of both signs formed in the gas by the passage of the energetic particles. Most of these residual charged particles have quite low
energies, although a small fraction may have energies as great as several hundred electron volts. The currents collected are measured by means of electrometers. Suppression of secondary electron emission has been provided and an arrangement of guard electrodes serves to define the effective target thickness in such a way that no end corrections are required.

The ion and electron currents observed here will include any contributions from charge-changing events, in which the incident particle either gains or loses electrons. Whenever the contribution from such events is appreciable, it will be manifested in an inequality of the positive ion and electron currents collected from the collision region. The cross sections for capture and loss of electrons by fast H and He atoms and ions in various gases have been measured previously by others\(^1\),\(^2\) by an entirely different technique, based on observations of the composition of the beam after traversal of a thick target. Our measurements, based on collection of the slow products formed in a thin target, will constitute an essentially independent check of these results. If both sets of data are reliable, the difference between our cross sections for the production of positive ions and of electrons should agree with the difference between the electron capture and loss cross sections. For those cases where the capture and loss data exists and agrees satisfactorily with our data in the sense described, we can use it to assess the contribution of charge-changing processes to our results. On subtracting this contribution, we will obtain the apparent cross section for the production of ion pairs, which we have often referred to as the gross ionization cross section.

It is of course essential that we maintain satisfactory thin target conditions to assure that the composition of the beam does not change appreciably as it crosses the collision volume.

III. Present Status of the Experiment Work

At the present stage of the research, measurements for incident He$^+$ ions are nearing completion. Preliminary results for targets of H$_2$, He, and Ne were obtained some time ago, and were presented in Technical Status Report No. 10. These data had been obtained with essentially the same apparatus as had been used in the earlier measurements with incident protons. Certain improvements had been made in the beam entrance tube, in order to assure that the beam would not be appreciably contaminated with particles in other than the singly-charged state, but the arrangement of the collision chamber itself was unchanged.

Although this apparatus appeared to be entirely satisfactory for the light target gases, preliminary tests with a N$_2$ target indicated that it was not satisfactory for the heavier target gases, simply because of the larger magnitudes of their cross sections. In the tests with N$_2$, it was not possible to maintain adequate "thin target" conditions without resorting to impractically low target gas pressures.

Accordingly, the arrangement of the collision chamber was extensively modified in order to decrease the length of the beam path in the gas. New miniaturized collection electrode assemblies were built. Particular attention was given to reducing the length of the beam path outside the "effective" collision volume, because the validity of the thin target approximation is more sensitive to changes of beam composition due to charge-changing collisions than it is to multiple collisions in the effective target region.
Additional improvements were made in the beam collimation slit assembly to alleviate an apparent problem arising from energetic secondary electrons produced at the slit edges. More complete details of this reconstruction have been given in Technical Status Report No. 10. As was indicated there, tests have indicated that the redesign achieved the stated objectives. It was our plan to recheck the preliminary results for \( \text{He}^+ \) on \( \text{H}_2 \), \( \text{He} \), and \( \text{Ne} \) with the new arrangement, and then to proceed with measurements for \( \text{He}^+ \) on the heavier gases \( \text{Ar}, \text{N}_2, \text{and CO} \).

However, additional difficulties appeared during the course of these detailed checks, and most of the current period has been occupied by diagnosis of these problems and with further modification of the apparatus to eliminate them. As a result, final verification of the preliminary \( \text{He}^+ \) results on the light gases and extension to the heavier gases have not yet been completed.

As first constructed, the miniaturized collector assembly, like the larger original assembly used in the proton measurements, had identical suppressor grids in front of both the positive ion and electron collector plates. While no grid is actually required on the electron collector, since the collection field itself is of proper sign and sufficient magnitude to provide suppression, the symmetrical arrangement permitted ready interchange of the roles of the two collectors. A simple check for self-consistency of measurements made with the normal and reversed roles has proved to be extremely valuable, particularly in assessing whether apparent differences in the positive and negative collected currents were real or merely instrumental. It was of course realised that the presence of the grid introduces the possibility of certain difficulties. The grid intercepts a small fraction (about 5%) of the electrons being collected from the collision region. These
have been accelerated to energies of a few hundred ev by the collision field.
Unlike the accelerated positive ions impinging on the other grid, these electrons might produce appreciable numbers of secondary electrons from the grid, some fraction of which may reach the electron collector. Thus the measured electron current might be either larger or smaller than the correct value by a few percent because of the grid.

It was reasoned that the magnitude of any net effect should be sensitive to the magnitudes of the collection field and of the potential difference between the electron collector and its grid. The first would affect the energies of the electrons striking the grid, and therefore the yield of secondary electrons, and the second would affect the fraction of these which reached the collector. In careful tests that were run repeatedly while using the original collector and grid assemblies, it had been found that the collected electron current was independent of both voltages, within all other experimental uncertainties, for all reasonable values of the collection field, as long as the potential of the electron collector was held at least 30 volts higher than that of its grid. In addition, throughout all of the incident proton measurements, the collected electron current had always been equal to the collected positive ion current for the higher proton energies, as was expected from existing knowledge of the charge-changing cross sections for protons. It had therefore been concluded that any net effect of the grid was negligible compared with other experimental uncertainties.

Unfortunately, similar tests with the new, miniaturized assemblies did not produce the same happy result. The collected electron current increased monotonically with increase of the grid-to-collector potential. Beyond about 100 volts the increase was not rapid, but it still amounted to about
% across the region from 100 to 300 volts. In test runs using incident protons, the electron current could be made either smaller or larger than the positive ion current. Although this behavior did not interfere with determination of the cross section for production of positive ions with satisfactory accuracy, the difference between the positive ion and electron cross sections was rendered almost indeterminate for incident He at the higher energies, which would preclude any inferences about the charge-changing cross sections.

The reasons for these differences in the behavior of the new, miniaturized assembly from that of the original assembly are not fully understood. The grid wires are of the same material, have the same diameter, and the same nominal spacing. There is only one obvious physical difference. The construction of the old grids was such that, inadvertently, the wires did not all lie in one plane. Rather, they were staggered alternately in two parallel planes, so that the actual distance between wires was a little greater than the projected distance on a plane parallel to the grid. The new grids are so constructed that all wires are in one plane. Although this was thought to be only a trivial difference, it is possible that it makes an appreciable difference in the field shape near the grid wires, and causes a disproportionate change in the effective opacity.

It was therefore decided that one of the grids should be removed, even though this meant giving up the advantages of interchangeability. First, the latter feature was used to check very carefully for any geometrical asymmetries leading to unequal collection efficiencies for the two collectors, and several small flaws were detected and corrected. Only after we were convinced that all effects of this kind had been satisfactorily eliminated was one of the grids removed.
The results that were obtained with this arrangement were at first quite puzzling. Now the magnitude of the collected electron current was found to be sharply dependent on the magnitude of the collection field, i. e., on the potential of the electron collector. This was a definite departure from all previous experience. After an extensive series of observations had been made, it was eventually concluded that the "active" collision region was no longer adequately guarded by the surrounding electrodes, i. e., the electrostatic field in this region was not parallel and uniform. Under these conditions the "effective volume" from which slow charges reach the active collectors was not well defined, nor even the same for electrons as for positive ions.

The spacing between the two grids had been 1 inch originally. When the one grid was removed, the positions of all other components had been left unchanged, so that the total gap across which the collection field acted, namely the distance from the electron collector to the opposite grid, was then 5/4 inch. Further, this gap was not symmetrically located with respect to the beam or with respect to grounded components at the ends of the structure. In retrospect, it was hardly surprising that the field should be significantly distorted.

The supporting parts of the structure have now been modified to reduce the gap to 1/2 inch, and to locate it symmetrically with respect to the beam. This change makes the ratio of the gap dimension to the overall length of the parallel structures about 1/6, comparing favorably with the ratio that prevailed with the old, larger assembly. Early measurements indicate that the situation is now greatly improved. Present efforts are being directed toward evaluation of the possible necessity for further adjustments. As soon as we
are satisfied that the apparatus is providing reliable results, the remaining measurements with incident He\(^+\) ions will be completed as quickly as possible.

Preliminary design work on the charge-exchange chamber and beam analyzer to be used in subsequent measurements with incident He\(^{++}\) and H\(^+\) particles has proceeded concurrently with the activities described above. Most of the new vacuum equipment that will be required has been ordered. It is anticipated that all of the shop work for the new construction will be completed during the coming quarter.

IV. Travel and Publications During the Present Reporting Period

J. W. Hooper attended the Third Symposium on the Engineering Aspects of Magnetohydrodynamics held at the University of Rochester March 28-30, 1962.


Respectfully submitted,

D. W. Martin
Project Director

Approved:

A. L. Bennett, Chief
Physical Sciences Division
TECHNICAL STATUS REPORT NO. 12
Project No. B-176
Covering the Period
June 1, 1962 to August 31, 1962

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By
D. W. Martin
J. W. Hooper
D. S. Harmer
R. A. Langley

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee

September 1, 1962

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia
TECHNICAL STATUS REPORT NO. 12

Project No. B-176

Covering the Period

June 1, 1962 to August 31, 1962

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By

D. W. Martin
J. W. Hooper
D. S. Harmer
R. A. Langley

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee

September 1, 1962
I. Title

Ionization and Charge Transfer Cross Sections

II. Objective and Method

The objective of the research being performed under Contract AT-(40-1)2591 is the measurement of the cross sections for the production of slow positive ions and free electrons in gaseous targets by fast hydrogen and helium ions and atoms with energies in the range 0.15-1.10 Mev. A thin target method is used, involving electrostatic collection of the slow products formed in the gas, with absolute measurements of the collected currents and of the incident beam.

The beam of energetic particles, which is obtained from a 1-Mev Van de Graaff positive ion accelerator, is analyzed and is passed through differentially pumped collimating apertures into the collision chamber containing the target gas. The chamber dimensions and the gas pressure are such that only about one percent of the incident particles engage in even one ion-producing collision, and a negligible fraction engage in two or more such collisions. All but a negligible fraction of those particles which do collide lose only a small fraction of their energy, and suffer only a small change in their direction of motion. After they have traversed the active collision volume, the particles are collected, and the measured intensity at this point is taken to be a measure of the intensity of the incident beam. For the present cases where the fast beam particles are ions, the collector is simply a Faraday cup, the total current to which is measured.

Polarized electrodes within the collision volume collect essentially all of the charged particles of both signs formed in the gas by the passage of the energetic particles. Most of these residual charged particles have quite low
energies, although a small fraction may have energies as great as several hundred electron volts. The currents collected are measured by means of electrometers. Suppression of secondary electron emission has been provided and an arrangement of guard electrodes serves to define the effective target thickness in such a way that no end corrections are required.

The ion and electron currents observed here will include any contributions from charge-changing events, in which the incident particle either gains or loses electrons. Whenever the contribution from such events is appreciable, it will be manifested in an inequality of the positive ion and electron currents collected from the collision region. The cross sections for capture and loss of electrons by fast H and He atoms and ions in various gases have been measured previously by others\textsuperscript{1,2} by an entirely different technique, based on observations of the composition of the beam after traversal of a thick target. Our measurements, based on collection of the slow products formed in a thin target, will constitute an essentially independent check of these results. If both sets of data are reliable, the difference between our cross sections for the production of positive ions and of electrons should agree with the difference between the electron capture and loss cross sections. For those cases where the capture and loss data exists and agrees satisfactorily with our data in the sense described, we can use it to assess the contribution of charge-changing processes to our results. On subtracting this contribution, we will obtain the apparent cross section for the production

\textsuperscript{1} S. K. Allison, Rev. Mod. Phys. 30, 1137 (1958).

of ion pairs, which we have often referred to as the gross ionization cross section.

It is of course essential that we maintain satisfactory thin target conditions to assure that the composition of the beam does not change appreciably as it crosses the collision volume.

III. Present Status of the Experimental Work

In past reports we have described the replacement of the original collision chamber electrode structure, which was used successfully throughout the incident proton measurements, with a miniaturized structure of similar design. This scaling down of the apparatus dimensions was required for incident He$^+$ ions on the heavier gases because, with the larger cross sections encountered in these cases, it would not otherwise be possible to maintain adequate thin target conditions without resorting to impractically low target gas pressures.

In Report No. 11 we described a number of difficulties that were encountered in trying to obtain results with the new collector arrangement that were self consistent and in agreement with the earlier measurements with the larger structure. Several physical changes in the structure were made, including complete removal of one of the two suppressor grids. As of the time of Report No. 11, the worst of the problems had been overcome, and we were of the opinion that our regular program of data collection could be resumed.

Verification checks were then made by remeasuring the cross sections for incident protons on H$_2$ and He, for comparison with our own well established older results. The values that were now obtained for $\sigma^+$, the apparent cross section for the production of slow positive ions, were found to be in good agreement. However, the values for $\sigma^-$ computed from the collected electron currents were still found to be unsatisfactory.
The magnitude of the collected electron current was found to increase gradually as the magnitude of the collection electrostatic field was increased through the range where a plateau was expected. The current did not level off until the potential of the electron collector was made 400 or 500 volts positive, whereas it was expected that a negligible fraction of the slow electrons liberated in ionization collisions would have energies in excess of about 100 ev. In addition, the value of the electron current when this saturation point was reached was larger than the positive ion current, at energies near 1 Mev, by an amount of the order of 15 percent. For incident protons at these energies, it was well established that the electron current should be equal to the positive ion current. This is expected because the known charge transfer cross sections for protons are at least two orders of magnitude smaller than our measured ionization cross sections; the expected equality of the currents had been confirmed repeatedly in our own earlier work.

Further study of this matter led eventually to the suspicion that the excess electrons were fast electrons coming into the chamber from the beam entrance aperture. Presumably they are "knock-on" secondaries produced by the grazing impact of fast beam ions on slit edges. Problems with such electrons had been encountered in the past, but were thought to have been eliminated by careful reconstruction of the beam collimator (see Report No. 10). It now appears that despite these precautions, such secondaries remain a problem that must be treated with care.

The gradual increase in the collected electron current with increase of the ion collection field is now believed to be due to deflection of a steadily increasing fraction of these fast secondaries to the electron collector. (And probably this also explains the difficulties of an earlier period that were
blamed on the grid in front of the electron collector.) If the collection field could be made great enough, all these secondaries could be deflected to the guard electrode before they reached the active electron collector; with the original larger collector assembly used in our proton measurements, the length of the guard electrodes was great enough that this could be accomplished with reasonable voltages, and the fast secondaries gave us no trouble. However, with the present miniaturized structure, the guard length has been so reduced that the voltage necessary would be excessive, and could be expected to introduce other serious problems.

Alternatively, if the collection field were to be made sufficiently small, most of the fast secondaries would pass completely through the sensitive volume without sufficient deflection to reach the collector. Of course, the field cannot be made too small or there will no longer be efficient collection of the slow ions and electrons produced by true ionization in the target gas.

Accordingly, further tests were made using potentials on the electron collector of less than 100 volts, corresponding to smaller collection fields than we had ever used previously in this experiment. It was found that the electron current saturates for potentials of about 40 volts, and displays a quite satisfactory plateau in the region from 40 volts to about 90 volts. The aforementioned rise sets in only for potentials above 100 volts, and continues, as stated above, up to 500 volts. At the same time, the collected positive ion current also saturates at about 50 volts and remains constant. The electron currents obtained for voltages within the plateau were equal to the positive ion currents within 4% for incident protons at energies near 1 Mev. The cross sections obtained for incident protons were now in entirely satisfactory agreement with the older results.
It is believed that this mode of operation is successful only because the collimation of the incident beam is such that the secondaries entering the collision chamber through the beam entrance aperture are almost entirely limited to a selected high energy group of almost dead-ahead knock-ons. Since the mean energy of this group is related to the energy and mass of the incident ions, the plateau has been carefully checked at several energies covering our range for both incident protons and He$^+$ ions. A collection voltage of about 65 volts appears to be satisfactory for most cases, but it is intended that this will be rechecked at frequent intervals in the future.

It should be added that the contamination of the beam with these fast electrons does not seriously perturb the results of the experiment because of ionization of the target gas by the electrons. In our experience the number of these electrons is only about 15% of the number of slow electrons liberated in the gas by ionization collisions, but this current in turn is never more than 1% of the incident beam. Thus the beam contamination amounts at most to a fraction of 1%. The fast electrons presumably have speeds of the order of twice the speed of the ions, so in our energy range the ionization cross section of the electrons will always be less than that of the ions.

Rechecking of our preliminary results for He$^+$ incidents on H$_2$, He, and Ne following the new procedures has now been completed. The results for H$_2$ and He agree in detail with those presented in Report No. 10, Figures 2 and 3, except that some of the point scatter in evidence there is now much improved. The new results for Ne are appreciably different from those shown in Figure 4 of Report No. 10, and are presented in Figure 2 of this report.
Figure 1. Gross Cross Sections for the Production of Positive Ions and Electrons by Singly-Charged Helium Ions Incident on Helium.
Figure 2. Gross Cross Sections for the Production of Positive Ions and Electrons by Singly-Charged Helium Ions Incident on Neon.
Figure 3. Gross Cross Sections for the Production of Positive Ions and Electrons by Singly-Charged Helium Ions Incident on Argon.
Figure 4. Gross Cross Sections for the Production of Positive Ions and Electrons by Singly-Charged Helium Ions Incident on Molecular Hydrogen.
The older measurements for Ne, obtained with the original large structure, were made at such low target gas pressures, in order to preserve thin target conditions, that the background corrections were as great as 40% in some cases, so that the data were expected to have a low reliability. In the new measurements, the background corrections were at all times less than 10%. Additional measurements for He$^+$ incident on Ar have been completed and are presented here.

A preliminary comparison has been made of the differences between our cross sections for the production of positive ions and of electrons and the differences between the electron capture and loss cross sections of Pivovar, et. al.$^2$ Agreement is quite satisfactory for the cases so far examined. Further comparisons will be made and a detailed discussion of this topic will be included in our next report.

Completion of the He$^+$ measurement program by extension to targets of N$_2$ and CO is now in progress, and should be essentially completed by the time this report is issued. It is expected that an article presenting all of the He$^+$ results will be prepared in the near future for submission to *The Physical Review* for publication.

Design of the charge exchange cell and beam analyzer for extension of the measurements to He$^{++}$ and H$^+$ projectiles has been completed, and the materials for their construction are on order. The bulk of the new vacuum equipment that will be required has been delivered. It is expected that the construction, assembly, and test of the new system will constitute the bulk of the experimental effort in the coming period, but that some preliminary results for incident He$^{++}$ will be available for the next report.
IV. Travel, Publications, and Personnel Changes

D. W. Martin and R. A. Langley attended the meeting of the American Physical Society held in Evanston, Illinois, June 12-14, 1962. A paper was given presenting the preliminary results for He\(^+\) incident on \(\text{H}_2\), He, and Ne from Report No. 10. The miniaturization of the collision chamber structures for the later measurements was also described. The reference is *Bull. Am. Phys. Soc.* 7, No. 6, page 399 (1962).

For internal administrative convenience, the work on this project has been transferred from the Physical Sciences Division to the newly created Nuclear Sciences Division of the Engineering Experiment Station, effective July 1, 1962.

Effective September 1, 1962, Dr. J. W. Hooper will end his formal association with this project to assume full time duties in the School of Electrical Engineering of Georgia Tech. It is expected that he will continue to maintain an active interest in the further progress of this research in an informal consultative capacity.

Respectfully submitted,

D. W. Martin  
Project Director

Approved by:

W. B. Harrison, Chief  
Nuclear Sciences Division
TECHNICAL STATUS REPORT NO. 13

PROGRESS REPORT

PROJECT No. B-176

Covering the Period

March 1, 1962 to November 30, 1962

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By D. W. Martin
D. S. Harmer
R. A. Langley

Contract No. AT-(40-1)-2591

U. S. ATOMIC ENERGY COMMISSION
OAK RIDGE, TENNESSEE

1 December 1962

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia
TECHNICAL STATUS REPORT NO. 13

PROGRESS REPORT

Project No. B-176

Covering the Period

March 1, 1962 to November 30, 1962

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By

D. W. Martin

D. S. Harmer

R. A. Langley

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee

December 1, 1962
I. Title
Ionization and Charge Transfer Cross Sections

II. Period Covered by Report
The period covered by this report is March 1, 1962 through November 30, 1962. This period corresponds to the first 9 months of the 12-month extension provided for by Modification No. 3 of Contract No. AT-(40-1)-2591. The Statement of Current Expenditures contained in Section VI of this report will, however, cover only the first 8 months to October 31, 1962.

III. Scope of the Research and Results Achieved
The general objective of the research being performed under this contract has been the measurement of the apparent cross sections for the production of slow positive ions and free electrons in gaseous targets by fast hydrogen and helium ions and atoms with energies in the range 0.15 to 1.0 Mev. A thin target method has been used, involving the electrostatic collection of the slow products formed in the gas. The numbers of these products formed and the intensity of the incident beam have been measured absolutely, so that the cross sections obtained are also absolute.

Results obtained prior to the period covered by the present report have included measurements of these cross sections for protons incident on targets of He, Ne, Ar, H₂, N₂, O₂, and CO. Detailed comparisons were made with the available measurements for electrons of the same velocity, and with the available theoretical calculations in the Born approximation for hydrogen and helium. These results have been summarized in the last Progress Report (Technical Status Report No. 9) of December 1, 1961, and in the Annual Summary Report (Technical Status Report No. 10) of March 1, 1962.
Other results obtained prior to the period covered by this report included preliminary measurements of the cross sections for He$^+$ ions incident on targets of H$_2$, He, and Ne. Final verification of these measurements, and extension of the measurements to targets of Ar, N$_2$, and CO within the prior period ending February 28, 1962 had been anticipated at the time that Report No. 9 and the Proposal for Extension for the present period were in preparation.

However, unexpected difficulties in attaining reproducibility have delayed completion of the He$^+$ measurements to our complete satisfaction until well into the present period. Detailed description of the problems, and of the modifications in both the apparatus and the techniques that were developed to deal with them, have been given previously in Technical Status Reports 10, 11, and 12. The situation may be summarized very briefly as follows:

The cross sections for He$^+$ in the heavier gases were found to be much larger than for the case of protons. With the existing apparatus that had been used successfully for protons, it became necessary to resort to impractically low target gas pressures in order to preserve the thin target conditions essential to the accuracy of the method. In order to avoid this situation, the collision chamber electrode structure and the beam entrance collimator structure were rebuilt so as to reduce the length of the beam path in the target gas, in particular those parts of the path external to the "effective" collision volume.

Following this change in the apparatus, it was found that the magnitude of the collected electron current failed to reach a saturation value with increase of the electrostatic collection potential applied to the collector until the unrealistically large potential of about 500 volts was reached, at which point the electron current was judged to be upwards of 15% too large compared
to the positive ion current. It was eventually concluded that the excess was attributable to fast electrons, produced at slit edges in the beam entrance collimator. With the old arrangement of the collision chamber, any such electrons had been swept out of the beam to the guard electrodes before reaching the effective volume; in the new reduced-scale arrangement, this could not be accomplished without using collection potentials so large that there would be serious difficulties with arcing and discharges in the target gas.

The problem was finally resolved by a combination of a careful collimator design that limits the electrons entering the collision chamber to a nearly monoenergetic group of "dead ahead" knock-ons, and the use of an electrostatic collection field small enough to permit these electrons to pass completely through the effective volume. A satisfactory current plateau was found between, on the one hand, a potential too small to collect all the true slow secondary electrons, and, on the other hand, a voltage large enough to begin to collect the fast beam electrons. With this arrangement, it was found possible to reproduce the old proton measurements, and to obtain results for He\(^+\) having a satisfactory degree of self-consistency.

Final results for He\(^+\) incident on He, Ne, Ar, H\(_2\), N\(_2\), O\(_2\), and CO were completed about the middle of September. The results for the first four of these gases were presented in Technical Status Report No. 12. All of these results were presented in a paper read at the Fifteenth Annual Gaseous Electronics Conference in Boulder, October 10-12, and an article presenting them will soon be prepared for publication. The results were found to be in very satisfactory agreement with similar measurements at lower energies up to 0.18 Mev\(^1,2\), and the differences we obtained between the electron and positive ion

1. N. V. Federenko and V.V. Afrosimov, Soviet Physics-JETP 1, 1872 (1956).
production cross sections were in reasonable agreement with existing data on the charge exchange cross sections.\(^3\), \(^4\)

The major new task that had been proposed for the present period was the addition to the apparatus of a gas cell and a beam analyzer with which energetic beams could be produced, by charge transfer, of either neutral atoms or of ions in charge states that are not produced directly by the accelerator ion source. Specifically, it was proposed that cross section measurements be made on targets of \(\text{H}_2\) and \(\text{He}\), first with a beam of \(\text{He}^{++}\) ions, and second with a beam of neutral \(\text{H}^0\) atoms.

The previously discussed delays in the completion of the \(\text{He}^+\) measurements have, of course, delayed the beginning of this phase of the research. At the time of this writing, construction of all of the new components has been essentially completed, including leak checking of the new components of the vacuum system. A much more substantial supporting structure for the apparatus than has been used previously is being constructed, in anticipation of the greater difficulty that is expected in achieving and maintaining satisfactory alignment of the several parts of the apparatus.

Final assembly of the apparatus has begun, and this should be largely completed by the time this report is issued. If no unexpected difficulties are encountered in the operation of the newly enlarged apparatus, it is quite possible that the proposed measurements for \(\text{He}^{++}\) and \(\text{H}^0\) on \(\text{H}_2\) and \(\text{He}\) can still be completed as proposed by the close of the present period on February 28, 1963. However, since the remaining time is rather less than we had proposed to spend on this phase of the effort, it is also possible that

IV. Publications

The following article was listed as publication No. 5 in the Progress Report last year, having been submitted to The Physical Review, but not having yet appeared at that time. The article has since been published, and a reprint is attached.


Also attached is a reprint of publication No. 4 of last year's Progress Report, from the Proceedings of the Fifth International Conference on Ionization Phenomena in Gases, Munich, 1961. No reprint was available last year.

The following papers were presented orally at meetings during the present period. Copies of the abstracts are attached.


A description of a portion of this research was also included in the following invited paper read by E. W. McDaniel at the International Symposium on Space Phenomena and Measurement held in Detroit on October 16-18, 1962.

Technical Status Report, No. 13, Project No. B-176

V. Incident Report

There have been no incidents, as defined in Attachment "A" of letter of instructions dated November 5, 1962, during the performance of the research under this contract in the present reporting period.

VI. Statement of Current Expenditures

As was anticipated in the Progress Report of this date last year, there were no residual funds from the previous period remaining at the beginning of the present period on March 1, 1962.

Expenditures for the present period are as follows:

<table>
<thead>
<tr>
<th></th>
<th>Expenditures for the period March 1, 1962 through October 31, 1962</th>
<th>Expenditures Estimated for the period December 1, 1962 to February 28, 1963</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.E.C. FUNDS</td>
<td>GA. Tech FUNDS</td>
<td>A.E.C. FUNDS</td>
</tr>
<tr>
<td>Salaries and Wages</td>
<td>$10,059</td>
<td>$3,147</td>
</tr>
<tr>
<td>Overhead</td>
<td>6,337</td>
<td>1,987</td>
</tr>
<tr>
<td>Permanent Equipment</td>
<td>0</td>
<td>475</td>
</tr>
<tr>
<td>Materials and Supplies</td>
<td>537</td>
<td>324</td>
</tr>
<tr>
<td>Travel</td>
<td>462</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>$17,395</td>
<td>$5,933</td>
</tr>
</tbody>
</table>

It is anticipated that no residual funds will remain on hand at the close of the present contract period on February 28, 1963 and further that Georgia Tech's commitment to contribute a total of $7301 to the support of the research will have been fulfilled.

Respectively submitted,

David W. Martin
Project Director
TECHNICAL STATUS REPORT NO. 14

ANNUAL SUMMARY REPORT

PROJECT NO. B-176

Covering the Period

March 1, 1962 to February 28, 1963

IONIZATION AND CHARGE TRANSFER
CROSS SECTIONS

By D. W. Martin
D. S. Harmer
R. A. Langley

Contract No. AT-(40-1)-2591

U. S. ATOMIC ENERGY COMMISSION
OAK RIDGE, TENNESSEE

1 March 1963

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia
TECHNICAL STATUS REPORT NO. 14

ANNUAL SUMMARY REPORT

Project No. B-176

Covering the Period

March 1, 1962 to February 28, 1963

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By

D. W. Martin
D. S. Harmer
R. A. Langley

Contract No. AT-(40-1)-2591

U. S. Atomic Energy Commission
Oak Ridge, Tennessee

March 1, 1963

TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Title</td>
<td>1</td>
</tr>
<tr>
<td>II. Period Covered by Report</td>
<td>1</td>
</tr>
<tr>
<td>III. Scope of the Research</td>
<td>1</td>
</tr>
<tr>
<td>A. Prior Results: Ionization by Protons</td>
<td>2</td>
</tr>
<tr>
<td>B. Ionization by Singly Charged Helium Ions</td>
<td>3</td>
</tr>
<tr>
<td>1. Experimental Results</td>
<td>3</td>
</tr>
<tr>
<td>2. Comparison of He(^+) and Proton Ionization</td>
<td>12</td>
</tr>
<tr>
<td>C. Ionization by Doubly-Charged Helium Ions and Neutral Hydrogen Atoms</td>
<td>19</td>
</tr>
<tr>
<td>1. Charge-Changing Cell and Analyzer</td>
<td>20</td>
</tr>
<tr>
<td>2. Status of the Research</td>
<td>28</td>
</tr>
<tr>
<td>IV. Publications</td>
<td>28</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Cross Sections for the Gross Production of Positive Ions and Free Electrons by He(^+) Incident on Helium</td>
<td>4</td>
</tr>
<tr>
<td>2.</td>
<td>Cross Sections for the Gross Production of Positive Ions and Free Electrons by He(^+) Incident on Neon</td>
<td>5</td>
</tr>
<tr>
<td>3.</td>
<td>Cross Sections for the Gross Production of Positive Ions and Free Electrons by He(^+) Incident on Argon</td>
<td>6</td>
</tr>
<tr>
<td>4.</td>
<td>Cross Sections for the Gross Production of Positive Ions and Free Electrons by He(^+) Incident on Molecular Hydrogen</td>
<td>7</td>
</tr>
<tr>
<td>5.</td>
<td>Cross Sections for the Gross Production of Positive Ions and Free Electrons by He(^+) Incident on Molecular Nitrogen</td>
<td>8</td>
</tr>
<tr>
<td>6.</td>
<td>Cross Sections for the Gross Production of Positive Ions and Free Electrons by He(^+) Incident on Molecular Oxygen</td>
<td>9</td>
</tr>
<tr>
<td>7.</td>
<td>Cross Sections for the Gross Production of Positive Ions and Free Electrons by He(^+) Incident on Carbon Monoxide</td>
<td>10</td>
</tr>
<tr>
<td>8.</td>
<td>Comparison of Gross Ionization Cross Sections for He(^+) Ions and Protons of Equal Velocity Incident on Helium</td>
<td>17</td>
</tr>
<tr>
<td>9.</td>
<td>Comparison of Gross Ionization Cross Sections for He(^+) Ions and Protons of Equal Velocity Incident on Molecular Hydrogen</td>
<td>18</td>
</tr>
<tr>
<td>10.</td>
<td>Schematic View of Apparatus</td>
<td>21</td>
</tr>
<tr>
<td>11.</td>
<td>Interior View of Electrostatic Analyzer with Faraday Cups</td>
<td>24</td>
</tr>
<tr>
<td>12.</td>
<td>Exterior View of Electrostatic Analyzer and Collision Chamber</td>
<td>25</td>
</tr>
</tbody>
</table>
I. Title

Ionization and Charge Transfer Cross Sections

II. Period Covered by Report

This report covers the period from March 1, 1962 through February 28, 1963, which corresponds to the 12-month extension provided for by Modification No. 3 of Contract No. AT-(40-1)-2591.

III. Scope of the Research

The general objective of the research being performed under this contract has been the measurement of the apparent cross sections for the production of slow positive ions and free electrons in gaseous targets by fast hydrogen and helium ions and atoms with energies in the range 0.15 to 1.0 MeV. The projectile source is a Van de Graaff positive-ion accelerator equipped for beam analysis and stabilization. The method of measurement used requires "thin" target conditions, in which less than one percent of the incident ions undergo a single ion-producing collision, so that only a negligible fraction undergo multiple collisions. The "slow" ions produced in a defined volume of target gas are collected by two charged parallel-plate arrays which collect respectively the positive and negative ions, and the total current to each array is measured by sensitive electrometers. For the case of charged incident particles, the intensity of the incident beam is determined by collecting the beam of fast ions emerging from the collision region in a Faraday cup. The total charge of the products formed and the intensity of the incident beam are measured absolutely, so that the cross sections obtained are also absolute.
These total production cross sections include contributions from any charge-changing events, in which the incident particle gains or loses electrons in the collision. This class of events is distinguished from the simple ionization events, which latter class we define to include only events in which the incident particle does not change its charge. Information on the cross sections for charge-changing events is for some of the cases considered available from other types of experiments, and wherever such information is sufficient to assess these contributions, they are subtracted to obtain the apparent ionization cross section. The term apparent is used because the present method measures the total charge produced rather than the number of ions, so that the results include a weighted sum of contributions from events that produce multiply-charged ions. (This usage is consistent with that of other workers in the field). The apparent ionization cross section is of interest because certain simple relationships are expected to hold at high energies in this cross section for various projectile ions in a given target.

A. Prior Results: Ionization by Protons

Results obtained under this program prior to the period covered by the present report have included measurements of the apparent ionization cross sections for protons incident on targets of He, Ne, Ar, H₂, N₂, O₂, and CO. For incident protons of energies between 0.15 and 1.0 MeV, only a negligible fraction of the total ion production is attributable to charge changing collisions, so that the positive and negative ion-production cross sections were essentially equal over the energy range studied. Their common value we have called the gross ionization cross section. Detailed comparisons were made

with the available measurements for electrons of the same velocity, and with
the available theoretical calculations in the Born approximation for hydro-
gen and helium. These results have been summarized in the Progress Report
(Technical Status Report No. 9) of December 1, 1961, and in the Annual
Summary Report (Technical Status Report No. 10) of March 1, 1962, and in
addition have been published in the open literature. 1-3

B. Ionization by Singly Charged Helium Ions

1. Experimental Results

Results obtained prior to the period covered by this report
included preliminary measurements of the cross sections for He $^+$ ions incident
on targets of $H_2$, He, and Ne. Final verification of these measurements, and
extension of the measurements to targets of Ar, $N_2$, $O_2$, and CO have now been
completed. Unexpected difficulties in attaining reproducibility delayed the
completion of the He $^+$ measurements to our complete satisfaction until well
into the present period. Detailed description of the problems, and of the
modifications in both the apparatus and the techniques that were developed
to deal with them, have been given previously in Technical Status Reports
10, 11, and 12.

A summary of the final results for He $^+$ incident on He, Ne, Ar, $H_2$, $N_2$,
$O_2$ and CO is presented in Figures 1 to 7. In these figures, the total

2 E. W. McDaniel, et al, Proc. Fifth Int. Conf. on Ionization Phenomena in Gases,
Figure 1. Cross Sections for the Gross Production of Positive Ions and Free Electrons by He$^+$ Incident on Helium.
Total Cross Section for Production of Free Electrons

\[ \text{He}^+ \rightarrow \text{Ne} \]

Figure 2. Cross Sections for the Gross Production of Positive Ions and Free Electrons by He\(^+\) Incident on Neon.
Figure 3. Cross Sections for the Gross Production of Positive Ions and Free Electrons by He$^+$ Incident on Argon.
Figure 4. Cross Sections for the Gross Production of Positive Ions and Free Electrons by He\(^+\) Incident on Molecular Hydrogen.
Figure 5. Cross Sections for the Gross Production of Positive Ions and Free Electrons by He$^+$ Incident on Molecular Nitrogen.
Figure 6. Cross Sections for the Gross Production of Positive Ions and Free Electrons by He$^+$ Incident on Molecular Oxygen.
Figure 7. Cross Sections for the Gross Production of Positive Ions and Free Electrons by He\(^+\) Incident on Carbon Monoxide.
apparent\textsuperscript{4} cross-section for the production of positive ions, $\sigma_+$, and of negative ions and/or electrons, $\sigma_-$, is given as a function of the incident He\textsuperscript{+} ion energy. The results repeated here for the target gases He, Ne, Ar, and H\textsubscript{2} have been given previously in Technical Status Report No. 12. This report includes the new data on N\textsubscript{2}, O\textsubscript{2} and CO. All of these data were included in a paper read at the Fifteenth Annual Gaseous Electronics Conference at Boulder, Colorado, in October, 1962. The comparison given in Section B-2 below was also included in this paper.

The data in Figures 1-7 were obtained with target gas pressures in the range 0.5 to 1.0 x 10\textsuperscript{-4} Torr. Over this range the measured cross-sections were shown to be independent of the pressure. The slow-ion currents were always less than one percent of the incident beam current, indicating that "thin" target conditions obtained. The measured values of the cross-sections were found to be in satisfactory agreement with similar measurements by other workers at energies up to 0.18 MeV,\textsuperscript{5,6} and the differences between the observed electron and positive-ion production cross sections were in reasonable agreement with published data on charge changing cross sections.\textsuperscript{7,8}

\textsuperscript{4}See page 2.

\textsuperscript{5}N. V. Federenko and V. V. Afrosimov, Soviet Physics-JETP 1, 1872 (1956).

\textsuperscript{6}H. B. Gilbody, Private Communication (to be published) (1962).


2. Comparison of He⁺ and Proton Ionization

A general theoretical treatment of the high-energy ionization process has shown that for high impact velocity the ionization cross section should be of the general form

\[ Q_{nl} = \frac{2\pi e^4 c_{nl} Z_{nl} Z_1^2}{m v^2 |E_{nl}|} \log_e \left( \frac{2m v^2}{C_{nl}} \right) \]  

(1)

Where \( e \) is the electronic charge, \( Z_{nl} \) is the number of electrons in the \( nl \) shell of the target atom, each of energy \( E_{nl} \), \( Z_1 \) is the charge of the incident ion in units of \( e \), \( c_{nl} \) is a reduced electron matrix element, \( C_{nl} \) a quantity related to the energy of an electron in the \( nl \) shell, \( m \) is the electron mass, and \( v \) is the collision velocity. Normally \( \sigma_1 \) is expected to be essentially equal to \( Q_{nl} \) for the outermost shell of the target atom. For a given target atom Eq.(1) can then be written in the form

\[ \sigma_1 = A \frac{Z_1^2 M}{E} \log_e \left( \frac{E}{M} \right) \]  

(2)

where \( E \) is the kinetic energy of the incident ion, \( Z_1 \) is its charge, and \( M \) its mass number. The constants:

\[ A = \frac{2\pi e^4 c_{nl} Z_{nl}^2}{2m/M_p} \quad \text{and} \quad B = \frac{4m/M_p}{C_{nl}} \]

where \( M_p \) is the mass of the proton, are dependent only on properties of the target atom. If \( A \) and \( B \) are empirically evaluated for a given target atom

\[ H. \ Bethe, \ Ann. \ Phys. \ 5, \ 325 \ (1930). \]
from experimental data for one incident ion, Eq.(2) may be used to estimate the ionization cross sections for the same target atom and other incident ions. The cross sections predicted, it must be emphasized, refer only to simple ionization events, as defined on page 2, in which the incident ion neither gains nor loses electrons.

Our earlier proton data have been fitted by a least squares technique to Eq. (2) to obtain empirical values of A and B for the target atoms and molecules He, Ne, Ar, H₂, N₂, O₂, and CO. These values are presented in Table III of Reference 3, and in Technical Status Report No. 10.

The relationship between the ionization cross sections for various projectile ions discussed here should, strictly speaking, apply only to point-charge ions, i.e., to bare nuclei. An incident ion carrying bound electrons might, however, be expected to be equivalent to a partially screened point charge having an "effective" charge $Z₁$ lying somewhere between its actual net charge and its nuclear charge. The value of $Z₁$ for a given ion, and indeed the validity of the whole concept of an effective charge, can for the present be evaluated only by experimental test. The concept will be useful only if $Z₁$ can be shown to be independent of the target atom and of the collision energy, or at least asymptotically so at high energies. If such independence can be established for a given incident ion by measurements taken over a limited energy range, one can use the effective $Z₁$ obtained to extrapolate the measurements to higher energies with Eq.(2). In addition, one can use the values of A and B for various targets obtained from incident proton measurements to predict the cross sections for other ions of determined effective $Z₁$ on these targets.
Accordingly, we have undertaken a detailed comparison of our He\(^+\) measurements with our earlier proton measurements. Unfortunately the comparison is not straightforward because for He\(^+\) there are appreciable contributions to the total slow ion production from charge-changing collisions in the energy range investigated, and with presently available information only an estimate can be made of the apparent cross section \(\sigma_1\) for simple ionization. An illustration of the nature of the difficulty may be obtained by a detailed examination of the relatively simple case of He\(^+\) ions incident on He. Presented in Table I is a partial listing of the more important ion-producing collisions that may occur in this case. The sum of the individual cross sections for the first two reactions is the "single electron pick-up" cross section \(\sigma_{10}\); the sum for the last three is the electron loss or "stripping" cross section \(\sigma_{12}\); the desired apparent ionization cross section \(\sigma_1\) is the sum of the cross section for the third reaction plus twice the cross section for the fourth. Our cross sections \(\sigma_+\) and \(\sigma_-\), however, correspond to the total slow charge of each sign produced by all seven reactions, and must be corrected for the contributions of charge-changing collisions to obtain \(\sigma_1\). Even though data on \(\sigma_{10}\) and \(\sigma_{12}\) in this energy range are available for several of these target gases (\(\text{H}_2\), He, Ar, and \(\text{N}_2\))\(^7\)\(^8\), it is still necessary to know the relative yields of each of the separate reactions in \(\sigma_{10}\) and \(\sigma_{12}\) to make proper corrections. Unfortunately data on this point is almost non-existent. It is known\(^10\),\(^11\) that the total production of multiply-charged slow ions in noble gases by He\(^+\) at these energies is only a small fraction of the production of singly-charged ions, so it appears reasonable to suppose

\(^{10}\) Jones, Ziemba, Moses, and Everhart, Phys. Rev. 113, 182 (1959).

### TABLE I
POSSIBLE ION PRODUCING REACTIONS OF SINGLY CHARGED He⁺ IONS

<table>
<thead>
<tr>
<th>Incident Ion</th>
<th>Target</th>
<th>Fast Ion</th>
<th>Slow Ions</th>
</tr>
</thead>
<tbody>
<tr>
<td>He⁺</td>
<td>He°</td>
<td>He°</td>
<td>He⁺</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>He⁺</td>
<td>He⁺⁺ + e⁻</td>
</tr>
<tr>
<td></td>
<td></td>
<td>He⁺⁺</td>
<td>He⁺⁺ + 2e⁻</td>
</tr>
<tr>
<td></td>
<td></td>
<td>He⁺⁺</td>
<td>He⁺⁺ + 3e⁻</td>
</tr>
</tbody>
</table>

that the reactions producing slow He⁺⁺ ions are relatively small contributors to $d_{10}$ and $d_{12}$ as well.

For the present case of He, it is therefore assumed that $d_{10}$ is mainly the first reaction. For lack of other information, it is assumed that the fifth and seventh reactions make relatively minor and roughly equal contributions to $d_{12}$, which is equivalent to assuming that all (1,2) collisions are reaction 6. Under these assumptions

$$d_1 = d_+ - (d_{10} + d_{12})$$

or

$$d_1 = d_- - 2d_{12}$$

The two values of $d_1$ thus obtained should agree, but such agreement actually
reflects only agreement between our difference \((\sigma_- - \sigma_+)\) and the difference \((\sigma_{12} - \sigma_{10})\), which should hold in any event.

For the higher energies above 0.6 MeV, the corrections amount at most to about 20%, so that inadequacy of the assumptions made cannot contribute an error of more than a few percent to \(\sigma_1\) in this region. At lower energies the situation is much less certain. However this does not really affect the goal of devising a means of extrapolating to high energies.

The other gases for which measurements of the charge changing cross sections are available \((H_2, Ar, N_2)\) were treated similarly to He. In all these cases \(\sigma_{12}\) is at least an order of magnitude greater than \(\sigma_{10}\) above 0.6 MeV. If it is assumed that this is also true for Ne, O\(_2\), and CO, for which no measurements of the charge changing cross sections are available, then our difference \((\sigma_- - \sigma_+)\) should be essentially equal to \(\sigma_{12}\) at these energies. Then

\[
\sigma_1 = \sigma_+ - \sigma_{12} = \sigma_+ - (\sigma_- - \sigma_+) = 2\sigma_+ - \sigma_-
\]

The \(\sigma_1\) curves obtained for He and H\(_2\) are shown in Figs. 8 and 9. Also plotted are the cross sections predicted by Eq.(2) for \(M = 4\) and two values of \(Z_1\), using the values of \(A\) and \(B\) obtained for these targets from our earlier proton measurements. Solid curve #1 in each Figure corresponds to \(Z_1 = 1\), and solid curve #2 corresponds to \(Z_1 = 2\). Also plotted are predictions of Eq.(2) for \(Z_1 = 1\) taken from theoretical results for protons on these gases. For He in Fig. 8 the calculation used was that of
Figure 8. Comparison of Gross Ionization Cross Sections for He\(^+\) Ions and Protons of Equal Velocity Incident on Helium.
Figure 9. Comparison of Gross Ionization Cross Sections for He$^+$ Ions and Protons of Equal Velocity Incident on Molecular Hydrogen.
Mapleton\textsuperscript{12}, and for $H_2$ in Fig. 9 it was that of Bates and Griffing\textsuperscript{13}.

It is evident that the $\sigma_1$ curves are indeed nearly parallel to the predicted curves above about 0.5 MeV. They run higher than the $Z_1 = 1$ curve by a factor of about 1.5 for both gases. Similar results were obtained for all five of the other gases.

Thus it is shown that the concept of an effective charge $Z_1$ lying between 1 and 2 does indeed have at least qualitative validity for simple ionization by He$^+$. The value of the effective charge obtained is

$$Z_1 \approx \sqrt{1.5} \approx 1.2.$$ 

It is noteworthy that this value is materially less than the effective charge of 1.69 deduced from variation calculations of the ground state of the neutral helium atom. This is hardly surprising, since the two situations are very different.

The upper curves in Figs. 8 and 9 ($Z_1 = 2$) are expected to represent rather closely the cross sections for incident He$^{++}$. Experimental checks of this prediction will be forthcoming in the near future when experimental data for He$^{++}$ becomes available from the next phase of this study.

C. Ionization by Doubly-Charged Helium Ions and Neutral Hydrogen Atoms

The current phase of the study is concerned with measurement of the ionization cross sections for incident doubly-charged helium ions and neutral hydrogen atoms. These projectiles are not produced directly by the Van de Graaff accelerator, so additional apparatus has been constructed to produce

them by means of charge-changing collisions from other ions that are available in the Van de Graaff beam. Design and construction of the necessary additions to the apparatus was completed in the latter portion of the period covered by this report. This has included the construction of a rather more substantial supporting structure for the apparatus, in view of the increased difficulty in achieving and maintaining satisfactory alignment of the whole system over a considerably longer beam flight path than had been used in previous measurements.

1. Charge-Changing Cell and Analyzer

The entire apparatus is shown schematically in Fig. 10. The new additions to the apparatus include essentially all of the components in the center of the drawing from beam-tube gate valve B26 to the valve 45, inclusive, plus certain added traps, valves, and vacuum gauge locations which need not be enumerated. Fig. 10 is essentially a side view of the apparatus, except that for clarity the electrostatic analyzer section and the collision chamber are shown rotated 90° about the beam axis into plan view. Thus the beam deflections produced by the analyzer are actually in the horizontal plane, rather than vertical as they appear in the Figure.

Stripping or neutralizing of a primary beam ion is accomplished by passing it through the 30-cm long gas cell, which contains a gas such as Argon at a pressure of up to about $2 \times 10^{-3}$ Torr. The pressure is maintained by balancing a continuous input of gas from a mechanical leak valve against the discharge of gas through the differentially pumped beam apertures "a" and "b" at the ends of the cell. These apertures are knife-edged round holes 1/16-inch in diameter, and serve to collimate the beam as well as to define the gas cell volume. The
Figure 10. Schematic View of Apparatus.
primary ions may undergo charge-changing collisions with molecules of the
gas in the cell, converting them into the desired species. With the pre-

cent path length and gas pressure, conversion of an appreciable fraction of
the incident beam may be accomplished under favorable conditions. The beam
tube pressure outside the gas cell region is kept low by continuous pumping;
the pumped chamber between "b" and "c", in particular, is intended to aid in
the maintenance of a relatively good vacuum in the analyzer region.

Following the gas cell, the beam enters the electrostatic analyzer,
which selects from the mixed beam those particles which happen to be in the
desired charge state. The analyzer consists of two parallel plates 17 cm
long and 1.2 cm apart, to which a variable potential difference of up to
5000 volts may be applied. With the "normal" operating voltage only half this
large applied to the plates, the three components of a 1-MeV helium beam (He°,
He+, and He++) are separated by about 2 centimeters at the exit end of the
analyzer section. The deflection plates are mounted on a holder which can be
rotated about the beam axis from an external control, permitting adjustment of
the plane of the deflected beams to coincide with the horizontal plane of the
beam detectors and the exit port. The gas cell with its apertures and the de-
fl ector assembly are so constructed that they can be rigidly assembled and
aligned optically before they are installed in the vacuum housing of the ana-
lyzer section.

Provision has been made for monitoring the intensities of all of the
separated components of the beam. Near the exit end of the analyzer section
are three small Faraday cups and a secondary-emission neutral detector. Each
unit has a lead screw by means of which it can be independently positioned
horizontally to collect one of the separated component beams. A frosted
glass "viewer" plate in the same region can be rotated into position to
intercept all of the beams, providing a visual indication of the beam lo-
cations by means of the fluorescence of the glass. The arrangement is shown
in the insert in Fig. 10, and Fig. 11 is a close-up photograph of this portion
of the apparatus. The detector corresponding to the component beam being used
for cross section measurements can be moved aside by means of its lead screw,
as is indicated in Fig. 10, permitting that beam to pass out through the exit
port, while the other detectors remain in position to monitor the remaining
components.

The collision chamber and its entrance collimator are constructed as a
rigid assembly that connects to the analyzer section through a flexible bel-
lows. This whole assembly can be moved horizontally relative to the analyzer
to align it at will with any of the three beam positions that fall within the
analyzer exit port (charge-energy ratio, $e/E = 0, 1, \text{or } 2$; see Fig. 10). In
Fig. 10 the collision chamber is shown aligned with the undeflected neutral
beam, where it will be placed for the $H^0$ measurements. For the $He^{++}$ measure-
ments the chamber is placed in line with the $e/E = 2$ position. Fig. 12 is a
photograph of the portion of the apparatus to the right of the shielding wall
in Fig. 10, viewed from the opposite side. The mechanical arrangements pro-
vided for the horizontal movements of the collision chamber can be seen as
well as a jackscrew arrangement provided in the supports to facilitate ver-
tical alignment adjustments. In Fig. 12 the collision chamber is shown off-
set toward the camera to align with the $e/E = 2$ beam position for $He^{++}$ meas-
urements.
Figure 11. Interior View of Electrostatic Analyzer with Faraday Cups.
Figure 12. Exterior View of Electrostatic Analyzer and Collision Chamber.
When the apparatus is aligned as described for He$^{++}$ measurements, application of the "normal" 2500 volts to the deflector plates directs 1.0-MeV He$^{++}$ ions into the collision chamber along the e/E = 2 trajectory, while the He$^+$ component is monitored by the Faraday cup at e/E = 1. Then by simply doubling the voltage, one can direct the He$^+$ beam into the chamber, while collecting and monitoring the He$^{++}$ component at e/E = 4. In addition, the ion-source gas supply in the Van de Graaff can be readily switched from helium to hydrogen, so that with only a readjustment of the field of the analyzing magnet, a beam of 1.0-MeV protons can also be directed into the chamber along e/E = 2 by the double voltage. Thus the He$^{++}$ measurements can very readily be checked against our well established H$^+$ and He$^+$ results without disturbing the mechanical alignment of the apparatus. This feature is proving to be extremely valuable in establishing confidence in the measurements.

With the present arrangement, a He$^{++}$ beam of satisfactory intensity can be obtained throughout the energy range from 1.0 MeV down to about 0.5 MeV, below which the yield falls very rapidly. The range could be extended downward somewhat if pressures greater than $2 \times 10^{-3}$ Torr could be used in the gas cell. Unfortunately the presently available pumping speed on the small chamber between "b" and "c" (Fig. 10) has proved to be inadequate to permit such pressures without a prohibitive increase in the pressure in the analyzer section. The criterion for the maximum pressure tolerable in this region is that recontamination of the separated He$^{++}$ beam by further charge-changing collisions between the deflector plates and the first slit of the collision chamber entrance collimator ("d" in Fig. 10) shall not exceed one percent. Since the
"electron pick-up" cross sections for He$^{++}$ increase rapidly with decreasing energy, the maximum-pressure criterion rapidly becomes more stringent in this direction, and it intersects the increasing minimum gas-cell pressure at around 0.5 MeV.

2. Status of the Research

As of the date of this report, installation, alignment and testing of all the new apparatus has been completed, including the addition of a larger and more sensitive McLeod gauge to measure the target gas pressure. These extensive modifications have consumed most of the effort in the last quarter. The new series of measurements with incident He$^{++}$ are now well underway, and they appear to be proceeding smoothly.

IV. Publications

The publications of the research in this contract period were listed in Report No. 13, and reprints were submitted at that time.

The final data on the He$^+$ measurements and preliminary He$^{++}$ results will be presented in a paper to be read by D. W. Martin at the Third International Conference on the Physics of Electronic and Atomic Collisions in London, 23-26 July, 1963, and the text will be published in full in the Proceedings of this meeting.

Respectfully submitted,

David W. Martin
Project Director