TECHNICAL STATUS REPORT NO. 15

PROJECT NO. B-176

Covering the Period

June 1, 1961 to May 31, 1963

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

Summary of Results for Fast Helium Ions

By R. A. Langley
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Contract No. At-(40-1)-2591

U. S. ATOMIC ENERGY COMMISSION
OAK RIDGE, TENNESSEE

1 June 1963

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

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PREFACE

This report summarizes the results and the changes in apparatus and techniques in the course of studies conducted under Contract AT-(40-1)-2591 on the ionization of gases by fast helium ions, both singly and doubly charged. This corresponds to the two-year period from June 1, 1961 to May 31, 1963. Repeated herein in summary form are most of the pertinent facts previously reported in Technical Status Reports 8 - 14 inclusive.

The text of this report is identical to the text of a thesis entitled "Total Cross Sections for the Production of Positive Ions and Free Electrons in Gaseous Targets" submitted by Robert A. Langley to the faculty of the Georgia Institute of Technology in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics. Having completed all other requirements, he was awarded this degree at the June 1963 commencement of the Georgia Institute of Technology. Dr. Langley is now on active duty with the United States Air Force at the Air Force-Cambridge Laboratories.

Drs. Earl W. McDaniel and John W. Hooper are included as authors although they are not now formally associated with the work conducted under this contract. Dr. McDaniel was project director when the studies on fast He ions were initiated. Since his termination as project director in September 1961, he has been available on an informal consulting basis for these studies. Dr. Hooper was actively engaged in the studies of He^{+} ionization up to September 1962.

Mr. L. J. Puckett and Mr. J. W. Martin of the Engineering Experiment Station assisted in the operation of the equipment during portions of this work.

Summary results of the ionization by He^{+} and He^{++} ions were presented at the Third International Conference on the Physics of Electronic and Atomic Collisions in London, 23-26 July 1963, and the text of this paper will be presented in full in the Proceedings of this meeting to be published by the North-Holland Publishing Company, Amsterdam. It is planned to submit articles detailing the He^{+} and He^{++} results and on their comparisons with theory to the Physical Review for publication.

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SUMMARY

The cross sections for the production of slow positive ions and free electrons for He^{+} ions incident on helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide have been measured for incident particle energies over the range from 0.133 to 1.00 MeV. Similar cross sections have been measured for He^{++} ions incident on helium and hydrogen for incident particle energies over the range from 0.50 to 1.00 MeV. Previous ionization measurements by other investigators in this field have been confined to incident particle energies below 0.18 MeV. The work reported here represents an extension of the cross sections into the energy region where the Born approximation is expected to be valid. Theoretical calculations using this approximation must be compared with experimental results in order to verify the adequacy of the wave functions of the struck atom or molecule used in the calculation.

Considering a binary or two-system collision, let us refer to one system as the target system and the other as the incident system. At the high energies of the present research generally only a small fraction of the momentum of the incident system is transferred and the incident particle suffers only a small loss of energy and emerges with only a slight deviation from its original direction of motion and therefore the identity of the incident system is well defined.

Of the several general types of elastic and inelastic processes that are possible in a binary collision, the present research is restricted to those events that produce one or more slow ions and/or free electrons.

Even with this restriction to ionization, charge transfer, and dissociation, there are still a number of distinct final states for a given pair of collision partners. Most types of experiments, however, observe all events of a certain class without distinguishing between them. If the charge state of the incident system is the same before and after the collision but the target particle is ionized we shall call the event an "ionization" event. In contrast are the "charge-changing" events in which the incident system gains or loses electrons. These include "charge-transfer" events in which the incident system takes electrons from or gives electrons to the target, and also "stripping" events in which the incident system is ionized in the collision, producing one or more free electrons. Either charge transfer or stripping events may be accompanied by ionization and/or dissociation of the target system.

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 this research, the source of energetic ions 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 a gas cell, an electrostatic analyzer, 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 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. A complete discussion of the design considerations and the detailed testing of the apparatus is given. Particular attention was paid to scattering of the incident beam from apertures, Faraday cup design for proper measurement of the incident beam current, the effect of background contributions and their proper assessment, target gas pressure determination, the suppression of secondary emission from the positive ion collection electrode structure, collection volume definition, collection efficiency, the effects of leakage currents, and the assessment of charge-transfer contributions.

Values for the cross sections for the production of slow positive ions and free electrons for helium ions incident on helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide are presented along with data of other investigators which are available in the lower energy range.

By far the greatest uncertainty in the experiment lies in the determination of the target gas pressure, for which McLeod gauges were used. Use of a cathetometer was believed to permit a relative reading uncertainty of the 400-ml McLeod Gauge used during the He^+ measurements of less than 4 per cent in the range around 1×10^{-4} Torr. This gauge had not been absolutely calibrated, however, so that a possible error of about ± 5 per cent must be admitted in the absolute reading. This led to proportionate possible systematic error in all of the measurements, but it is emphasized that the relative values of the cross sections at various energies are not subject to this systematic error. A larger 2.2-liter McLeod Gauge, used during the He^{++} measurements, was calibrated to an accuracy of about ± 1 per cent while deviation of any one pressure reading from an average of about five readings was as high as ± 5 per cent. This error was due to sticking of the mercury column in the capillary and was believed to be random.

The absolute error brackets for the cross sections involving He^{+} ions are about ± 8 per cent for σ_{+} and about ± 11 per cent for σ_{-}, while the relative accuracies of the cross sections with respect to each other are about ± 5 per cent. The absolute error brackets for the cross sections involving He^{++} ions are about ± 7 per cent for σ_{+} and about ± 10 per cent for σ_{-}, while the relative accuracies are about ± 5 per cent.

For most of the cross sections measured it was possible to estimate the cross section for simple ionization using values of "charge-changing" and "stripping" cross sections obtained by Pivovar et al. Theoretical calculations for ionization cross sections using the Born approximation have been made by Mapleton (He^{++} + He) and Bates and Griffing (He^{++} + H) for point-charge ions, i.e., completely stripped nuclei, and were found to agree well with the present results. A theoretical treatment of He^{+} incident on atomic hydrogen has been made by Boyd et al. and Bates and Griffing. A doubling of the theoretically determined atomic ionization cross section to obtain the molecular cross section is suspect in that it leads to a cross section higher than the experimentally observed cross section. A scaling procedure used for point-charge ions was applied to the theoretical calculations and agreement between the estimated experimental ionization cross section and the scaled theoretical cross section was excellent.

A general theoretical treatment of high energy ionization by Bethe for incident point-charge ions was compared with the data for He^{++} incident on both helium and hydrogen. Known experimental proton ionization cross sections were used to determine empirically certain needed constants in this theory. The agreement between this theory and present results is good. Also the estimated experimental ionization cross sections of several gases by He^{+} ions were compared with Bethe's calculations to examine the proposition that the Bethe results could be used for the case of an ion carrying bound electrons by using an "effective" charge Z_i lying between the nuclear charge and the actual net charge of the ion. To be a useful concept, the effective charge for a given incident ion must be found to be independent of the target gas and of the incident ion energy. The theoretical calculations referred to here describe only "simple" ionization events in which the incident ion does not gain or lose electrons. Therefore the present experimental data on the total ion and electron production by He^{+} had to be corrected for the appreciable contributions from charge-changing events encountered at high energies. It was found that the estimated cross section for simple ionization was greater than that for incident protons of the same velocity by a factor that was very nearly independent of energy above 0.6 MeV, and varied only from 1.3 to 1.5 for the four gases hydrogen, helium, argon, and nitrogen. Thus the concept of an effective charge of about 1.2e for He^{+} does seem to have at least a qualitative validity. It is noteworthy that this value is appreciably less than the effective charge 1.69e deduced in variation calculations of the ground state wave functions of helium. This difference is not unexpected since the two cases are quite different, and may be most sensitive to quite different spatial regions of the wave function.

CHAPTER I

INTRODUCTION

The field of atomic collisions is of basic interest since the nature of the interactions between atoms and molecules can be investigated through observations of collision phenomena. In principle, quantum mechanical calculations could be made for any atomic collision process if a complete set of wave functions for the partners in a collision were known. However, wave functions adequate to describe collision phenomena are not known at the present time except for hydrogenic atoms and ions. Detailed theoretical calculations have not been made except for the simplest cases, i.e., those involving electrons, protons, neutral hydrogen atoms, and singly and doubly charged helium ions as projectiles incident on targets of atomic hydrogen, helium, and lithium. Even for most of these simple cases the calculations were difficult and involved approximations whose validity is difficult to assess except by resort to comparison with experimental results. The calculations are particularly sensitive to the form of the wave functions at large radius. In contrast, most calculations involving properties of bound states, from which most of the existing detailed knowledge of wave functions is drawn, are not particularly sensitive to the details in this region.

Most of the existing calculations for ionization processes at high energies have been made in the Born approximation, which is expected to be valid only for high relative impact energies. In the present research experimental observations have been extended to sufficiently high energies that the results provide a check of the validity of the assumptions made in both existing and future calculations. The comparison between theory and experiment will therefore yield information about atomic and molecular wave functions, especially at large radius.

Earlier experimental work on atomic ionization processes has been confined to lower energy regions, and until recently most practical interest in such collisions has been confined to similar energies. Recent developments in the field of high temperature plasma physics have engendered a renewed interest in basic data on all kinds of collision phenomena at higher energies. A major difficulty in attaining a very hot plasma is "cooling" of the ions in the plasma by collisions with contaminants in the system. Among the approaches to the problem of controlled thermonuclear reactions there are several schemes 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 value.

Other areas in which high energy ionization processes are of interest include astrophysics, the physics of the upper atmosphere, and the technology of various types of detection devices in high energy nuclear physics.

Chapter II contains a discussion of some of the more pertinent terms used in the field of high energy atomic collisions, a statement of the purpose of the experiment reported in this thesis, a list of pertinent review articles dealing with the field of atomic collisions, and a discussion of some existing theories of binary collisions.

Chapter III deals specifically with phenomena related to the passage of helium ions through a gas. A cross-section notation is discussed and applied to the collision of singly-charged helium ions incident on molecular hydrogen. Particular theoretical calculations dealing with incident helium ions are discussed, with a method through which theory and experiment may be compared.

The experimental equipment and method is discussed in Chapter IV. Chapter V contains discussions of data corrections, comparison of present results with other experimental investigations, and errors. In Chapter VI available theoretical calculations are compared with the present experimental results.

CHAPTER II

DEFINITIONS AND THEORETICAL BACKGROUND

This chapter contains a discussion of some of the terms used in the field of high energy atomic collisions, a statement of the purpose of the experiment reported in this thesis, a list of pertinent review articles dealing with the field of atomic collisions, and a discussion of some existing theories of binary collisions.

A number of types of events may occur when atomic or molecular systems collide. There may be simple elastic scattering, where momentum is transferred but the internal structures of both systems remain unchanged. Other events classified as inelastic may involve electron transfer between the two systems, or excitation, ionization or dissociation of one or both of the colliding systems. Elastic scattering, excitation and simple dissociation events will not be further considered here.

Considering a binary or two-system collision, let us refer to one system as the target system and the other as the incident system. At the high energies of the present research generally only a small fraction of the momentum of the incident system is transferred. The incident particle suffers only a small loss of energy and emerges with only a slight deviation from its original direction of motion, so that the identity of the incident system is well defined.

Even with the restriction to ionization, charge transfer, and dissociation, there are still a number of distinct final states for a given pair of collision partners. Most types of experiments, however, observe all events of a certain class without distinguishing between them. If the charge state of the incident system is the same before and after the collision but the target particle is ionized we shall call the event an "ionization" event. In contrast are the "charge-changing" events in which the incident system gains or loses electrons. These include "charge-transfer" events in which the incident system takes electrons from or gives electrons to the target, and also "stripping" events in which the incident system is ionized in the collision, producing one or more free electrons. Either charge-transfer or stripping events may be accompanied by ionization and/or dissociation of the target system.

In order to study collision reactions in detail, it is necessary to be able to express the probability of a given reaction as a quantitative measure. This quantity must be one that may be measured experimentally and calculated theoretically so that experimental and theoretical values can be compared. The concept of collision cross section is frequently used (see Appendix). This concept permits the assignment of a hypothetical size, which is related to the probability of occurrence of a specific event, to the target systems.

Most present experimental observations have fallen into two distinct classes: 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 and the "thin" target approach in which the probability of multiple collisions by a single incident system is negligible. Most charge-changing collision experiments have involved thick targets and observations on the emerging fast particles. In contrast, most of the ionization measurements have been thin target experiments and have involved observation of the residual slow particles.

The purpose of the experiment reported in this thesis is to measure the total cross sections for the production of positive ions and free electrons in gaseous targets by helium ions in the energy range 0.133-1.00 MeV. The target gases are helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide. The "thin" target method is used. The total cross sections for the production of positive ions and free electrons involve the sum of the apparent ionization cross section and certain charge-changing cross sections. The apparent ionization cross section, as defined by Massey and Burhop,[1] is the cross section for single ionization plus twice the cross section for double ionization plus three times the cross section for triple ionization, etc. With respect to the slow ions, only the total current is observed and it has not been ascertained directly what fraction of this current is due to multiply charged ions or what part is due to events in which the charge state of the incident ion is changed.

Previous work with incident helium ions has dealt primarily with ionization cross sections at lower energies and with charge-changing cross sections at both high and low energies.

Experimental work prior to 1951 has been thoroughly surveyed by Massey and Burhop.[1] Reviews of the charge-transfer field prior to 1957 by Allison are pertinent.[2,3] A recent article by Federenko reviews ionization reactions.[4] A work soon to be published by McDaniel reviews the field of atomic collisions.[5]

A discussion is presented on some of the existing theories pertinent to this research. The range of energies in this research is such that the range of impact velocities is large compared with the velocities of orbital atomic electrons, but small compared with the velocity of light, i.e.,

$10^8 < v < 5 \times 10^9$ cm/sec. In general, the partners in a collision have internal structure, i.e., nucleus plus electrons, so that the collision process is essentially an interaction involving many particles. It is necessary to reduce this many body problem to a binary collision problem in order to use one of the formulations which have been devised to deal with binary collisions. Some of these binary collision formulations are presented below.

Partial Waves[6]

The method of partial waves was devised to deal with collision problems which involve spherically symmetric interaction potentials. In the space-time representation of scattering, the incident particle beam is considered as a plane wave incident on a scattering center. The scattered wave is expanded as an infinite series of spherical harmonics with each term multiplied by an appropriate radial wave function. Each term in this expansion is called a "partial wave." As a result of the interaction with the scattering center each scattered wave is shifted in phase from that which it would have had if the scattering center had not been there. The cross section for a particular reaction is given by an infinite sum in which each term involves a function of one of the phase shifts. The cross section may then be found if all the phase shifts are known. In order to calculate these phase shifts one must essentially solve the Schrödinger equation, however.

This method is most useful if the series converges rapidly enough so that only a few phase shifts need be calculated. The number of phase shifts that will influence the cross section in any given case can be obtained from the equation

$$\ell(\ell+1) = k^2 r_o^2 \tag{2-1}$$

where ℓ is the number of phase shifts that must be calculated, k is the wave number of the incident wave, and r_o is the radius beyond which the scattering potential has become negligible.

This method is used with short range potentials such as those encountered in nuclear physics. The high energy of the incident particles used in this experiment and the long range scattering potential involved render this method impracticable because of the large number of phase shifts that must be calculated, but it is used at much lower energies to calculate elastic scattering and charge-transfer cross sections for atomic systems.

Born and Distorted Wave Approximations[6]

The time-independent Schrödinger wave equation for a binary collision in which the collision partners have internal structure is

$$\left[-\frac{\hbar^2}{2m}\nabla_r^{\,2} + T_A(\bar{r}_A) + T_B(\bar{r}_B) + V_A(\bar{r}_A) + V_B(\bar{r}_B) + V(\bar{r},\bar{r}_A,\bar{r}_B)\right]\psi(\bar{r}_A,\bar{r}_B,\bar{r}) = E\psi \tag{2-2}$$

where the atomic systems are denoted by A and B. In Equation (2-2), T_A and T_B are respectively the kinetic energy operators for systems A and B, and V_A, V_B are their internal potential energies. To obtain an approximation to ψ suitable for the determination of cross sections, it is usual to expand ψ in the form

$$\psi(\bar{r}_A,\bar{r}_B,\bar{r}) = \sum_n \varphi_{An}(\bar{r}_A)\,\varphi_{Bn}(\bar{r}_B)\,\psi_n(\bar{r}) \tag{2-3}$$

where φ_{An} and φ_{Bn} are the wave functions describing the internal states of A and B and $\psi_n(\bar{r})$ describes the relative motion in state n. Using the relations

$$[T_A + V_A - E_{An}]\ \varphi_{An} = 0 \qquad (2\text{-}4)$$

$$[T_B + V_B - E_{Bn}]\ \varphi_{Bn} = 0 \qquad (2\text{-}5)$$

$$\frac{2m}{\hbar^2}[E_{An} + E_{Bn} - E_{Ao} - E_{Bo}] = k_o^{\,2} - k_n^{\,2} \qquad (2\text{-}6)$$

and multiplying Equation (2-2) through by $\varphi^*_{An}\ \varphi^*_{Bn}$ and integrating over $\bar{r}_A$ and $\bar{r}_B$ leads to the infinite set of coupled differential equations for ψ_n

$$(\nabla_r^{\,2} + k_n^{\,2})\ \psi_n(\bar{r}) = \sum_m U_{nm}\ \psi_m(\bar{r}) \qquad (2\text{-}7)$$

where

$$U_{nm} = \frac{2m}{\hbar^2}\int \varphi^*_{An}(\bar{r}_A)\ \varphi^*_{Bn}(\bar{r}_B)\ V(\bar{r}_A,\bar{r}_B,\bar{r})\ \varphi_{Am}(\bar{r}_A)\ \varphi_{Bm}(\bar{r}_B)\ d\bar{r}_A d\bar{r}_B \qquad (2\text{-}8)$$

The summation sign is meant to include integration over states of positive energy as well as bound states of the atoms A and B. Solutions of these equations are required to be well-behaved functions with asymptotic form

$$\psi_n \sim \frac{f_n(\theta,\varphi)}{r}\ e^{i\bar{k}_n\cdot\bar{r}} + e^{i\bar{k}_o\cdot\bar{r}}\ \delta_{on} \qquad (2\text{-}9)$$

The differential cross section for inelastic scattering in which the system goes from state o to state n is then

$$I_{on}(\theta,\varphi)\ d\Omega \ = \ \frac{v_n}{v_o}\ |f_n(\theta,\varphi)|^2\ d\Omega \qquad (2\text{-}10)$$

with v_o and v_n the velocities of relative motion in the two states. The differential cross section for elastic scattering is

$$I_{oo}(\theta,\varphi)\ d\Omega \ = \ |f_o(\theta,\varphi)|^2\ d\Omega \qquad (2\text{-}11)$$

A major difficulty is to obtain a complete orthogonal set of wave functions φ_{An} and/or φ_{Bn} which must be known in order to obtain Equation (2-7). The set of wave functions must contain bound state and continuum state wave functions. A complete set of exact wave functions is actually known only for one atom, the hydrogen atom. In all other cases they must be approximated. Most theoretical calculations to date have assumed the validity of Equation (2-7) even though the explicit wave functions subsequently used in the computation are not truly orthogonal. Unfortunately it is very difficult to reach any a priori conclusion as to the extent of the inaccuracy in the results caused by this approximation. Only by comparison with experimental results can any conclusions be reached.

Born's approximation considers the interaction between the colliding systems as a small perturbation to the total Hamiltonian of the system. This results in putting all terms other than the matrix element associated with the incident wave equal to zero so that Equation (2-7) becomes the single equation

$$(\nabla_r^{\ 2} + k_n^{\ 2})\ \psi_n(\bar{r}) \ = \ U_{no}\ e^{i\bar{k}_o\cdot\bar{r}} \qquad (2\text{-}12)$$

Using the Green's function

$$G(r,r_1) = -\frac{1}{4\pi}\frac{e^{\pm ik_n|\bar{r}-\bar{r}_1|}}{|\bar{r}-r_1|} \tag{2-13}$$

one obtains the solution with the asymptotic form of Equation (2-10) as

$$\psi_n(r) = +\delta_{on}\, e^{i\bar{k}_o\cdot\bar{r}} - \frac{1}{4\pi}\int U_{no}(\bar{r}_1)\frac{e^{i\bar{k}_o\cdot\bar{r}_1}\, e^{ik_n|\bar{r}-\bar{r}_1|}}{|\bar{r}-\bar{r}_1|}\, d\bar{r}_1 \tag{2-14}$$

This method of calculation has been used to calculate ionization cross sections for a bare nucleus and for a bare nucleus plus one (1s) electron incident on atomic hydrogen and helium for the case that $\frac{k^2h^2}{2m} \gg E_o$, where E_o is the internal energy of the struck atom.

A less drastic approximation is the distorted wave approximation. For this one assumes that transitions through intermediate states may be ignored so that only the matrix elements $U_{no}(=U_{on})$, U_{nn} and U_{oo} are considered, then the set of coupled Equations (2-7) become

$$(\nabla_r^2 + k_n^2 - U_{nn})\,\psi_n(\bar{r}) = U_{no}\,\psi_o(\bar{r}) \tag{2-15}$$

$$(\nabla_r^2 + k_o^2 - U_{oo})\,\psi_o(\bar{r}) = U_{on}\,\psi_n(\bar{r}) \tag{2-16}$$

An additional approximation may be made if U_{no} is small by putting the right hand side of Equation (2-16) equal to zero. This method has been used for atomic processes at low relative energy for which the Born approximation becomes inadequate.

The formulation presented here must be altered in order to deal with identical particles, but this presents only more numerical difficulty.

The Classical Approach of Gryzinski[7]

Gryzinski has given a classical theory of atomic cillisions in which he assumes that elastic scattering, ionization, excitation, and other inelastic interactions between charged particles and atoms can be described by a Coulombic type interaction between the incident ion and the atomic electrons, treated classically, and depend on the atomic electron's binding energy and momentum distribution treated quantum mechanically.

Gryzinski used the results of Chandrasekhar[8,9] in which the energy transfer between two colliding free particles moving arbitrarily with respect to each other and interacting through an inverse square force was calculated classically in terms of general kinematical parameters describing the collision.

Gryzinski has integrated Chandrasekhar's results over distributions of the collision parameters appropriate to the impact of fast ions on electrons orbiting about a fixed target atom to obtain $\sigma(\Delta E,\theta)$, the classical cross section for scattering of an incident particle in direction θ with change of energy ΔE. He has further obtained $\sigma(\Delta E)$, the classical cross section for the incident particle to have an energy change ΔE, without regard to θ.

The cross section for a collision with energy loss greater than U is

$$Q(U) = \int_{U}^{\Delta E_{max}} \sigma(\Delta E)\, d(\Delta E) \tag{2-17}$$

and similarly the cross section for an encounter with loss of energy in the interval $U_1 \leq \Delta E \leq U_2$ is

$$Q(U_2;U_1) = \int_{U_1}^{U_2} \sigma(\Delta E)\, d(\Delta E) \qquad (2\text{-}18)$$

Gryzinski asserts that the cross section for ionization of an atom is given simply by the classical cross section for transfer to the atomic electron, treated as a free particle but with a speed distribution appropriate to its bound initial state, of energy at least as great as the ionization potential. Thus the ionization cross section for an atom is

$$Q_j^{atom} = \sum_i \int_o^\infty N^i(v_e)\, Q(U_j^{(i)})\, dv_e \qquad (2\text{-}19)$$

where $N^i(v_e)$ is the velocity distribution of i shell electrons of the atom and $U_j^{(i)}$ is their ionization potential. For the simplest case, $N^i(v_e)$ is approximated by the single velocity obtained from the expectation value of the electron kinetic energy appropriate to electrons in the i shell.

Similarly, the cross section for excitation of the atom to the level n is represented as the classical cross section for transfer of energy at least as great as the excitation energy of level n but less than the excitation energy of any higher level. Thus the cross section for the excitation of the level n is

$$Q^n_{exc} = \sum_i \int_o^\infty N^{(i)}(v_e)\, Q(U^{(i)}_{n+1}\,;\,U^{(i)}_n)\, dv_e \qquad (2\text{-}20)$$

where $U_n^{(i)}$ and $U_{n+1}^{(i)}$ are the excitation energies of the levels n and n + 1 respectively from the shell i.

Quantal effects are thus considered only indirectly, by restricting the energy transfer to the electron to values compatible with the fact that it is bound in a quantized state, and by the use of an initial speed distribution for the electrons deduced from the quantum mechanical description of the initial state.

Agreement between this theory and experimental results for inelastically scattered electrons from molecular hydrogen is very good for the total cross section although it is relatively inaccurate for describing the angular distributions.[10,11] Agreement is excellent for ionization cross sections of hydrogen and helium by electrons. In light of some of the assumptions made the agreement between this theory and experiment is rather surprising.

CHAPTER III

PHENOMENA RELATED TO THE PASSAGE OF HELIUM IONS THROUGH A GAS

This chapter deals specifically with phenomena related to the passage of helium ions through a gas. To illustrate the multiplicity of possible events, a list of reactions for the case of fast singly-charged helium ions incident on molecular hydrogen is presented. A cross section notation is discussed and applied to these reactions. Definitions of total production cross sections and some charge-changing cross sections are given. Cross-correlation between the two types of cross sections are discussed. Particular theoretical calculations using the Born approximation are discussed, and a method is presented by which theory and experiment may be compared.

A list of reactions for the case of fast singly-charged helium ions incident on molecular hydrogen is presented below. The first symbol appearing on the left and right hand side of each equation denotes the fast incident particle before and after the collision, respectively. This particle may or may not experience a change in its charge state as the result of the reaction, but in any event theory and experiment show that most of the time it retains essentially all of its initial energy and its original direction of motion if the velocity of relative motion is large compared to the atomic orbital electron velocity, as was the case for this experiment. The second symbol on the left hand side of the equation denotes the target particle before the collision. The remaining terms on the right hand side represent the fragments of the target particle after collision plus any free electrons stripped from the incident projectile.

$$He^{+} + H_2^{o} \rightarrow He^{+} + H_2^{+} + e \qquad {}_{10}\sigma_{11}^{i} \qquad (3\text{-}1)$$

$$He^{+} + H^{+} + H^{o} + e \qquad {}_{10}\sigma_{11}^{id} \qquad (3\text{-}2)$$

$$He^{+} + H^{+} + H^{+} + 2e \qquad {}_{10}\sigma_{12}^{id} \qquad (3\text{-}3)$$

$$He^{+} + H^{+} + H^{-} \qquad {}_{10}\sigma_{10}^{id} \qquad (3\text{-}4)$$

$$He^{o} + H_2^{+} \qquad {}_{10}\sigma_{01}^{c} \qquad (3\text{-}5)$$

$$He^{o} + H^{+} + H^{o} \qquad {}_{10}\sigma_{01}^{cd} \qquad (3\text{-}6)$$

$$He^{o} + H^{+} + H^{+} + e \qquad {}_{10}\sigma_{02}^{cid} \qquad (3\text{-}7)$$

$$He^{++} + H_2^{o} + e \qquad {}_{10}\sigma_{20}^{s} \qquad (3\text{-}8)$$

$$He^{++} + H^{o} + H^{o} + e \qquad {}_{10}\sigma_{20}^{sd} \qquad (3\text{-}9)$$

$$He^{++} + H_2^{+} + 2e \qquad {}_{10}\sigma_{21}^{si} \qquad (3\text{-}10)$$

$$He^{++} + H^{+} + H^{o} + 2e \qquad {}_{10}\sigma_{21}^{sid} \qquad (3\text{-}11)$$

$$He^{++} + H^{+} + H^{+} + 3e \qquad {}_{10}\sigma_{22}^{sid} \qquad (3\text{-}12)$$

$$He^{++} + H_2^{-} \qquad {}_{10}\sigma_{2\bar{1}}^{c} \qquad (3\text{-}13)$$

$$He^{++} + H^{-} + H^{o} \qquad {}_{10}\sigma_{2\bar{1}}^{cd} \qquad (3\text{-}14)$$

$$He^{++} + H^{+} + H^{-} + e \qquad {}_{10}\sigma_{20}^{cid} \text{ or } {}_{10}\sigma_{20}^{sid} \qquad (3\text{-}15)$$

Reaction (3-1) is the simple ionization collision, while Reaction (3-5) is the simple charge-transfer event, and Reaction (3-8) is the simple stripping reaction. Reactions (3-5) through (3-15) are charge-changing collisions.

The same information contained in each reaction equation may be conveyed by use of a generalization of a cross section representation introduced by Hasted.[12] We shall let ${}_{ab}\sigma_{mn}$ represent the cross section for the reaction in which a and m are the initial and final charges respectively of the fast incident particle, while b and n are the initial and final charges respectively of the target particle. A superscript c, i, d, or s indicates charge transfer, ionization, dissociation, and stripping, respectively. In the preceding list of reactions the cross section representing each reaction is given following it.

As has been stated in Chapter I, a given experiment measures the sum of some group of the individual cross sections. The cross sections measured in this research are denoted by σ_+ and σ_-, where σ_+ represents the total cross section for the production of slow positive ions and σ_- represents the total cross section for the production of free electrons and negative ions. These cross sections may be represented for the collision of He^+ on H_2 as follows:

$$\sigma_+ = \left[{}_{10}\sigma_{11}^{i} + {}_{10}\sigma_{11}^{id} + 2\,{}_{10}\sigma_{12}^{id} + {}_{10}\sigma_{10}^{id}\right] + \left[{}_{10}\sigma_{01}^{c} + {}_{10}\sigma_{01}^{cd} + 2\,{}_{10}\sigma_{02}^{cid}\right] + \left[{}_{10}\sigma_{21}^{si} + {}_{10}\sigma_{21}^{sid} + 2\,{}_{10}\sigma_{22}^{sid} + {}_{10}\sigma_{20}^{cid}\right] \qquad (3\text{-}16)$$

and

$$\sigma_- = \left[{}_{10}\sigma^{i}_{11} + {}_{10}\sigma^{id}_{11} + 2\,{}_{10}\sigma^{id}_{12} + {}_{10}\sigma^{id}_{10}\right] + \left[{}_{10}\sigma^{cid}_{02}\right] + \left[{}_{10}\sigma^{s}_{20}\right. \quad (3\text{-}17)$$

$$\left. + {}_{10}\sigma^{sd}_{20} + 2\,{}_{10}\sigma^{si}_{21} + 2\,{}_{10}\sigma^{sid}_{21} + 3\,{}_{10}\sigma^{sid}_{22} + {}_{10}\sigma^{c}_{2\bar{1}} + {}_{10}\sigma^{cd}_{2\bar{1}} + 2\,{}_{10}\sigma^{cid}_{20}\right]$$

It is now evident that what has been measured in this research is the weighted sum of individual cross sections. In a "thin" target experiment these cross sections are calculated from the relations

$$\sigma_+ = (I^+/I_i)(1/n\ell) \text{ cm}^2/\text{molecule} \quad (3\text{-}18)$$

$$\sigma_- = (I^-/I_i)(1/n\ell) \text{ cm}^2/\text{molecule} \quad (3\text{-}19)$$

where I^+ and I^- are the positive and negative currents collected from a collision region of length ℓ by traverse 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 the Appendix.

The cross sections for the incident He^+ ion to pick up an electron or be stripped of its electron are denoted by σ_{10} and σ_{12}, respectively, where the first figure in the subscript represents the charge state of the incident ion before collision and the second its charge state after collision. These cross sections, written in terms of the individual cross sections (3-1) through (3-15) for He^+ incident on hydrogen, are:

$$\sigma_{10} = {}_{10}\sigma^{c}_{01} + {}_{10}\sigma^{cd}_{01} + {}_{10}\sigma^{cid}_{02} \quad (3\text{-}20)$$

and

$$\sigma_{12} = {}_{10}\sigma^{s}_{20} + {}_{10}\sigma^{sd}_{20} + {}_{10}\sigma^{si}_{21} + {}_{10}\sigma^{sid}_{21} \quad (3\text{-}21)$$

$$+ {}_{10}\sigma^{sid}_{22} + {}_{10}\sigma^{c}_{2\bar{1}} + {}_{10}\sigma^{cd}_{2\bar{1}} + {}_{10}\sigma^{cid}_{20}$$

It is true in general that for singly-charged helium ions incident on any gas that the difference between σ_+ and σ_- is the same as the difference between σ_{10} and σ_{12}. A check of the present measurements against charge-transfer experiment measurements may therefore be made.

For four of the gases studied the cross sections σ_{10} and σ_{12} have been measured previously over at least part of the energy range of this experiment. The experimental technique used in the measurement of σ_{10} and σ_{12} is the measurement first of the ratio of the two cross sections by a thick target beam equilibrium method and second the measurement of one of them by a beam attenuation method.[2]

The gross apparent ionization cross section σ_i is the quantity which may be directly compared with existing theoretical and experimental data and is defined as the cross section for single ionization plus twice the cross section for double ionization plus three times the cross section for triple ionization, etc. It is therefore necessary to reduce σ_+ and σ_- to σ_i. This cross section for the specific reaction of He^+ incident on H_2 is given by:

$$\sigma_i = {}_{10}\sigma^{i}_{11} + {}_{10}\sigma^{id}_{11} + 2\,{}_{10}\sigma^{id}_{12} + {}_{10}\sigma^{id}_{10} \tag{3-22}$$

$$= \sigma_+ - \sigma_{10} - \sigma_{12} - {}_{10}\sigma^{cid}_{02} - {}_{10}\sigma^{sid}_{22} + {}_{10}\sigma^{s}_{20} + {}_{10}\sigma^{sd}_{20} + {}_{10}\sigma^{c}_{2\bar{1}} + {}_{10}\sigma^{cd}_{2\bar{1}} \tag{3-23}$$

$$= \sigma_- - 2\,\sigma_{12} - {}_{10}\sigma^{cid}_{02} - {}_{10}\sigma^{sid}_{22} + {}_{10}\sigma^{s}_{20} + {}_{10}\sigma^{sd}_{20} + {}_{10}\sigma^{c}_{2\bar{1}} + {}_{10}\sigma^{cd}_{2\bar{1}} \tag{3-24}$$

Although the values of σ_+, σ_-, σ_{10}, and σ_{12} have been determined experimentally for several of the gases studied, the cross sections for the individual reactions are not known at present, therefore reasonable estimates must be made in order to find an approximate σ_i.

Not all atomic systems form negative ions, but those that do usually form then with low binding energy. It is expected that if the collision is hard enough to strip the bound electron from the incident helium ion then it is probable that no negative ion will be formed. This assumption cannot be proved at present, but it may possibly be justified by the fact that some of the cross sections involving formation of negative ions have been measured at much lower energies than the present experiment and have generally been found to fall off rapidly with increasing energy. All cross sections involving the formation of negative ions will be considered negligible.

It will be convenient to define a quantity "a" as the ratio to σ_{12} of the cross section for simple stripping events including dissociation of molecular targets.

For the particular reaction of He^+ incident on hydrogen

$$a = \frac{{}_{10}\sigma^{s}_{20} + {}_{10}\sigma^{sd}_{20}}{\sigma_{12}} \tag{3-25}$$

and

$$\sigma_i = \sigma_+ - (\sigma_{10} + \sigma_{12}) + a\,\sigma_{12} - {}_{10}\sigma^{cid}_{02} - {}_{10}\sigma^{sid}_{22} \tag{3-26}$$

$$= \sigma_- - 2\,\sigma_{12} + a\,\sigma_{12} - {}_{10}\sigma^{cid}_{02} - {}_{10}\sigma^{sid}_{22} \tag{3-27}$$

It is argued that "a" is small, for if the collision is "hard" enough to strip the bound electron from the incident helium ion then it is highly probable that the target system will also be ionized. The ionization potential of the electron of He^+ is 54.4 volts and the ionization potentials of the outer electrons of all target gases studied in this research are less than 25 volts. It is then assumed that "a" is equal to zero. The remaining individual cross sections in Equations (3-26) and (3-27) represent complex events and it seems quite likely that they are improbable and contribute in only a minor fashion. Therefore the apparent ionization cross section for incident He^+ projectiles on the target gases were obtained by the relations

$$\sigma_i \simeq \sigma_+ - (\sigma_{10} + \sigma_{12}) \qquad (3\text{-}28)$$

$$\simeq \sigma_- - 2\,\sigma_{12} \qquad (3\text{-}29)$$

For completeness it is necessary to examine here the process used for obtaining σ_i from σ_+ and σ_- for incident He^{++} projectiles on various target gases. The apparent cross section for ionization is given by

$$\sigma_i = \sigma_+ - \sigma_{21} - \sigma_{20} + x \qquad (3\text{-}30)$$

$$= \sigma_- + x \qquad (3\text{-}31)$$

where x represents a complex reaction and will be assumed small and set equal to zero. It is also seen that $\sigma_+ - \sigma_- = \sigma_{21} + \sigma_{20}$ with no approximations.

Theoretical calculations pertinent to this research have been made for a bare nucleus and for a bare nucleus plus one electron incident on atomic hydrogen and helium.

Bare Nucleus Incident On Hydrogen

Bates and Griffing[13] have calculated the cross section for the atomic process

$$X^{Ze} + H^{o}(1s) \rightarrow X^{Ze} + H^{+} + e \qquad (3\text{-}32)$$

using the Born approximation. A method of obtaining an approximate gross apparent ionization cross section for the molecular process has been indicated in reference 13. Although the results calculated for Equation (3-32) were presented only in graphical form rather than in explicit analytic form, the following generalization was made:

If a fast point charge of charge Z_b collides with a nucleus 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 13):

$$\sigma_i = \left(\frac{Z_b}{\Delta E}\right)^2 f\left(\frac{M\Delta E}{E}\right) \qquad (3\text{-}33)$$

in which:

ΔE 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 (3-33) 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 Equation (3-33) there is an explicit dependence on the ionization energy ΔE 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 point charge of energy E will be twice the given atomic cross section for the incident point charge 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 approximated gross experimental ionization cross section.

Bare Nucleus Incident on Helium

Theoretical calculations in the Born approximation of the cross sections for ionization and simultaneous ionization and excitation of helium by a point charge have been made by Mapleton.[14] He assumed that the helium electronic 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:	$Z_2 = 2,$	$Z_3 = 1$
Case II:	$Z_2 = 2,$	$Z_3 = Z_1$
Case III:	$Z_3 = Z_1$	for the $\ell = 0$ term of the wave function of the final state positive energy electron
	$Z_3 = 1$	for the $\ell > 0$ 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.

Ionization cross sections for He^{++} ion impact and electron impact on helium have been calculated by Erskine[15] through an application of the Born approximation.

The foregoing calculations imply that the ionization cross section for incident He^{++} ions should be four times the cross section for incident protons of the same velocity.

Bare Nucleus Plus One Electron Incident On Hydrogen

The gross ionization cross section for the reaction:

$$Y^{(Z-1)e}_{(1s)} + H(1s) \rightarrow Y^{(Z-1)e}_{(1s)} + H^{+} + e \qquad (3\text{-}34)$$

where Y represents an ion or atom consisting of a bare nucleus plus one electron in the 1s electronic state, having net charge (Z-1)e, has been calculated theoretically.[13,16] Again if a comparison between the present experiment and theory is to be made the cross sections for the atomic process must be scaled in order to obtain the cross sections for the molecular process. The earlier scaling procedure cannot obviously be easily applied for this case because the theoretical cross section is given by a sum of terms where the individual terms were not known. Boyd et al.[16] have suggested only that comparison between theory and molecular experimental results be made by regarding each molecule as two atoms, therefore just doubling the atomic cross section. Such a procedure would ignore the fact that the binding energy of the electron in the molecule is greater than it is in the atom. Application of the procedure described in the section "Bare Nucleus Incident On Hydrogen" to take account of the difference cannot be justified on the basis of any equations displayed in References 13 or 16. However, such a procedure was applied to this case, and the result was found to be in very good agreement with experimental results.

CHAPTER IV

EXPERIMENTAL EQUIPMENT AND METHOD

The objective of this research was the measurement of the cross section for the production of slow positive ions and free electrons for helium ions incident on helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide. The energy of the incident particles ranged from 0.133-1.00 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 differentially pumped collimating apertures 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 ion-producing 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 simultaneous electrometer measurements of the electron, ion, and the incident beam current.

A schematic drawing of the apparatus is given in Figure 1. 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

The ion source of the Van de Graaff had two gas inlet lines, each equipped with a thermomechanical leak. The two gases used in the ion source were molecular hydrogen and helium. The ion source, which is a RF excited source, provided ample beams of H^+ ions and He^+ ions but produced essentially no yield of He^{++} ions. The time required to switch from one beam to another was a matter of a few minutes.

The beam from the Van de Graaff entered the apparatus at the left hand side of Figure 1. It was then deflected through 90° in the analyzing magnet, which assured that it consisted essentially only of the desired ions. The beam ion energy was stabilized by electronic regulation of the accelerator voltage to maintain equal currents on the two stabilizer slit edges, 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 $H^3(p,n)He^3$, using a tritium-zirconium target.

Gas Cell

Since the ion source of the Van de Graaff provided only a minimal He^{++} beam, it was necessary to use the He^+ beam from the Van de Graaff

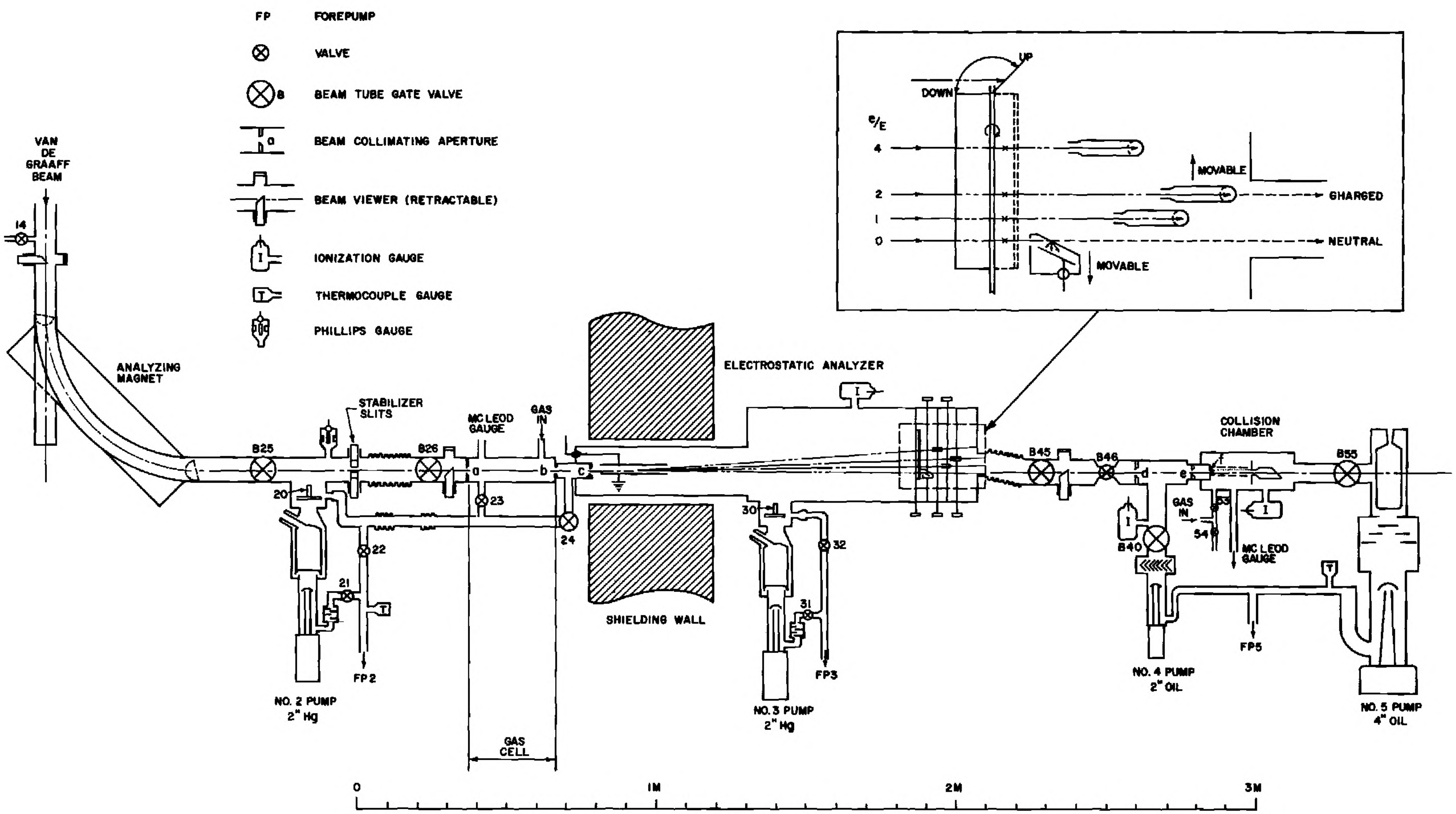

Figure 1. Schematic View of Apparatus.

accelerator to obtain an He^{++} beam. This was accomplished by passing the He^{+} beam through a gas cell which contained argon gas at pressures which ranged from 1.0 to 7.0 x 10^{-3} Torr. The He^{+} beam underwent charge-changing collisions so that the beam leaving the gas cell consisted of He^{o}, He^{+}, and He^{++}.

The apertures "a" and "b" of Figure 1 define the length of the gas cell. These apertures were round and knife-edged with a diameter of 1/16 inch. They were machined through 1/4-inch-thick brass plates which, except for the apertures, formed essentially vacuum-tight closures of the beam tube. With this arrangement, the pressure in the accelerator vacuum system remained within tolerable bounds only when the pressure in the gas cell remained below 7 x 10^{-3} Torr.

Gas entered the cell continually through a variable leak and was pumped continually through the apertures "a" and "b." The valve 23 of Figure 1 permitted the gas cell to be pumped to pressures of approximately 3 x 10^{-6} Torr with the gas inlet closed. Valve 23 was normally closed when working with the He^{++} beam. The pressure in the gas cell was measured with a McLeod gauge.

A differentially pumped vestibule was provided following the gas cell and is indicated in Figure 1. The pumping provided on this chamber sufficed to allow the pressure beyond aperture "c" to be kept below 2 x 10^{-5} Torr with gas present in the gas cell at the maximum working pressure. Aperture "c" was round and knife-edged and was machined through a 1/4-inch brass plate, which except for the aperture was essentially a vacuum-tight closure of the beam tube. The aperture had a diameter of 3/32 inch.

Electrostatic Analyzer Section

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. For clarity the electrostatic analyzer section and the collision chamber are shown rotated 90° about the beam axis into plane view in Figure 1. Thus the beam deflections produced by the analyzer are actually in the horizontal plane, rather than verticle as they appear in the figure. 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. This potential difference was maintained by a Hamner High Voltage Power Supply Model N-413. With the "normal" operating voltage of 2400 volts applied to the plates, the three components of a 1-MeV helium beam (He^{o}, 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 could 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 deflector assembly are so constructed that they could be rigidly assembled and aligned optically before they were installed in the vacuum housing of the analyzer section.

Provision was 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 locations by means of the fluorescence of the glass. The arrangement is shown in the insert in Figure 1, and Figure 2 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 Figure 1, 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 bellows. 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, or 2; see Figure 1). In Figure 1 the collision chamber is shown aligned with the undeflected neutral beam. For the He^{++} measurements the chamber is placed in line with the $e/E = 2$ position. Figure 3 is a photograph of the portion of the apparatus to the right of the shielding wall in Figure 1, viewed from the opposite side. The mechanical arrangements provided for the horizontal movements of the collision chamber can be seen as well as a jackscrew arrangement provided in the supports to facilitate vertical alignment adjustments. In Figure 3 the collision chamber is shown offset toward the camera to align with the $e/E = 2$ beam position for He^{++} measurements.

When the apparatus is aligned as described for He^{++} measurements, application of the "normal" 2400 volts to the deflector plates directs 1.0 MeV He^{++} ions into the collision chamber along the $e/E = 2$ trajectory,

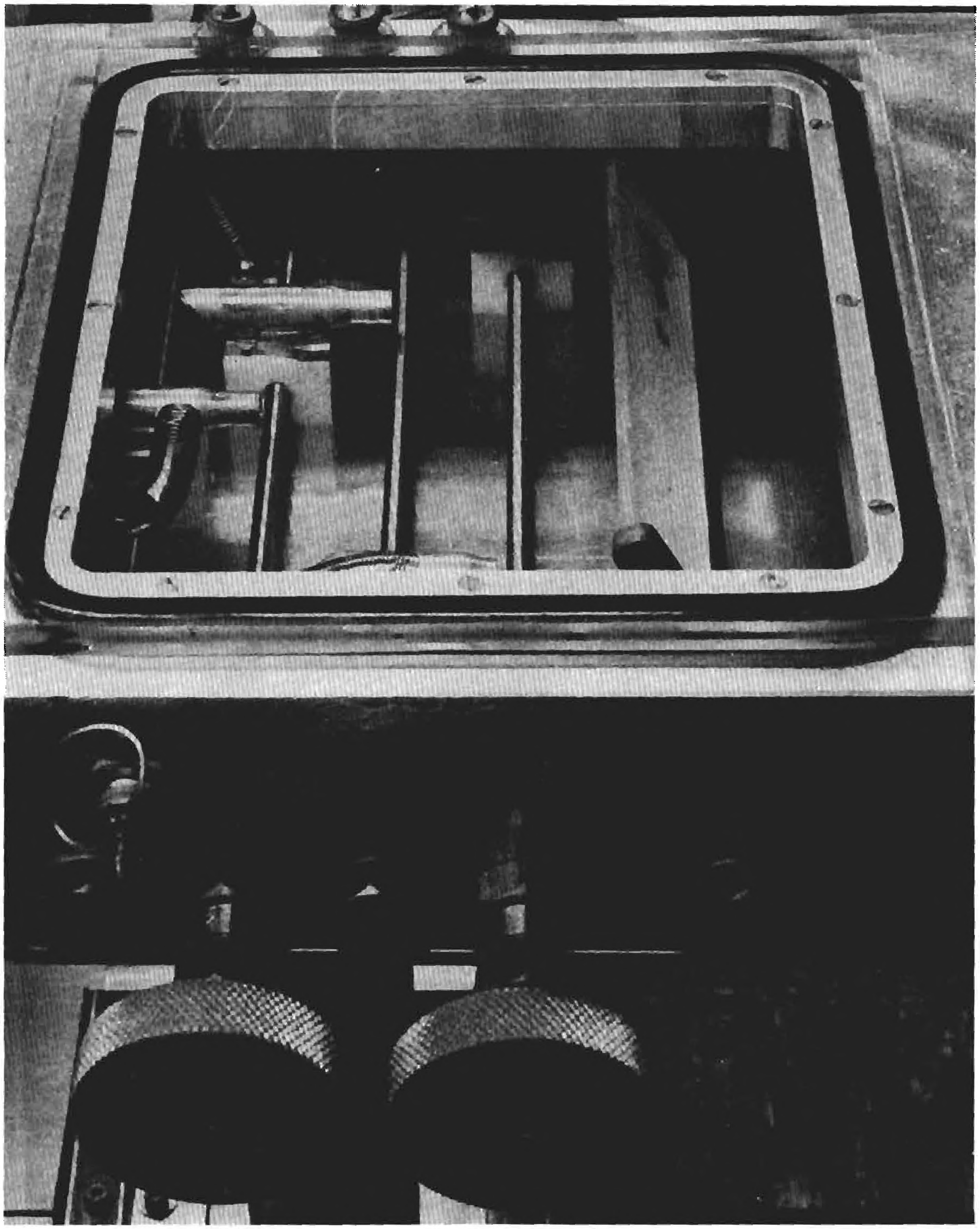

Figure 2. Interior View of Electrostatic Analyzer with Faraday Cups.

Figure 3. Exterior View of Electrostatic Analyzer and Collison Chamber.

while the He^{+} component is monitored by the Faraday cup at $e/E = 1$. By simply doubling the voltage, one can direct the He^{+} beam into the chamber, while collecting and monitoring the He^{++} component at the $e/E = 4$ position. 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 were readily checked against well established H^{+} and He^{+} results without disturbing the mechanical alignment of the apparatus. This feature proved 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 7×10^{-3} Torr could be used in the gas cell. Unfortunately the presently available pumping speed on the small chamber between "b" and "c" (Figure 1) 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 Figure 1) shall not exceed 1 per cent. 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, so that the minimum energy attainable with only a 1 per cent beam contamination is

0.50 MeV. The maximum permissible pressure versus beam energy is presented in Figure 4.

The pressure in the analyzer section was read with a Veeco type RG-75 Ionization Gauge. Since the nominal calibration of the ionization gauge is for nitrogen, each pressure reading was corrected for argon, since this was the gas used in the gas cell.

The Collision Chamber and Its Associated Differentially Pumped Collimator

For reference in the following discussion collimating apertures are designated by the letters with which they are labeled in Figures 1 and 5. Aperture designs and pumping speeds were chosen so that the greatest part of the pressure drop from the target region would occur at "f," so that the effective beginning of the flight path in the target gas began there. The total path length from there to the entrance of the Faraday cup was about 5 inches. Apertures "d" and "e" each have circular knife-edged openings 1/16-inch in diameter, and the minimum opening in "f" is a knife-edged hole slightly over 3/32-inch in diameter. Thus the collimation of the beam was defined by "d" and "e," and only a few scattered particles impinged on the edge of "f." The opening in "f" presented a small solid angle to the secondaries produced at "e," and very few should have passed through. However, as noted above, "f" is designed to have a relatively large pumping impedance, while the thin plate containing "e" is perforated with three large off-center holes to present a small pumping impedance.

As is indicated in Figure 5 the portion of the apparatus that contains the three apertures "d," "e," and "f" can be rigidly assembled before insertion into the collision chamber, so that all three apertures could be

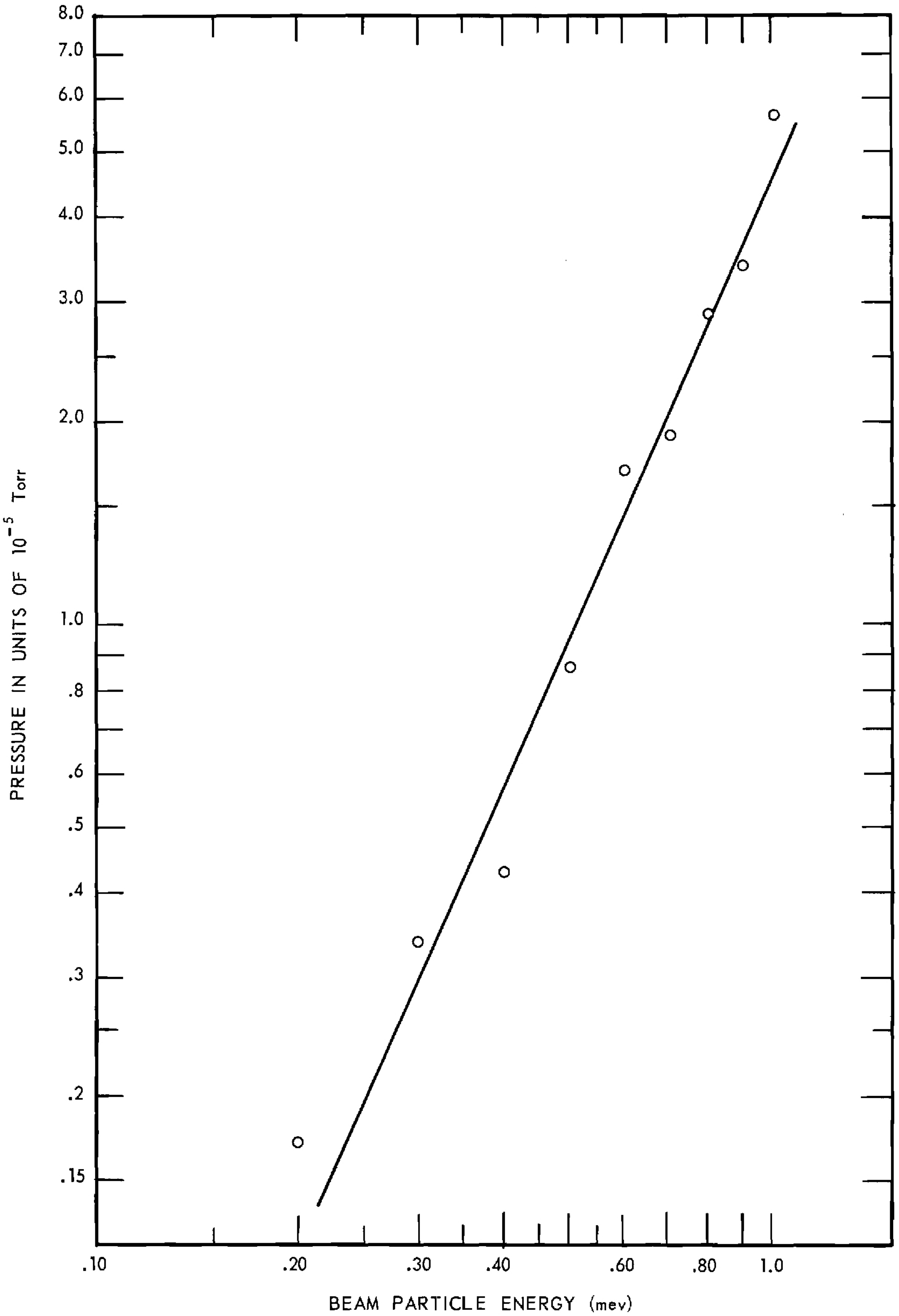

Figure 4. Maximum Permissible Pressure in Electrostatic analyzer Section for One Per Cent He^{++} Beam Contamination.

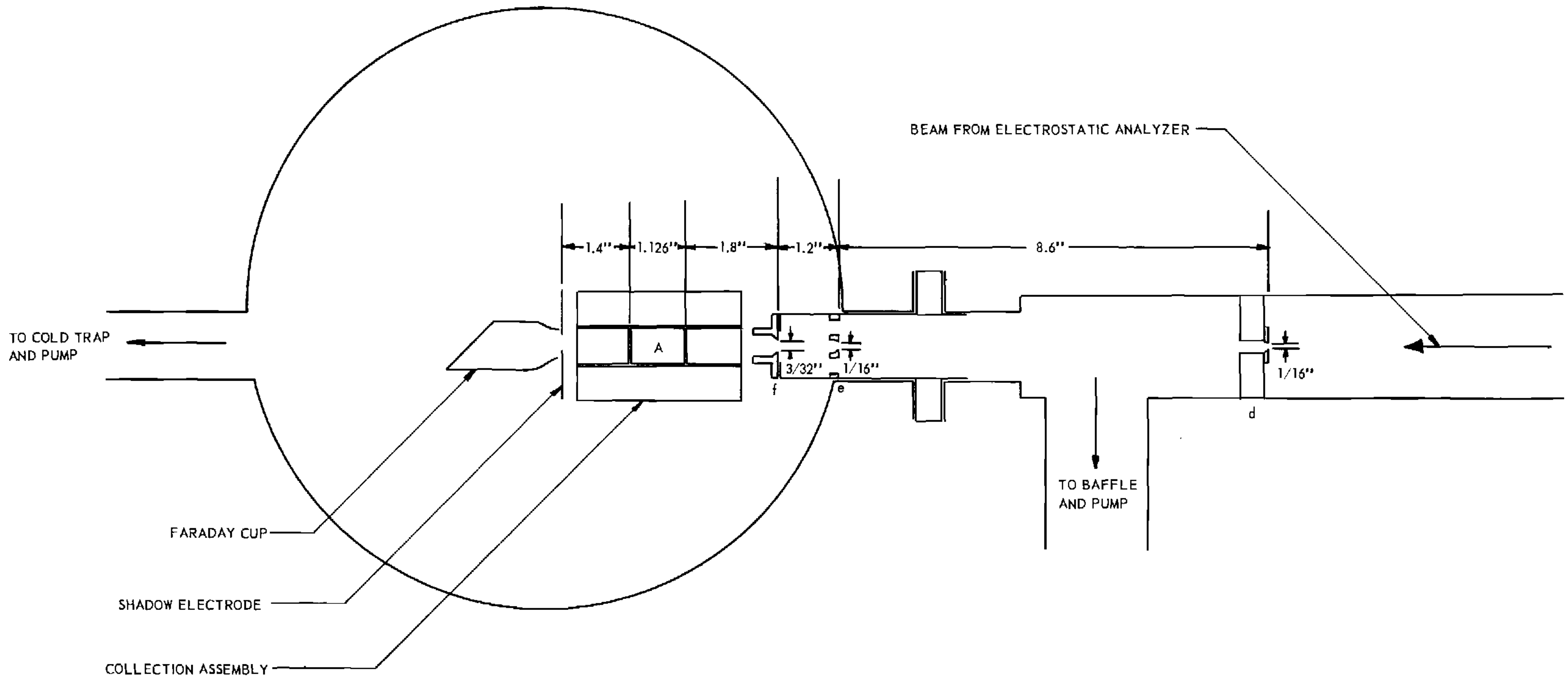

Figure 5. Schematic View of Collison Chamber.

accurately aligned optically. The pumping between apertures "d" and "f" was provided by a two-inch oil diffusion pump topped by a water-cooled baffle.

A photograph of the open collision chamber is shown in Figure 6. The collimated beam entered from the right and passed between the two electrode assemblies and into a Faraday cup. Electrical connections from the electrodes passed to the outside through seven kovar-glass seals in the rear wall of the chamber. The chamber was evacuated by the four-inch baffled and trapped oil diffusion pump at the left. A one-quart Stanley stainless steel vacuum bottle was installed between the pump and the valve to serve as a liquid nitrogen cold trap. An ionization vacuum gauge was attached to the chamber at a hole visible in the lower part of the chamber. The pressure could not be monitored continuously because the ionization gauge could not be left on while any ionization currents were being measured because electrons were "sucked" from the gauge on to the collection plates. A cold-trapped McLeod gauge was connected to a hole, hidden by the electrode assemblies, that looked directly into the space between the assemblies. A CEC GM-100 McLeod Gauge was used as the absolute pressure measuring device during the early part of these measurements involving incident He^+ ions while a more sensitive CEC GM-110 McLeod Gauge was used during the measurements involving He^{++} ions. Each McLeod gauge was read with a cathetometer. Target gases were admitted through a mechanical leak after being passed through a cold trap.

The gate valve B55 of Figure 1 could be used as a throttling valve to permit higher gas pressures in the collision chamber without an excessive gas throughput, which might give rise to pressure gradients in the

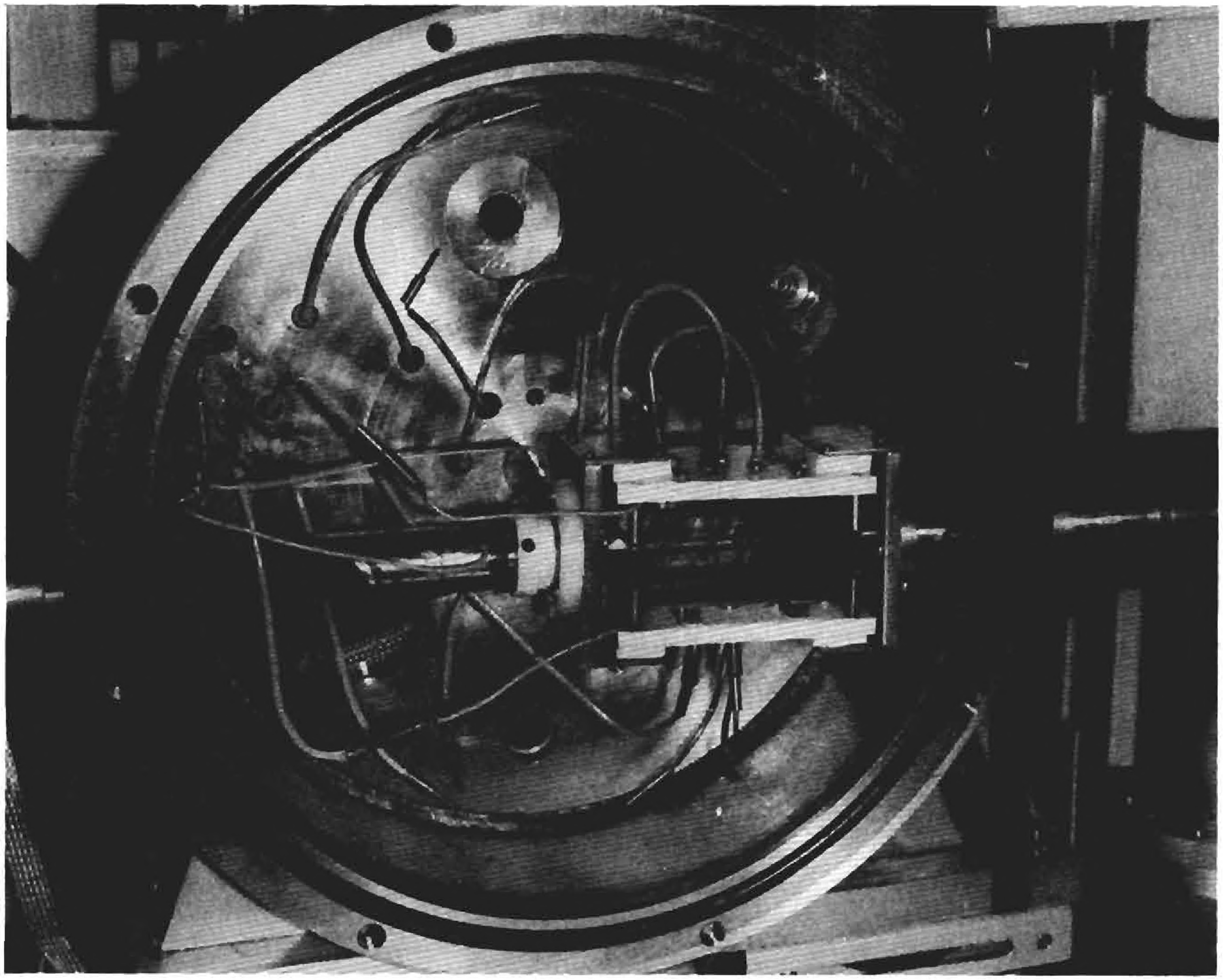

Figure 6. Interior View of Collison Chamber.

collision chamber and consequent uncertainties in the effective gas density in the collision region. Tests were made to insure that there were no gradients. The four-inch diffusion 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 0.5 to 10.0 x 10^{-4} Torr simply by adjusting the input rate. The purpose 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 5 to 10 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 gauge to have an average value of almost 3 x 10^{-6} Torr, 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 was unknown.

The target gas pressures ranged from 1.0 to 10.0 x 10^{-4} Torr for He^+ ions incident on helium and hydrogen, the gases with the smallest cross sections. For the other gases the upper limit on the highest pressure was less because the cross sections were correspondingly larger. With the installation of the more sensitive McLeod gauge the pressure could be read accurately to lower pressures and the pressure range for the measurements involving He^{++} ions incident on helium and hydrogen was 0.5 to 5.0 x 10^{-4} Torr.

Measurement of the Incident Beam Intensity I_i

Two different Faraday cups were used at different times to collect the incident ions after they had traversed the collision volume. One was a bottled-shaped copper cup whose diameter was smallest at the open neck. The 1/2-inch inside diameter of the neck subtended an angle of 6.5° at the entrance aperture, "f," and about twice that angle at a point on the beam axis at the center of the effective collision volume. The second was a deep copper cylinder having an entrance aperture of 1/2-inch and containing a wad of steel wool to serve as "electron velvet," that is, an essentially "black" absorber for the ion beam and the secondary electrons it produces. The second cup was installed midway in the measurements to deal with what appeared to be difficulties with secondary electrons and/or X-ray photons generated by impact of the beam within the cup. Both theoretical and experimental evidence indicated that only a few of the fast incident ions that have a collision would scatter more than a few degrees. With the "thin target" gas density used in these experiments, fewer than 4 per cent of the incident ions underwent any sort of ion-producing collisions, and the number undergoing large angle elastic scattering collisions should have been negligible. It was expected that far less than 1 per cent of all incident particles would fail to enter the collection cup.

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. It was found that a suppression voltage of 20 to 67-1/2 volts was sufficient to produce saturation in the measured value of the incident current. The convenient value of 67-1/2 volts was used throughout the measurements.

The Collector Assemblies and Electrometers

Preliminary measurement of the cross sections σ_+ and σ_- were made for He^+ on the target gases hydrogen and helium using the apparatus described in the thesis of J. W. Hooper.[17] The cross sections for the other target gases were about an order of magnitude larger than those for hydrogen and helium and could not be measured using this collection assembly while keeping thin target conditions without going to impracticably low target gas pressures. The above mentioned collection assembly was miniaturized to reduce the length of the flight path of the incident beam in the target gas. The cross sections σ_+ and σ_- for He^+ ions on the target gases hydrogen and helium were remeasured using the miniaturized collection assembly. The results obtained with the miniaturzied structure agreed quite well with those gotten using the larger structure after certain problems were solved.

The miniaturized collector assembly is described below. A diagram of one of the slow-particle collector assemblies is shown in Figures 5 and 8.

The collector plate had five segments, each separately mounted to the rigid 1/2-inch teflon backing, with its front surface 1/4-inch in front of the backing. The center segment was cut to an accurate length of 1.106 ± 0.001 inches in the beam direction, and all segments were accurately spaced 0.010 inch apart. All five 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 the center segment was 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" of the target gas from which the ions were drawn was the rectangular parallelepiped defined by the active segment 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.

In front of the positive ion collector assembly was placed a grid consisting of 0.004-inch diameter stainless steel wires strung 0.100 inch apart on a brass frame, and spaced 1/4-inch in front of the collector plate surface. The grid was held negative with respect to the collector to suppress the emission of secondary electrons. The other plate assembly which was held positive to collect electrons and negative ions did not require a suppressor. The photograph of the collection assembly in Figure 6 was taken while a grid was in front of the electron collector. After this photograph was made this grid was removed and the electron collector plates were moved in toward the beam axis, so that the negative ion collector plates and the grid on the positive ion collector were symmetrical about the beam axis and 1/2-inch apart. The ion transmission of the grid was assumed to be essentially equal to its geometric transmission, which was 96 per cent.

A fraction of the "slow" ions produced by energetic helium ions might in fact have had substantial energies of up to 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. The collection field was determined by the potentials of the suppressor grid and the electron collector. These were maintained at potentials of equal magnitude but opposite sign with respect to the grounded chamber so that the beam traveled the zero equipotential. This magnitude will hereafter be designated as V_c (c for "collection"). The positive ion collector plate was positive with respect to its grid by an amount designated as V_s(s for "suppression"). Thus the positive-ion collector was at the negative potential $-(V_c - V_s)$.

A number of difficulties were encountered in choosing suitable values of V_c and V_s. They had to be chosen large enough that the collected currents would show saturation. Verification checks were made by remeasuring the cross sections for incident protons on hydrogen and helium, for comparison with well established older results. The values that were obtained for σ_+, the apparent cross section for the production of slow positive ions, were found to be in good agreement. However, the values for σ_- computed from the collected electron currents were at first found to be unsatisfactory. Measurements of the cross sections involving incident helium ions were measured subsequent to solution of this problem.

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 per cent. 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 the measured ionization cross sections;[18] the expected equality of the currents had been confirmed repeatedly in earlier work.[17]

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 construction of the beam collimator. 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. If the collection field were to be made great enough, all these secondaries could be deflected to the guard electrode before they reached the active electron collector.

Alternatively, if the collection field were to be made sufficiently small, most of the fast secondaires 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.[17] In Figure 7, I^+/I_i and I^-/I_i are plotted versus collection voltage. It was found that the electron current saturates for potentials of about 90 volts, and displays a satisfactory plateau in the region from 80 volts to about 160 volts. The aforementioned rise sets in only for potentials above 160 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 per cent for incident protons at energies near 1 MeV. The cross sections obtained for incident protons were now in entirely satisfactory agreement with older results.[17]

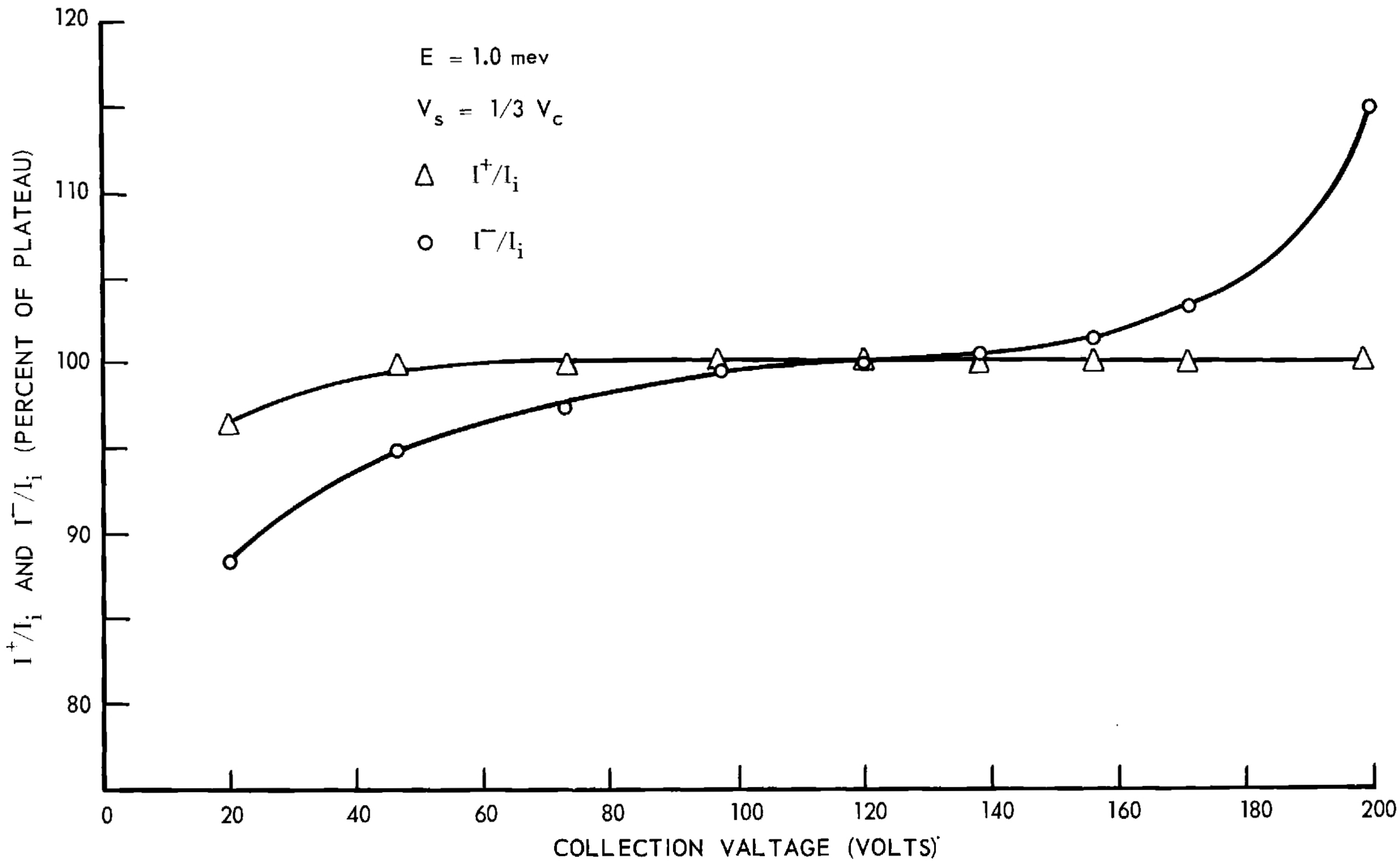

Figure 7. Apparent Ion and Free Electron Currents Versus Collection Voltage for H^+ Incident on H_2.

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 120 volts appears to be satisfactory for most cases, but was rechecked at frequent intervals in the experiment.

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. The number of these electrons is only about 15 per cent of the number of slow electrons liberated in the gas by ionization collisions, but this current in turn is never more than 4 per cent of the incident beam. The beam contamination amounts at most to a fraction of 1 per cent due to both charge-changing collisions and fast electrons. 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.

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 (2×10^{-12} amperes) encountered in the measurements described. A Keithley model 415 electrometer was used to measure I_i. The case of this electrometer was grounded.

The most serious source of noise in these experiments came directly from the behavior of the incident ion 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 shunting capacitors in the meter circuits of the electrometers were added to reduce the meter jitter. The meters were in close physical proximity so that all could be seen at the same time. The ratios I^+/I_i and I^-/I_i could be observed to an estimated 4 per cent maximum uncertainty, including both reading error and the inherent uncertainty of the electrometers. The roles of the two Keithley model 410 electrometers were interchanged periodically to ascertain if any systematic error had developed. These electrometers were returned to the factory midway in the experiment for recalibration.

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 double concentric type that would permit the same arrangement as in the cables.

Leakage currents, while not strictly ohmic, were small and steady and varied with collection 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.

The arrangement of the high-voltage connections seen in Figure 8 may be summarized as follows:

The central segment of each collector assembly had a separate lead. The remaining four outer guard segments were connected electrically. The grid of the positive ion collector had a separate lead. All leads passed out of the vacuum through separate kovar-glass seals, and through separate doubly shielded cables to a lucite patch board inside the electrometer cage.

The high-voltage tap of the polarizing battery pack was connected to a 5 megohm potentiometer. The center tap was connected directly to the electrometer frame and to the inner shields of the two leads from the guard and active segments of the collector. The physical arrangement was such as to avoid any "loops" for pickup. The leads from the outer guard

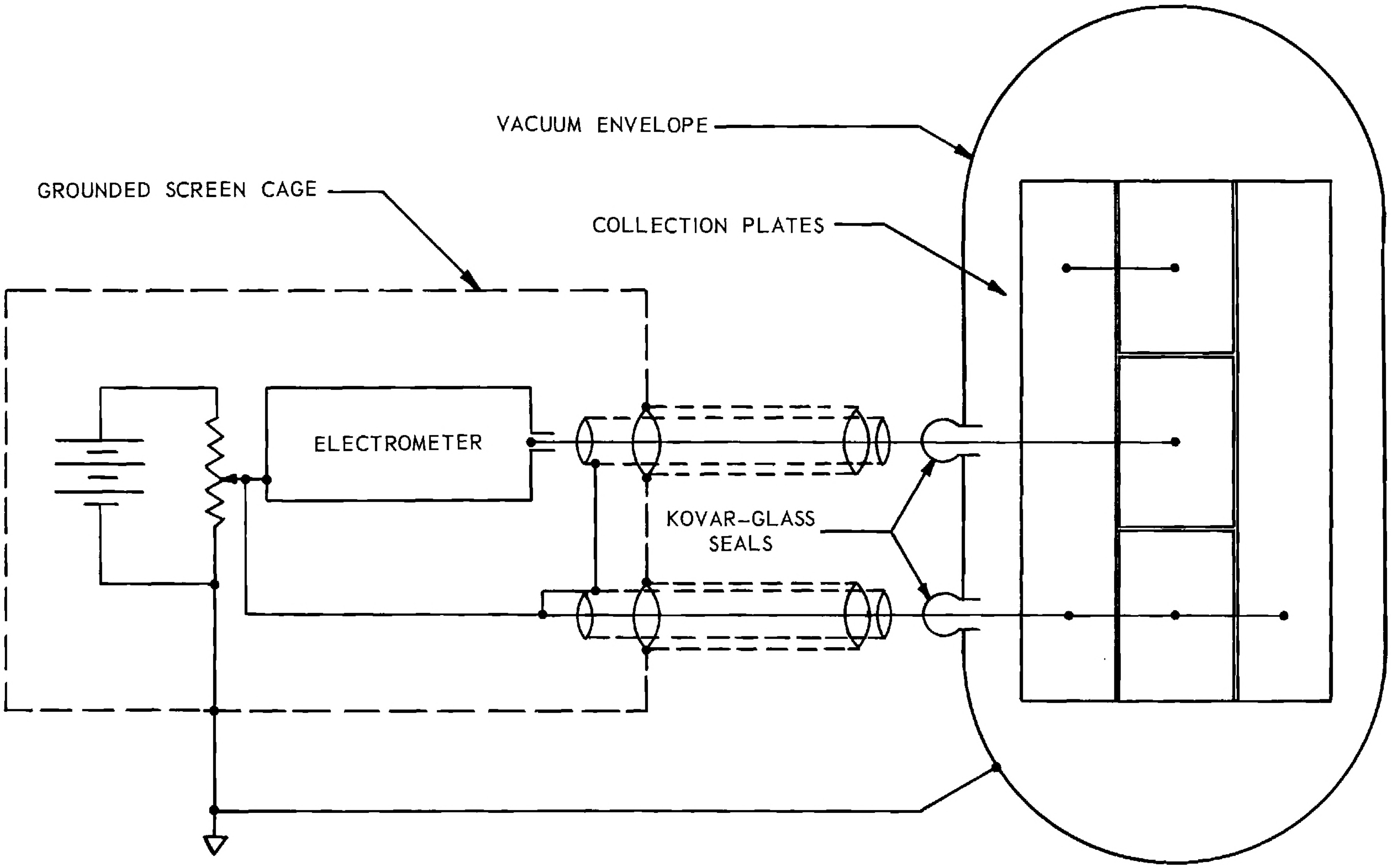

Figure 8. Schematic of Electrical Connections.

segments were also connected directly to the center tap of the 5 megohm potentiometer.

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 segment had essentially the same potential as the guards.

CHAPTER V

EXPERIMENTAL RESULTS

Summary of Experimental Method

The cross sections for the production of slow positive ions and free electrons for He^{+} ions incident on helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide were measured for incident particle energies over the range from 0.133 to 1.00 MeV and similar cross sections were measured for He^{++} ions incident on helium and hydrogen for incident particle energies over the range from 0.50 to 1.00 MeV. The incident ion energy was determined by 90° deflection in a regulated magnetic field, whose value was measured with a precision gaussmeter. The slow ion and electron currents 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 0.50×10^{-4} Torr to an upper limit of 10.0×10^{-4} Torr for gases with small cross sections. The effective collision volume was determined by the use of guard structures around the collector electrodes. Collection potentials of plus and minus 90 to 160 volts were used for the bulk of the measurements. A suppression potential of 30 to 50 volts was used between the positive ion collector and its associated grid.

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 1 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. The target gases were admitted through a mechanical leak subsequent to liquid nitrogen or dry ice and acetone trapping.

The actual pressure of the background gas could not be determined because of uncertainty as to its composition. The pressure indicated by an ionization gauge, using the calibration for nitrogen, ranged up to 3×10^{-6} Torr. However the pressure indicated by the McLeod gauge was always less than 5×10^{-7} Torr. It was concluded that the bulk of the background consisted of condensible vapors from gaskets, pumps, etc., rather than of leaking air or permanent gases outgassed from surfaces. Such condensible gases would be expected to have large ionization cross sections and thus contribute to the total ionization out of all proportion to their actual density. Therefore the ionization currents produced in the residual gas were measured frequently and subtracted from the currents obtained with target gas present, constituting corrections up to but never more than 10 per cent. However it was assumed that the reading of the McLeod gauge corresponded only to the partial pressure of the target gas, and its readings were therefore not corrected for background.

Because this procedure depends on the assumption that the background gas density is the same when the target gas is present as when it is not, it is only approximately correct. It was found that data taken at very low target gas pressures, for which the background correction was much greater than 10 per cent, failed to agree with data taken at higher pressures. Therefore data used in the compilation was taken only with pressures great enough that the background correction was less than 10 per cent.

A set of values obtained for the cross section σ_+ 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 falloff at pressures below 1.0×10^{-4} Torr exemplifies the situation described for which the background correction became too large. Similarly, the indication of rising values for pressures above 10×10^{-4} Torr 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. In computing the molecular density of the target gas, its temperature was taken to be that of the room.

Results

The experimental results of other investigators which are available are included with present results for the cross sections σ_+ and σ_- which are presented for the projectile He^{++} on helium and hydrogen in Figures 10 and 11, and for the projectile He^+ on helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide in Figures 12 through 18.

Cross-correlations between total production cross sections and charge-changing cross sections are presented in Figures 19 through 24. For the projectile He^{++}, $\sigma_+ - \sigma_-$ should be equal to $\sigma_{21} + \sigma_{20}$, and for the projectile He^+, $\sigma_+ - \sigma_-$ should be equal to $\sigma_{10} - \sigma_{12}$, as was explained

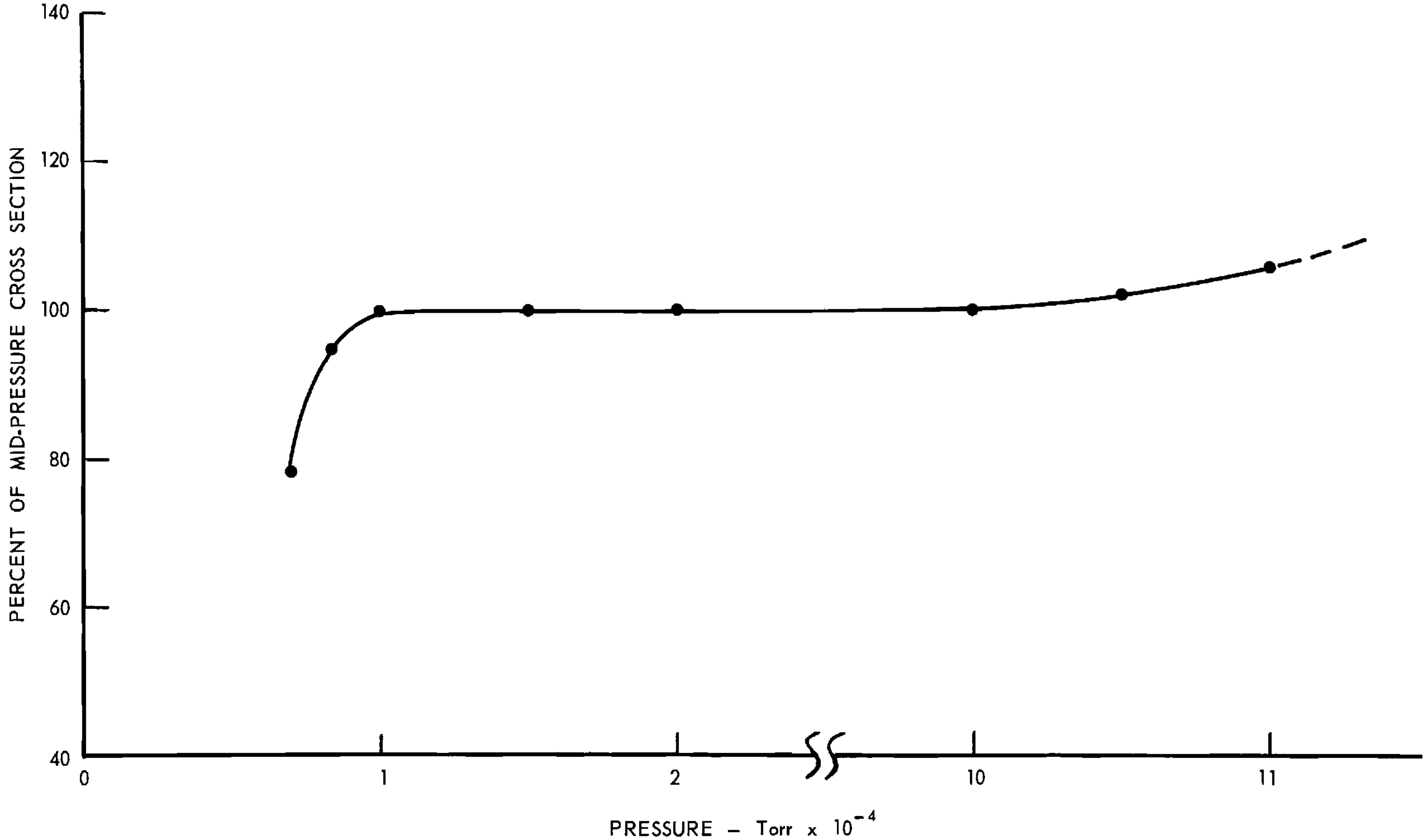

Figure 9. Computed $\sigma+$ (1 MeV) for Varying Target Gas Pressure for He^+ Ions Incident on Helium Using a CEC Gm-100 McLeod Gauge.

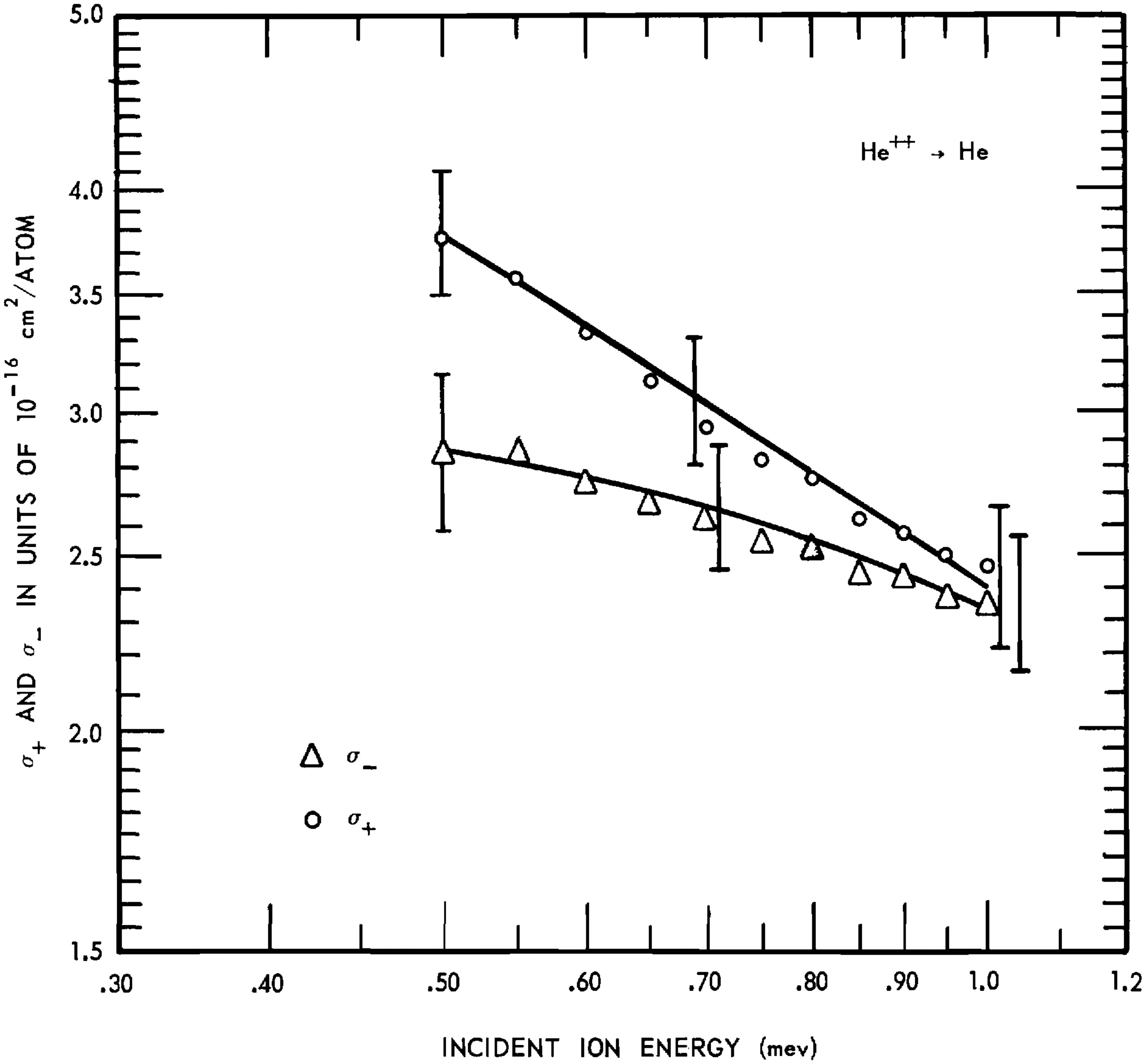

Figure 10. Cross Sections for the Gross Production of Positive Ions and Free Electrons by He^{++} Ions Incident on Helium.

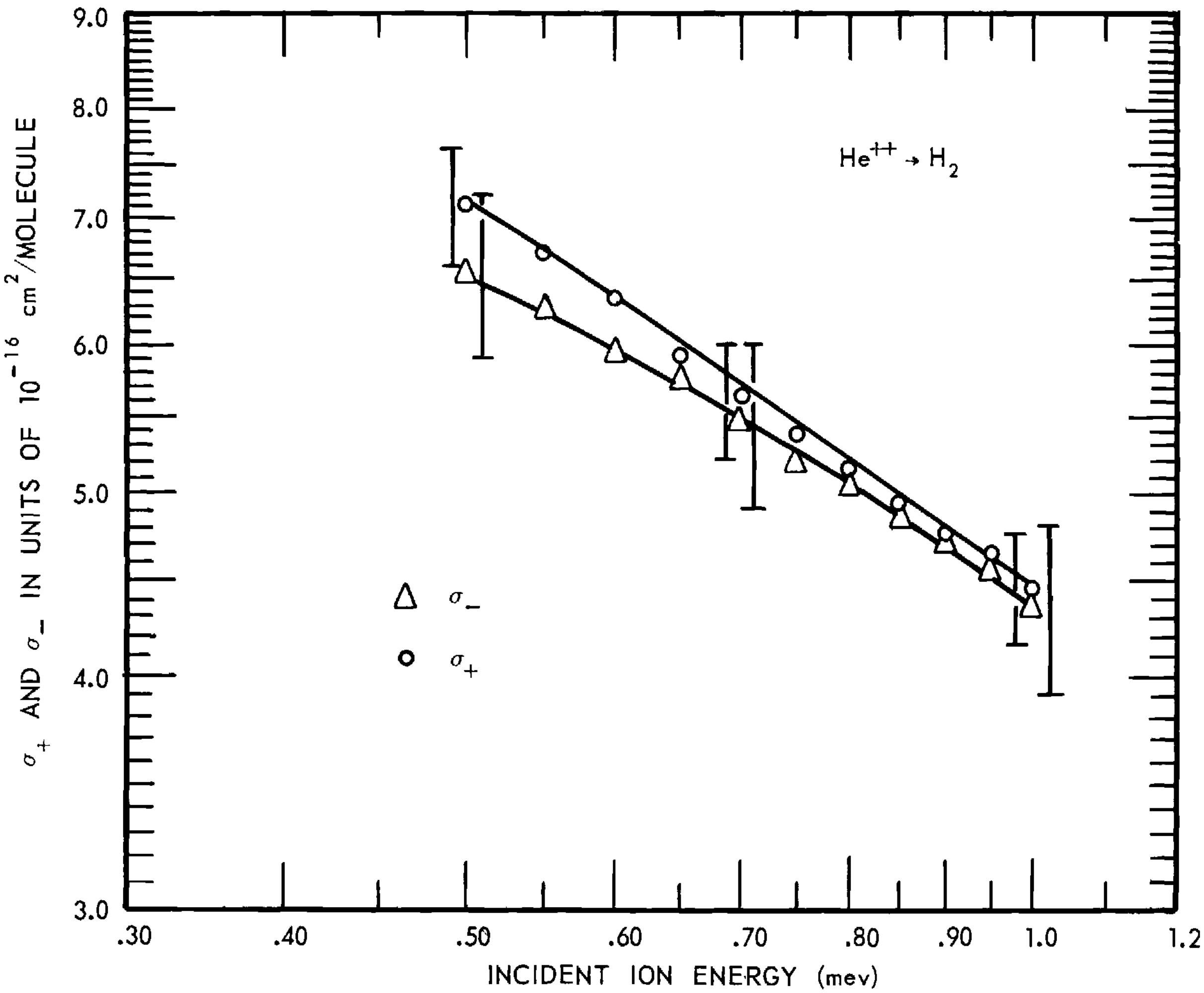

Figure 11. Cross Sections for the Gross Production of Positive Ions and Free Electrons by He^{++} Ions Incident on Molecular Hydrogen.

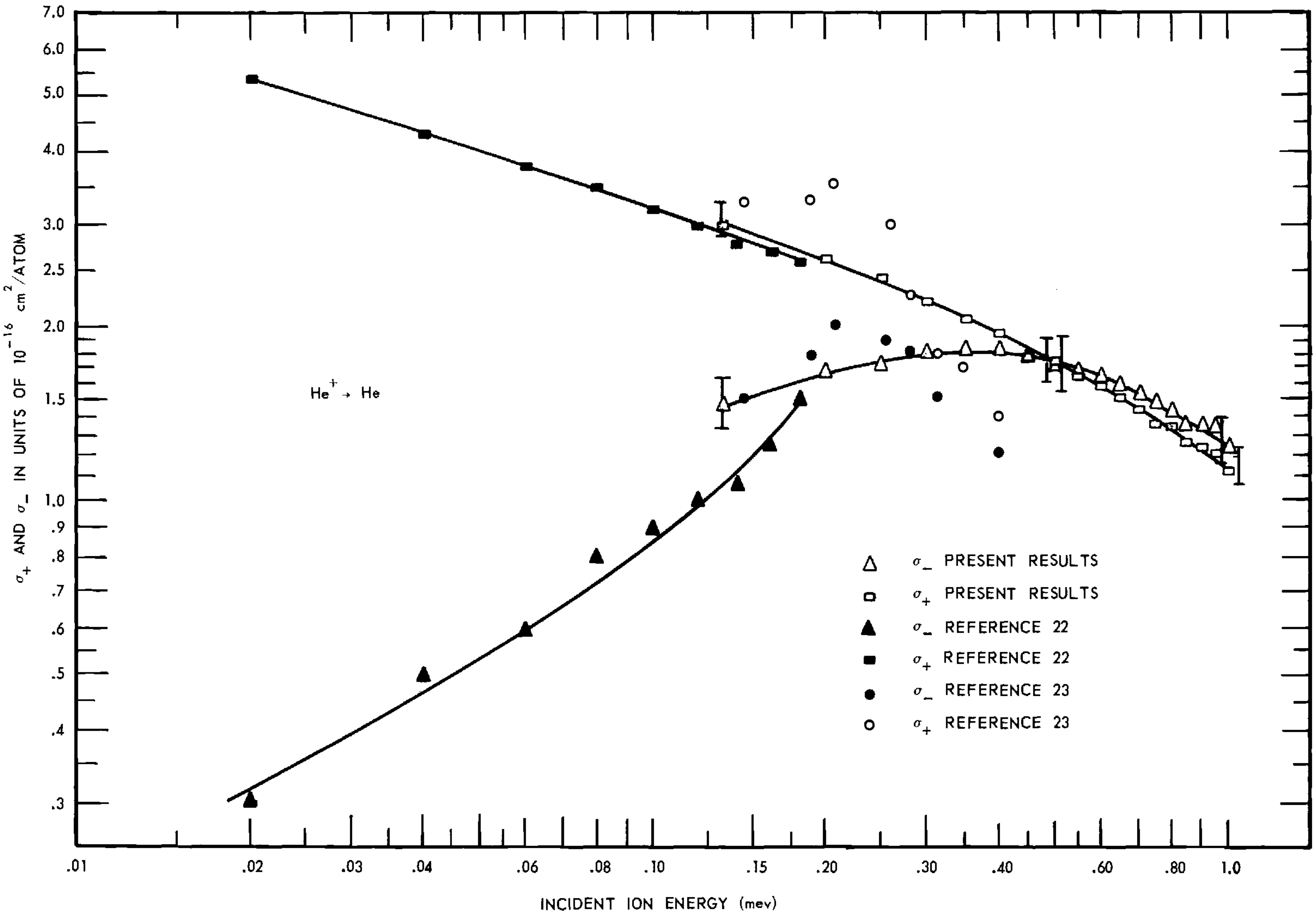

Figure 12. Cross Sections for the Gross Production of Positive Ions and Free Electrons by He^+ Ions Incident on Helium.

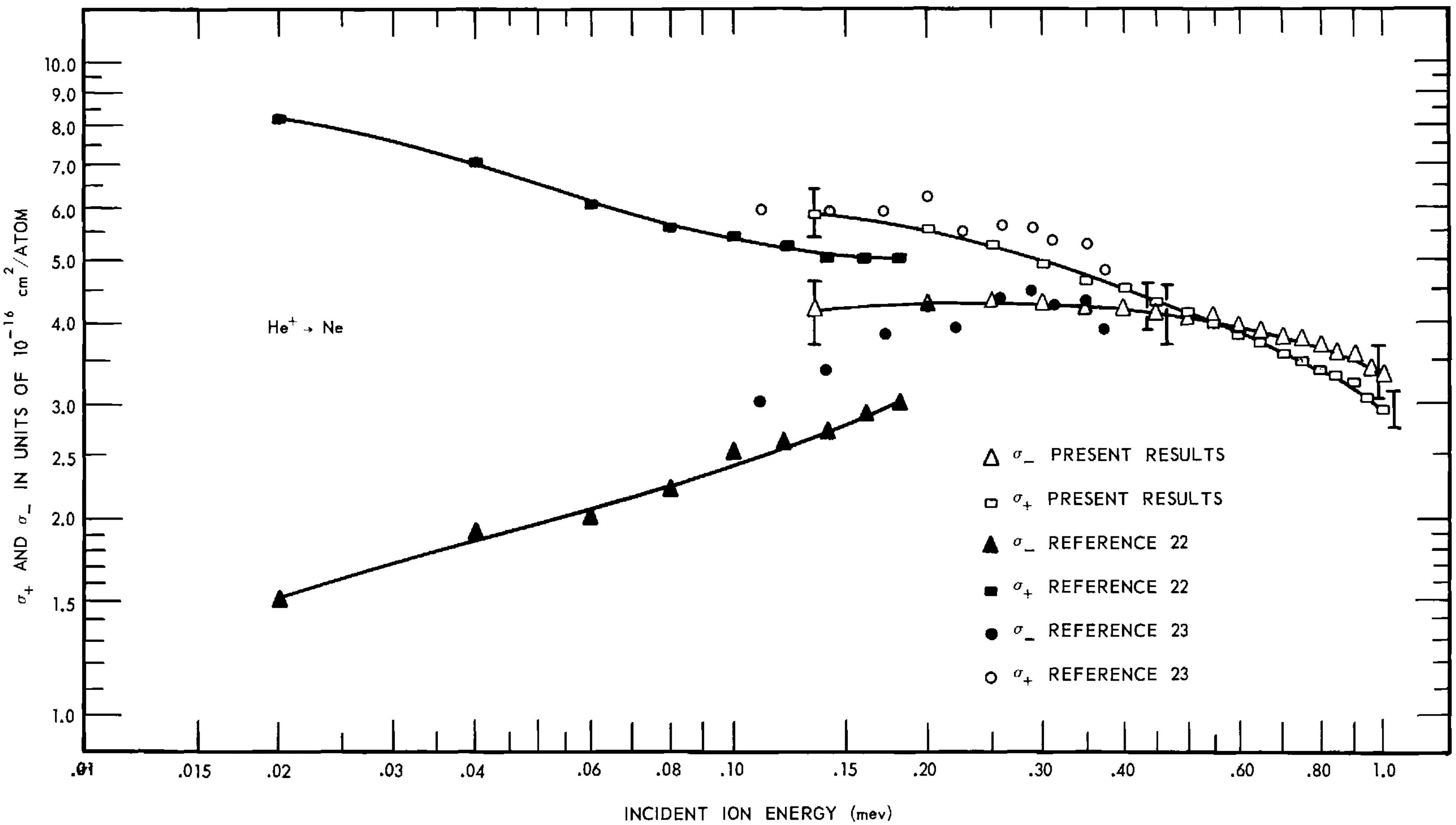

Figure 13. Cross Sections for the Gross Production of Positive Ions and Free Electrons by He^+ Ions Incident on Neon.

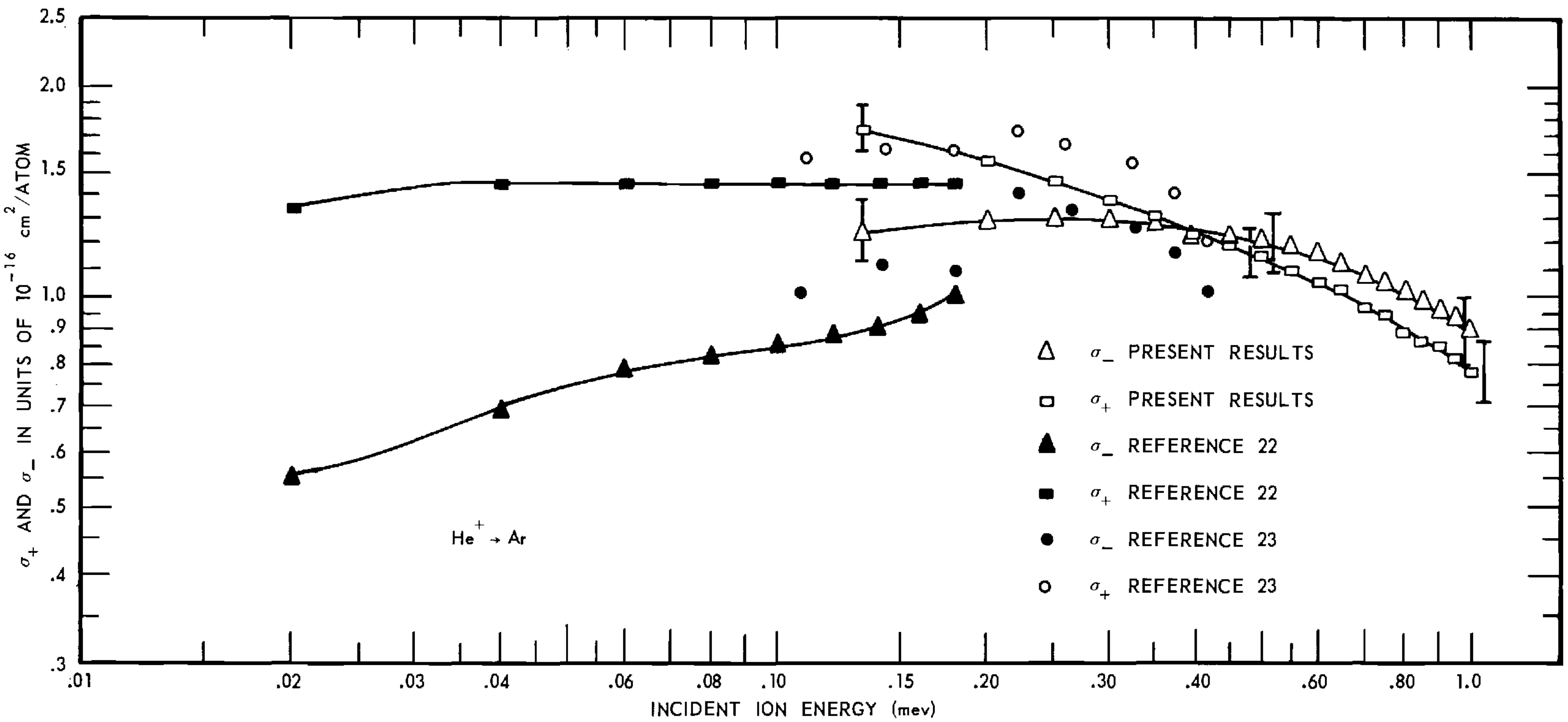

Figure 14. Cross Sections for the Gross Production of Positive Ions and Free Electrons by He^+ Ions Incident on Argon.

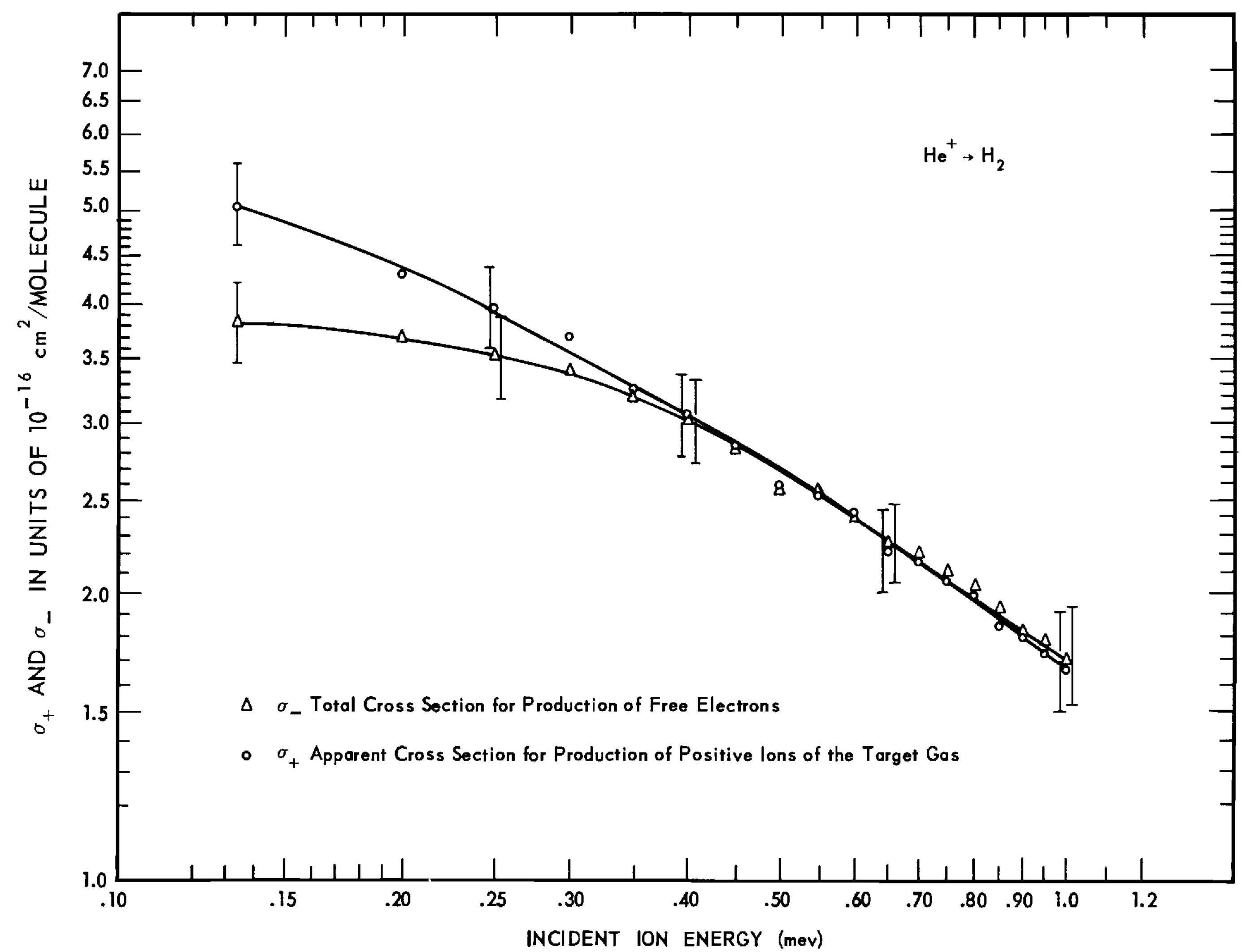

Figure 15. Cross Sections for the Gross Production of Positive Ions and Free Electrons by He^+ Ions Incident on Molecular Hydrogen.

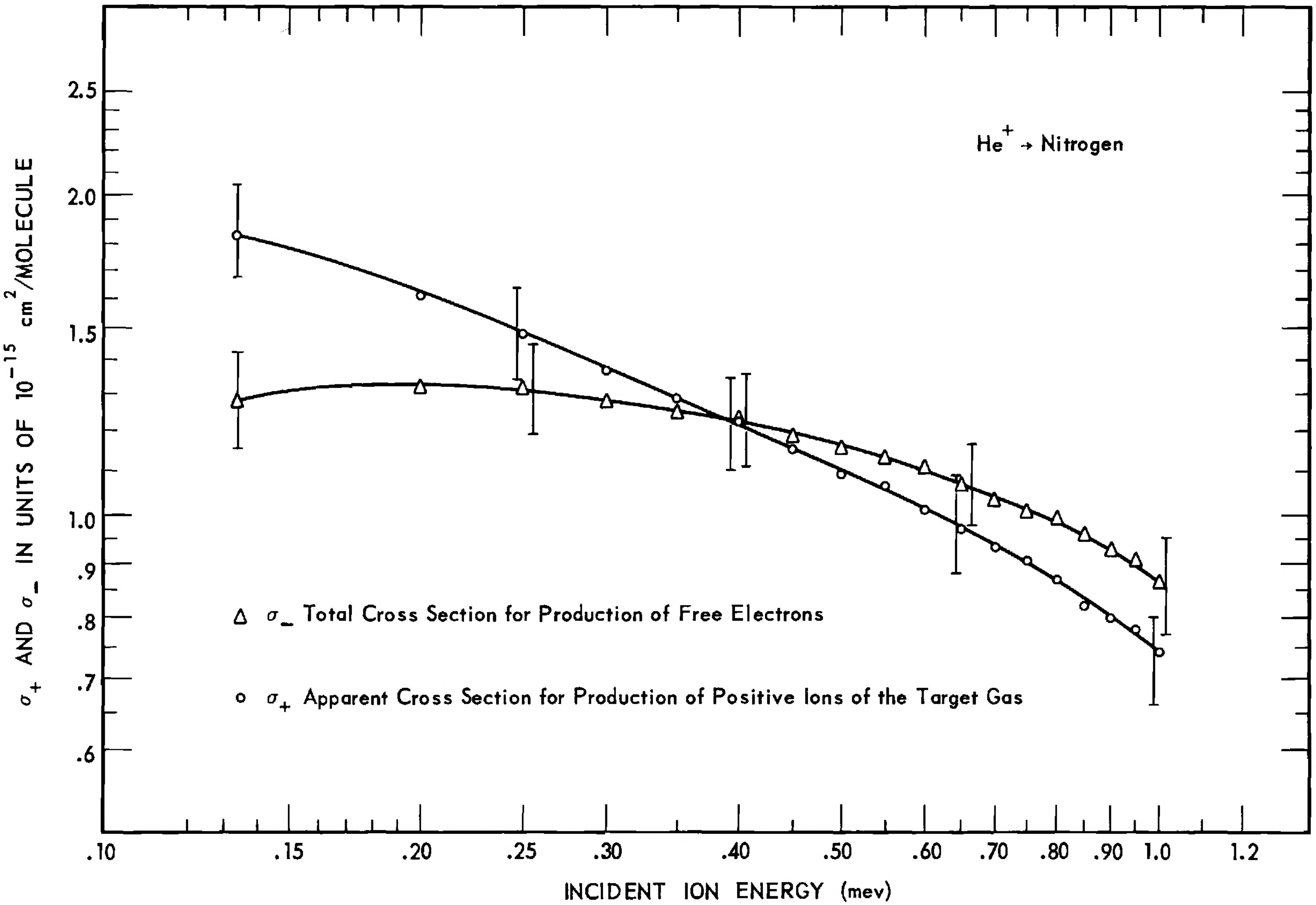

Figure 16. Cross Sections for the Gross Production of Positive Ions and Free Electrons by He$^+$ Ions Incident on Molecular Nitrogen.

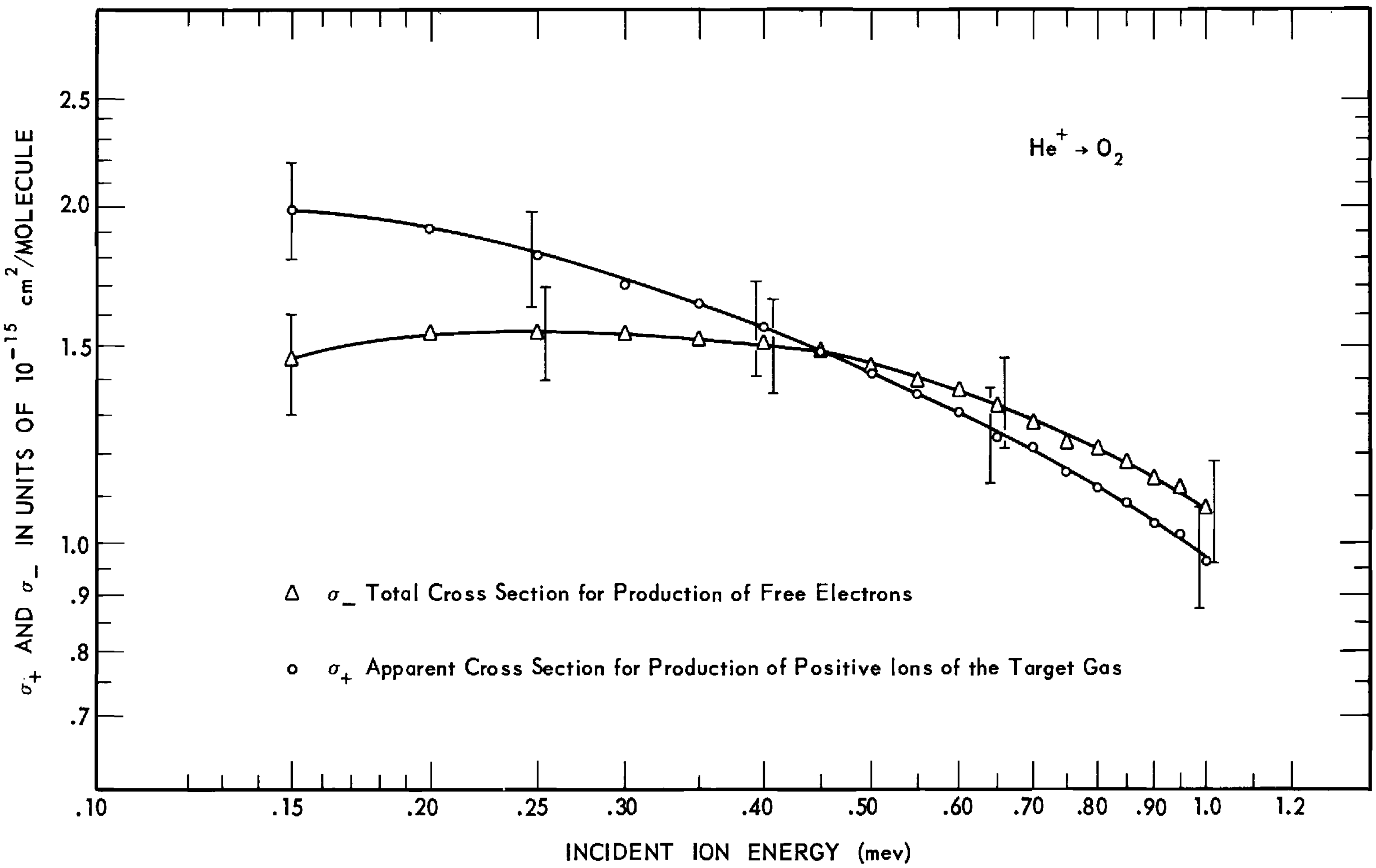

Figure 17. Cross Sections for the Gross Production of Positive Ions and Free Electrons by He^+ Ions Incident on Molecular Oxygen.

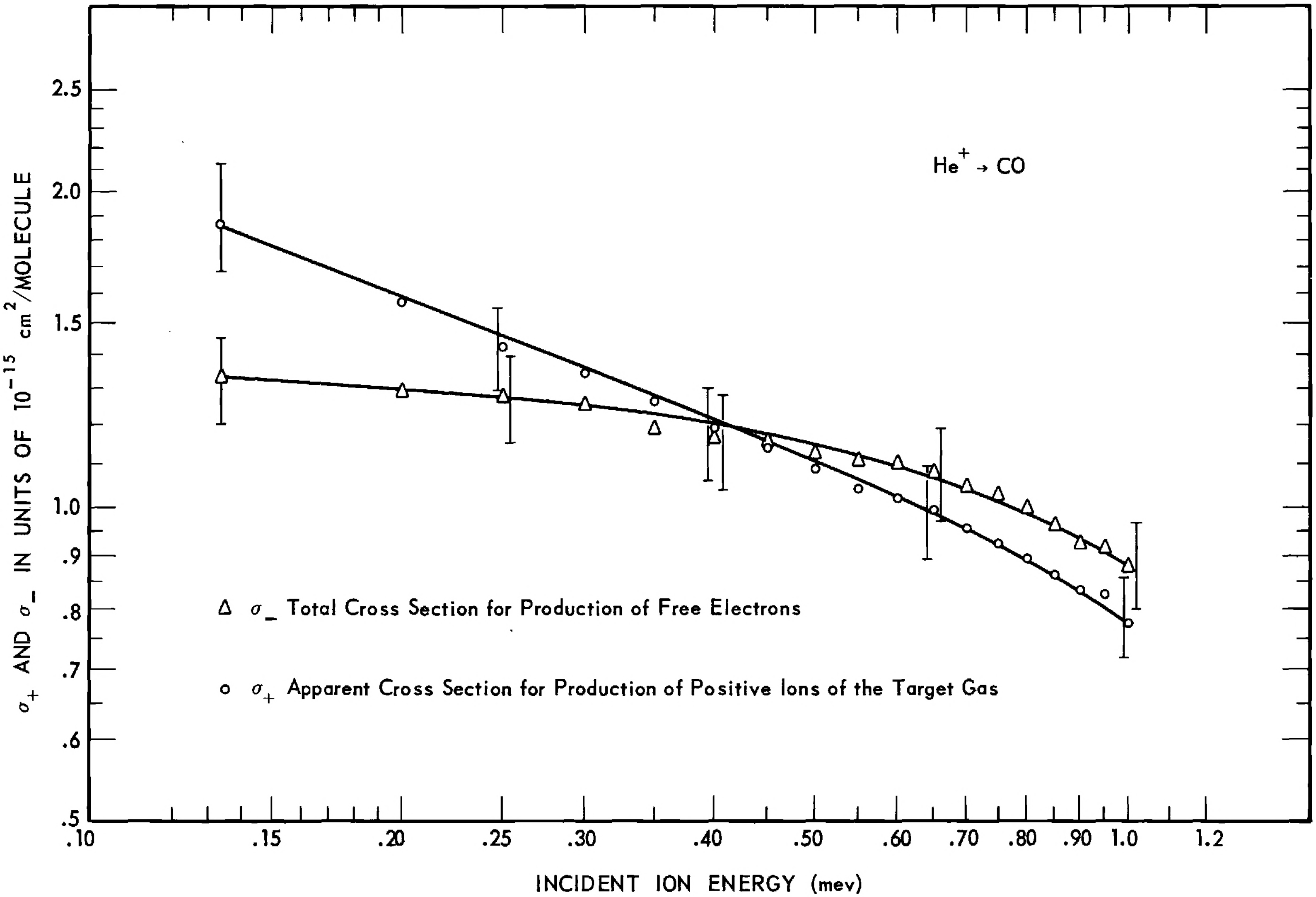

Figure 18. Cross Sections for the Gross Production of Positive Ions and Free Electrons by He^+ Ions Incident on Carbon Monoxide.

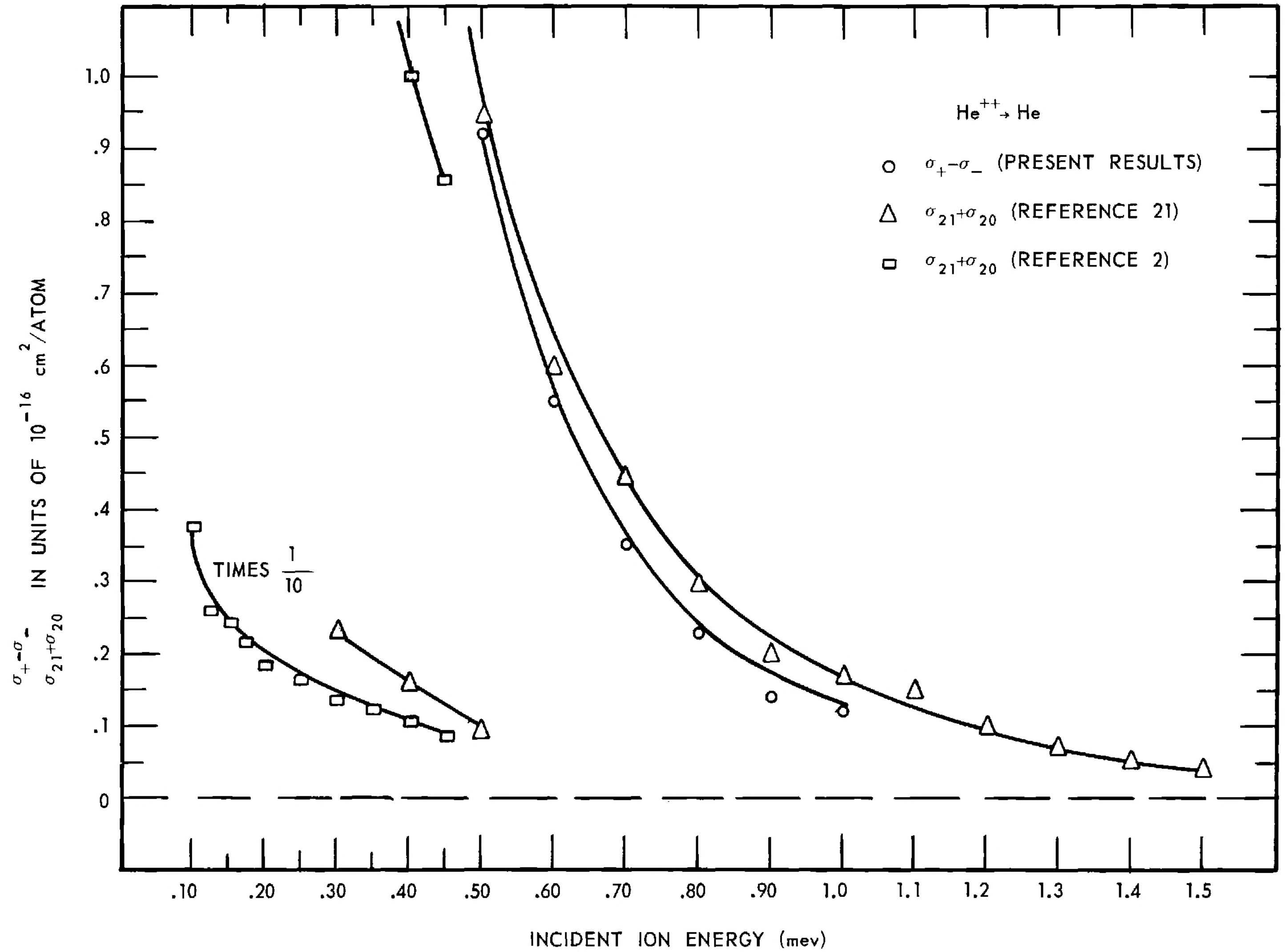

Figure 19. Cross-Correlation Between Total Production Cross Sections and Charge-Changing Cross Sections for He^{++} Ions Incident on Helium.

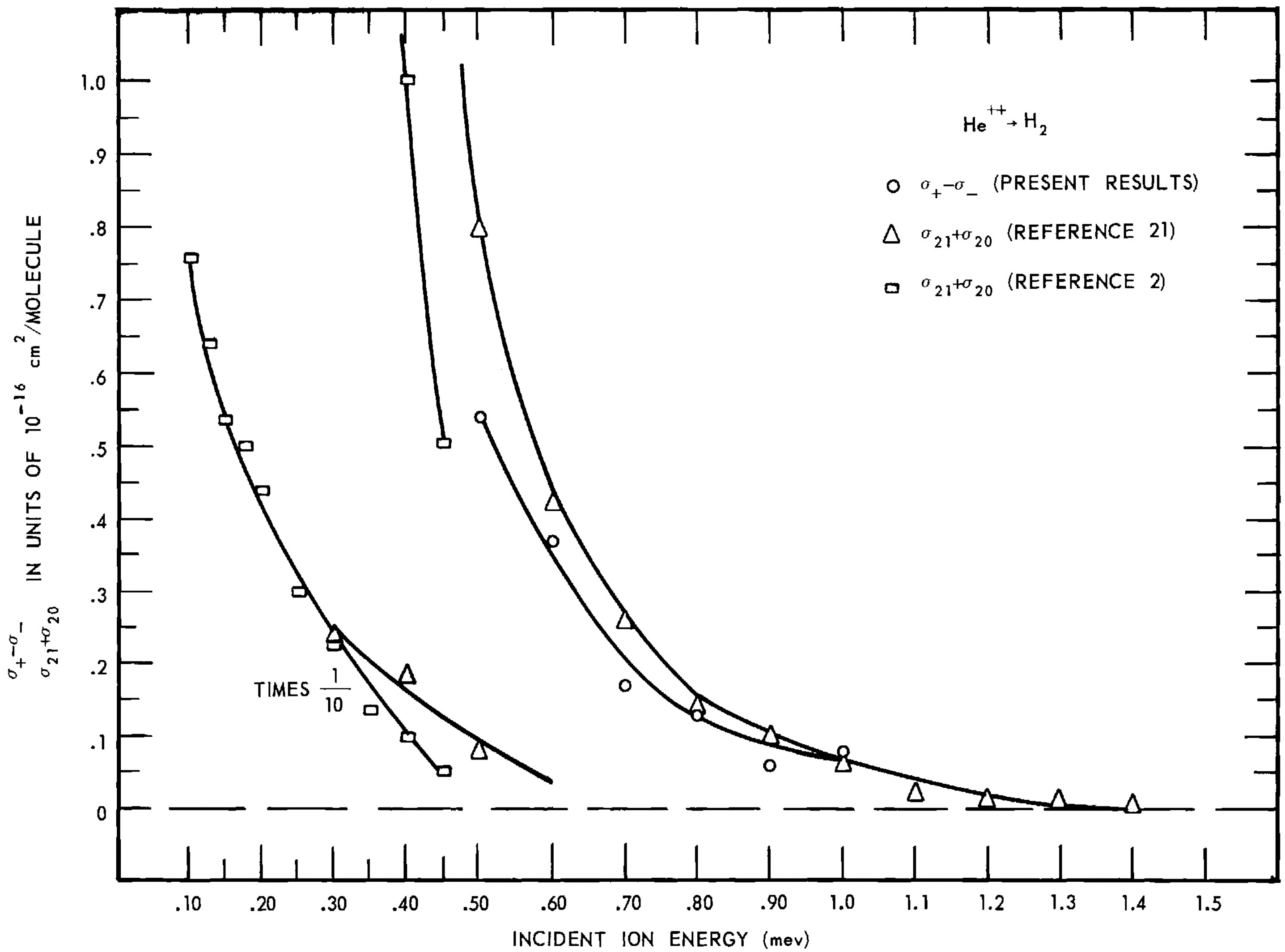

Figure 20. Cross-Correlation Between Total Production Cross Sections and Charge-Changing Cross Sections for He^{++} Ions Incident on Molecular Hydrogen.

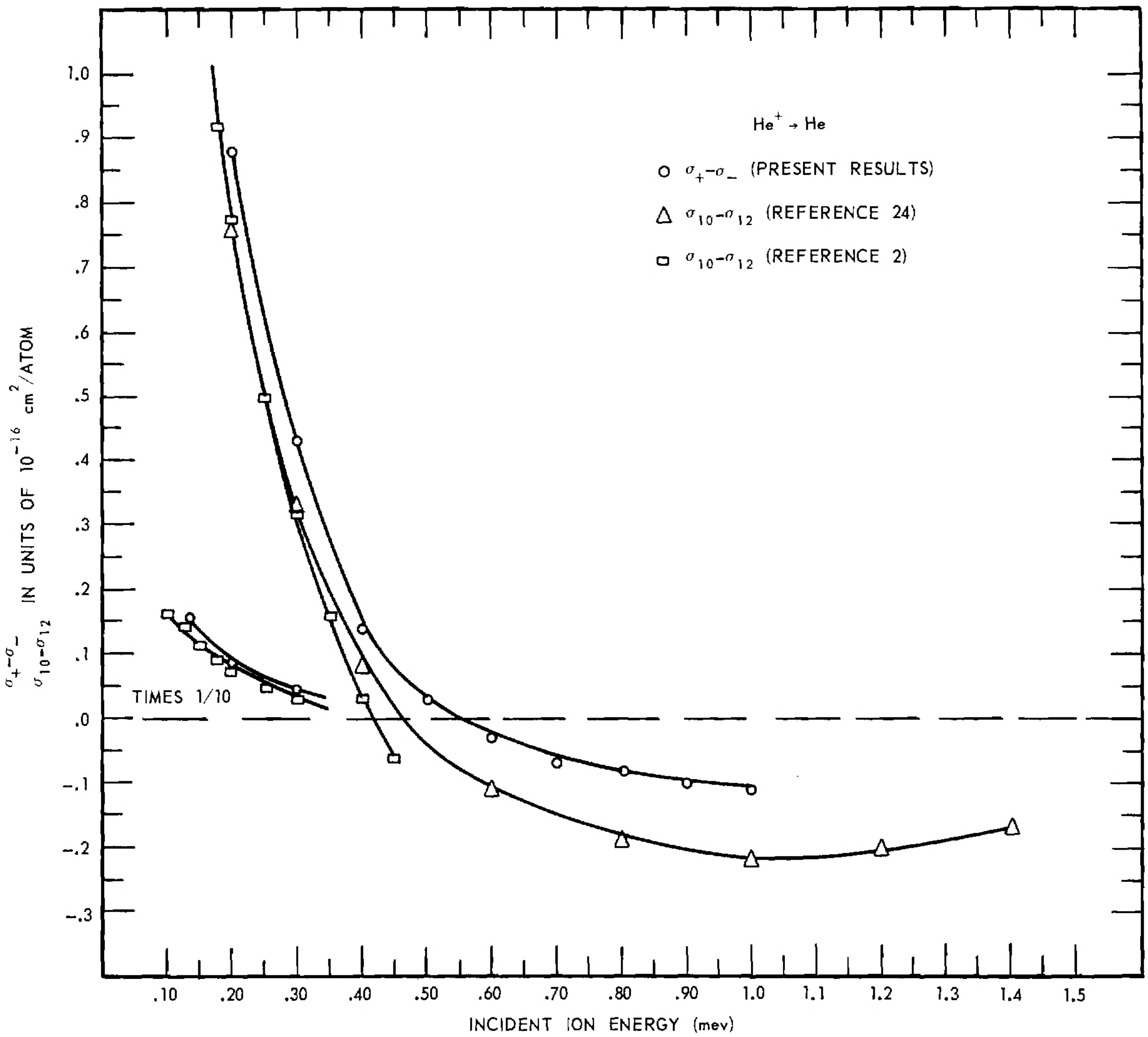

Figure 21. Cross-Correlation Between Total Production Cross Sections and Charge-Changing Cross Sections for He^+ Ions Incident on Helium.

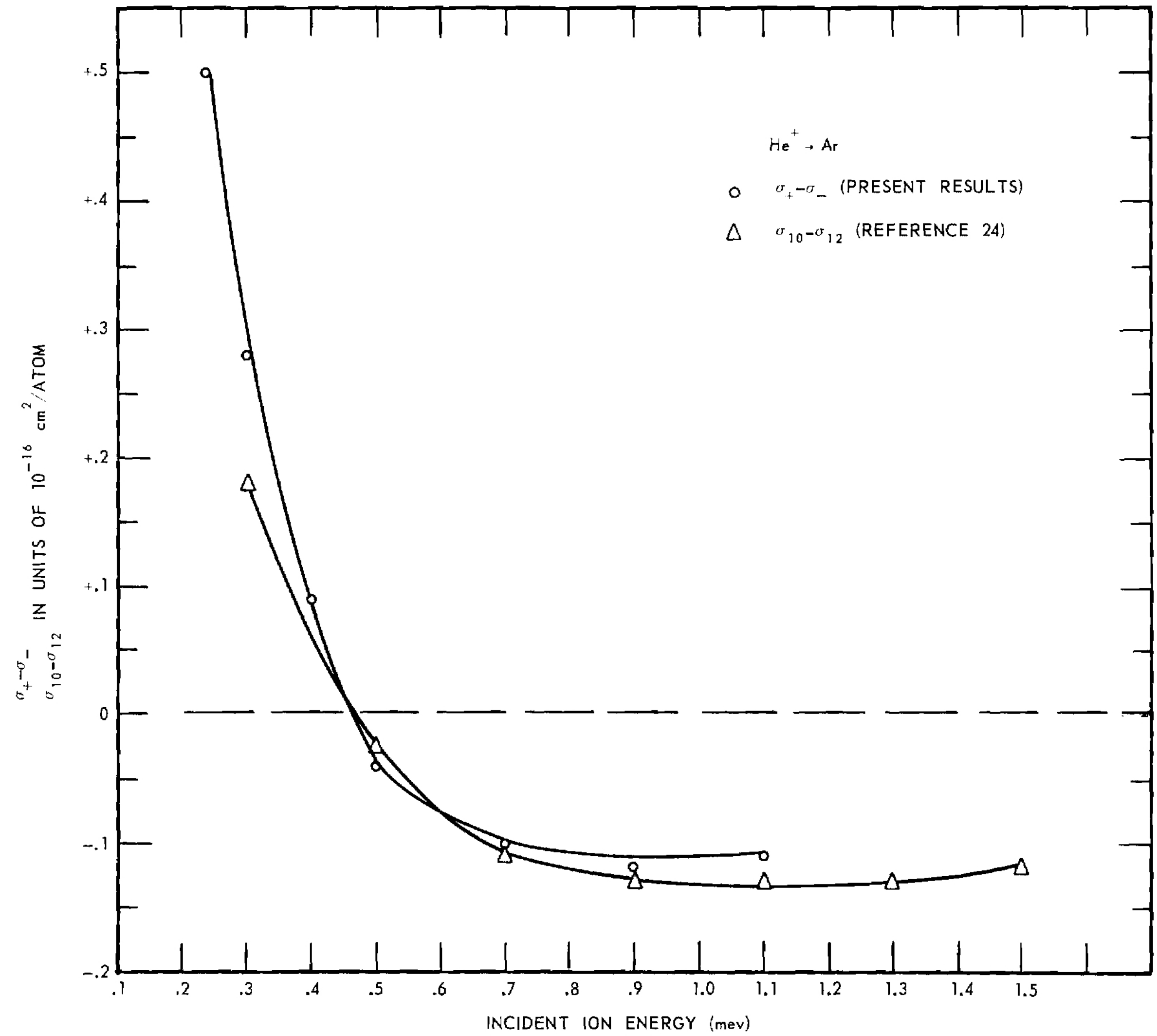

Figure 22. Cross-Correlation Between Total Production Cross Sections and Charge-Changing Cross Sections for He^+ Ions Incident on Argon.

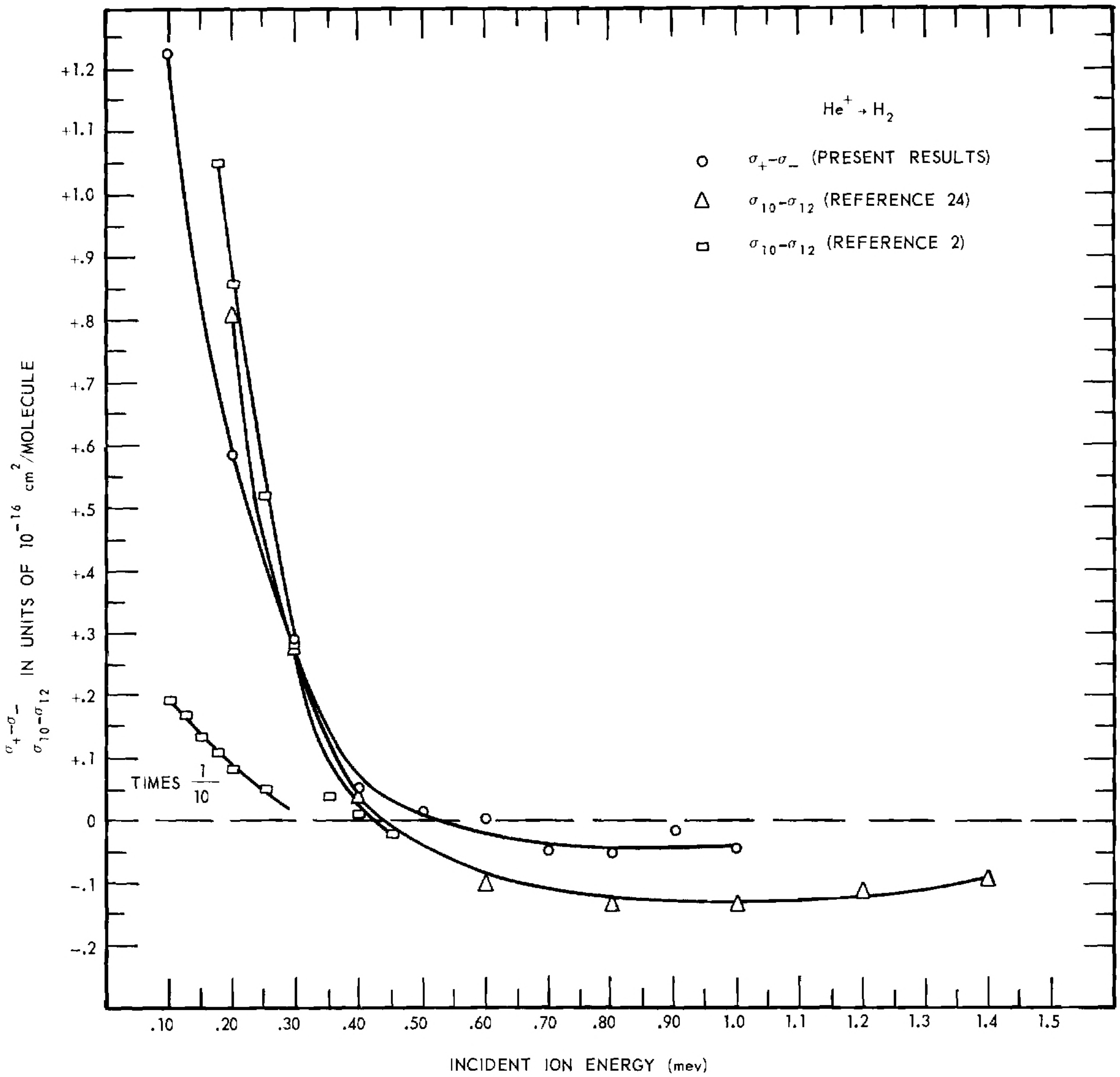

Figure 23. Cross-Correlation Between Total Production Cross Sections and Charge-Changing Cross Sections for He^+ Ions Incident on Molecular Hydrogen.

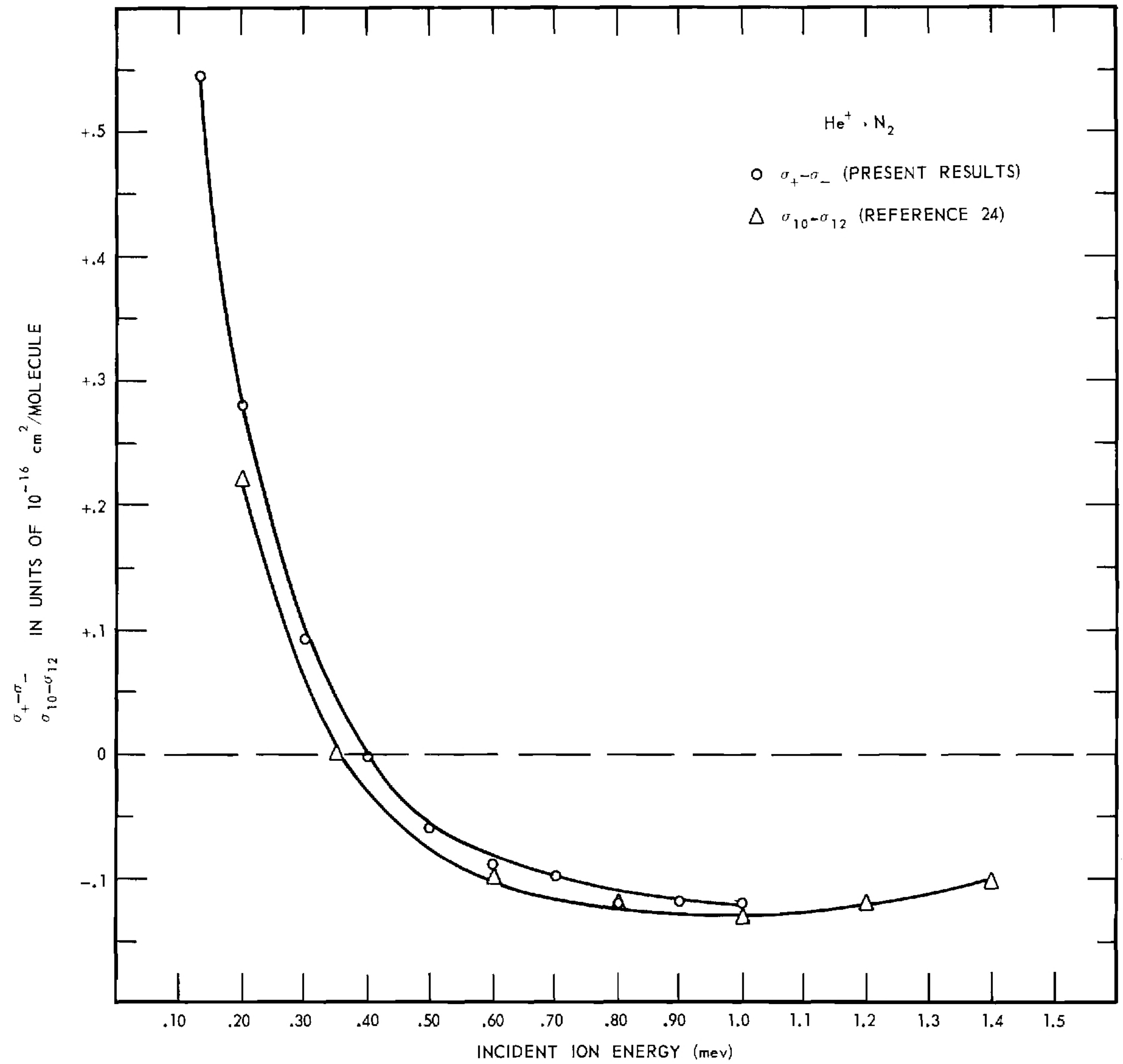

Figure 24. Cross-Correlation Between Total Production Cross Sections and Charge-Changing Cross Sections for He^+ Ions Incident on Molecular Nitrogen.

in Chapter III. The difference between σ_+ and σ_- was always only a fraction of either σ_+ or σ_-; therefore the different sets of data agree well in experimental error and vindicates the method of choosing V_c (see The Collector Assemblies and Electrometers, Chapter IV). Discussion of the possible error brackets shown on the curves is contained in the next section.

Discussion of Errors

It was indicated in Chapter IV 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 ± 4 per cent. The target gas temperature was not directly measured and may have been uncertain by perhaps ± 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 uncertainty of the CEC GM-100 McLeod Gauge, used during the He^+ measurements of less than 4 per cent in the range around 1×10^{-4} Torr. This gauge had not been absolutely calibrated, however, so that a possible error of about ± 5 per cent must be admitted in the absolute reading. This led to proportionate possible systematic error in all of the measurements, but it is emphasized that the relative values of the cross sections at various energies are not subject to this systematic error. The CEC GM-110 McLeod Gauge, used during the He^{++} measurements, was calibrated to an accuracy of about ± 1 per cent while deviation of any one pressure reading from an average of about five readings was as high as ± 5 per cent. This error was due to sticking of the mercury column in the capillary and was believed to be random.

As presented in Chapter IV, the excess of electrons found at high collection voltages presented some uncertainty. A plot of I^-/I_i and I^+/I_i on a relative scale versus collection voltage is presented in Figure 7. A discussion of the plot is made there. A lack of knowledge of just what to make the collection voltage led to an additional uncertainty in σ_- of not more than 3 per cent.

The absolute error brackets for the cross sections involving He^+ ions are about ± 8 per cent for σ_+ and about ± 11 per cent for σ_-, while the relative accuracies of the cross sections with respect to each other are about ± 5 per cent. The absolute error brackets for the cross sections involving He^{++} ions are about ± 7 per cent for σ_+ and about ± 10 per cent for σ_-, while the relative accuracies are about ± 5 per cent.

CHAPTER VI

COMPARISON WITH AVAILABLE THEORY

A general theoretical treatment[19] of the high-energy ionization process in the Bethe-Born Approximation has shown that for high impact velocity the ionization cross section should be of the general form

$$Q_{n\ell} = \frac{2\pi \; e^4 \; c_{n\ell} \; Z_{n\ell} \; Z_i^{\;2}}{mv^2 \; |E_{n\ell}|} \log_e \left(\frac{2mv^2}{C_{n\ell}}\right) \qquad (6\text{-}1)$$

where e is the electronic charge, $Z_{n\ell}$ is the number of electrons in the $n\ell$ shell of the target atom, each of energy $E_{n\ell}$, Z_i is the charge of the incident ion in units of e, $c_{n\ell}$ is a reduced electron matrix element, $C_{n\ell}$ a quantity related to the energy of an electron in the $n\ell$ shell, m is the electron mass, and v is the collision velocity. Normally σ_i is expected to be essentially equal to $Q_{n\ell}$ for the outermost shell of the target atom. For a given target atom Equation (6-1) can then be written in the form

$$\sigma_i = A \frac{Z_i^{\;2} \; M}{E} \log_e \left(B \frac{E}{M}\right) \qquad (6\text{-}2)$$

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

$$A = \frac{2\pi \; e^4 \; c_{n\ell} \; Z_{n\ell}}{2 \; m/M_p} \qquad \text{and} \qquad B = \frac{4 \; m/M_p}{C_{n\ell}}$$

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 from experimental data for one incident ion, Equation (6-2) 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 in Chapter II, in which the incident ion neither gains nor loses electrons.

Proton data have been fitted by a least squares technique to Equation (6-2) to obtain empirical values of A and B for the target atoms and molecules helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide.[20]

Incident He^{++} Ions

The ionization cross sections predicted for He^{++} ions incident on helium and hydrogen are presented along with the estimated experimental gross apparent ionization cross sections in Figures 25 and 26 and are labeled "Predicted from Experimental H^+; $Z_i = 2$" in the figures. The procedure by which σ_i was estimated from the experimental σ_+ and σ_- was discussed in Chapter III.

A detailed theoretical calculation of ionization cross sections using the Born approximation for He^{++} ions incident on helium has been made by Mapleton[14] and is presented in Figure 25. Also a similar calculation for He^{++} ions incident on atomic hydrogen has been made by Bates and Griffing.[13] The atomic cross section has been scaled to the molecular cross section by the procedure given in Chapter III and is presented in Figure 26.

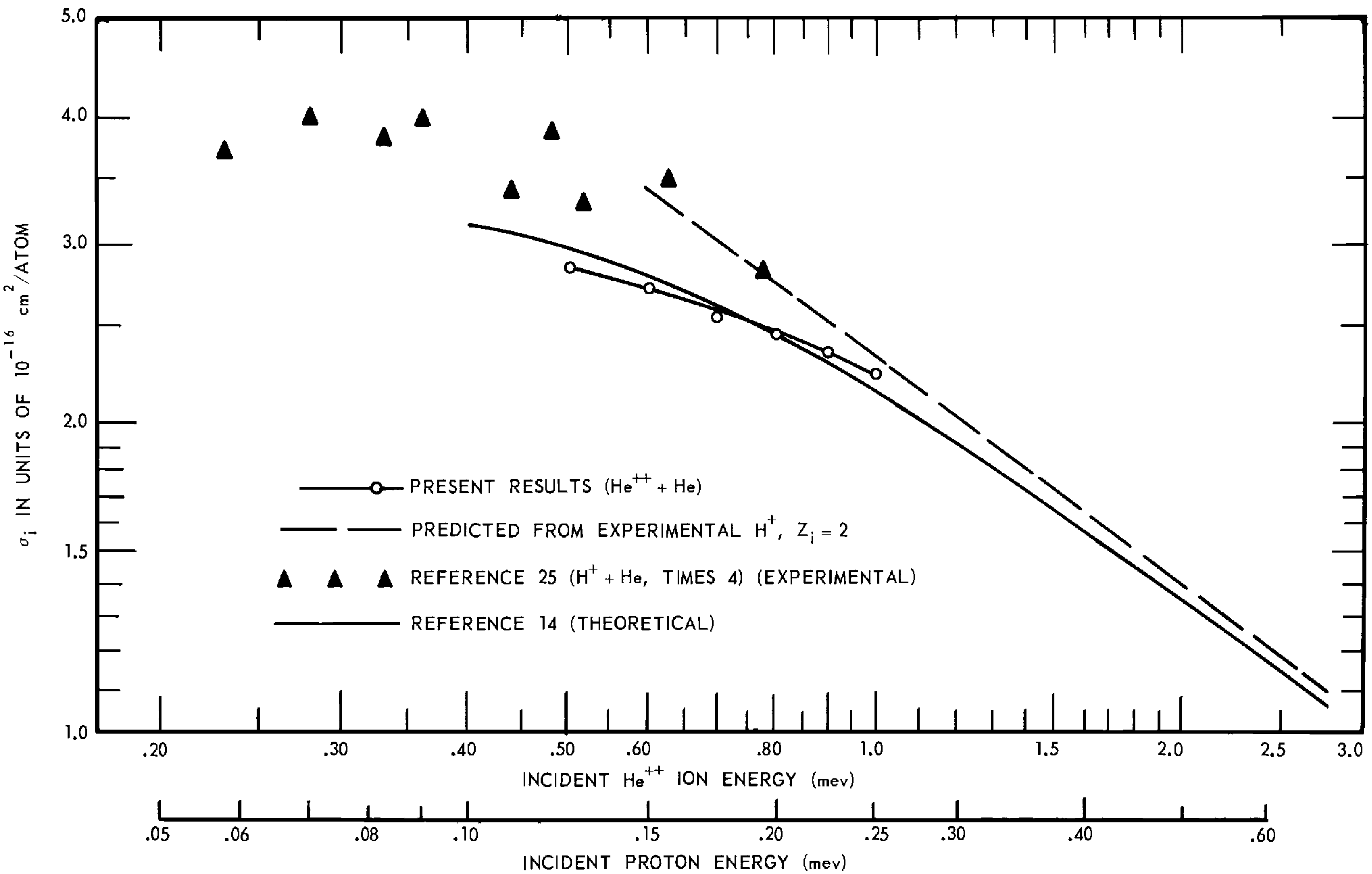

Figure 25. Comparison of Experimental and Theoretical Gross Ionization Cross Sections for He^{++} Ions and Protons of Equal Velocity Incident on Helium.

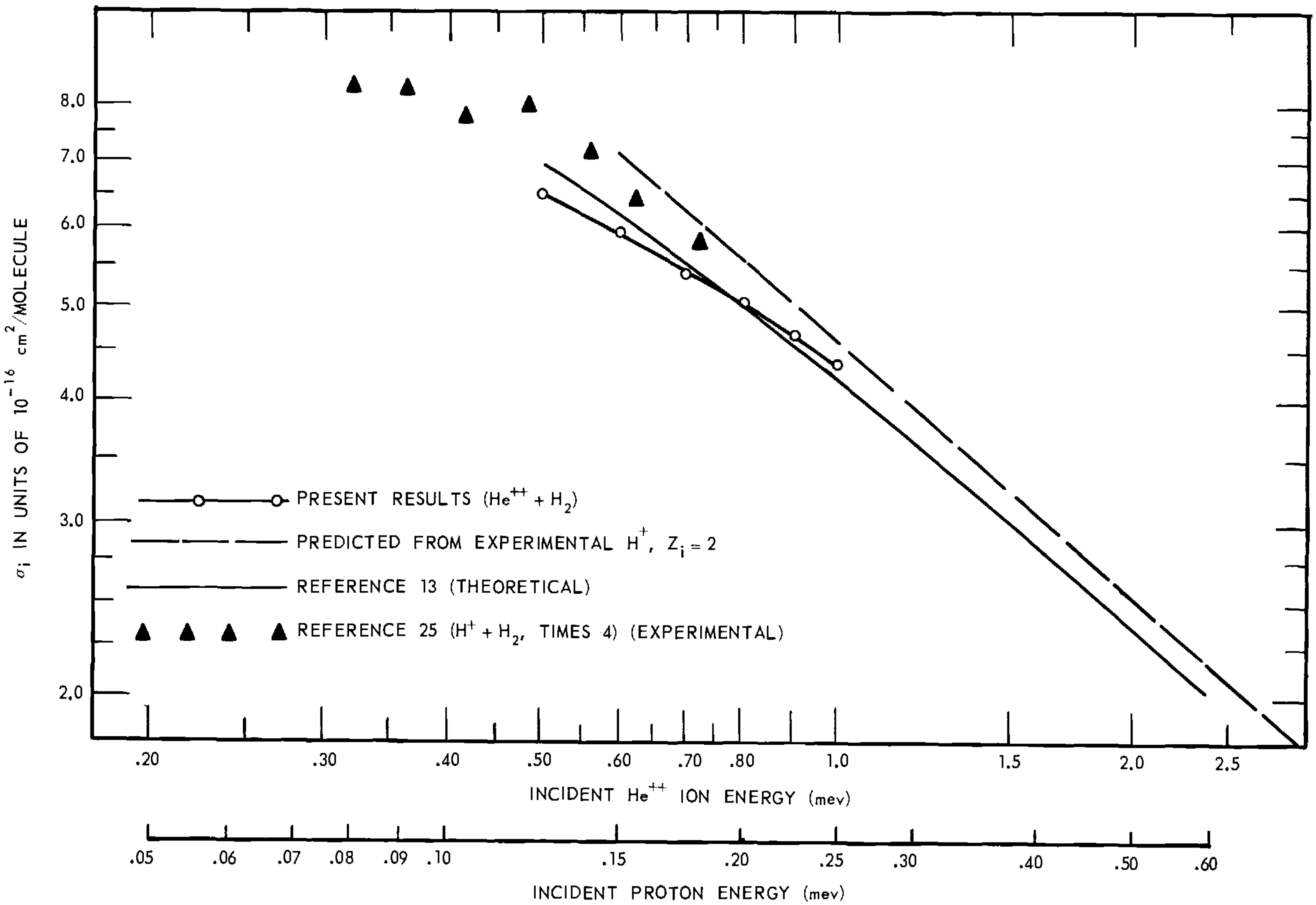

Figure 26. Comparison of Experimental and Theoretical Gross Ionization Cross Sections for He^{++} Ions and Protons of Equal Velocity Incident on Molecular Hydrogen.

The agreement between the present results and the more exact theoretical calculations is excellent while the Bethe-Born calculations using the values of A and B obtained from proton data lie consistently higher by about 10 per cent. This disagreement may have been due to an absolute error in the McLeod gauge that was used for the proton measurements from which the values of A and B were obtained.[17]

Incident He^+ Ions

The relationship between the ionization cross sections for various projectile ions discussed at the first of this chapter 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 Z_i lying somewhere between its actual net charge and its nuclear charge. The value of Z_i 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 Z_i 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 Z_i obtained to extrapolate the measurements to higher energies with Equation (6-2). 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 Z_i on these targets.

Accordingly, a detailed comparison of the present He^+ measurements with earlier proton measurements is presented. 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 σ_i for simple ionization. The procedure for arriving at a σ_i for incident He^+ ions is discussed in Chapter II.

The σ_i curves obtained for helium, argon, molecular hydrogen and molecular nitrogen are shown in Figures 27 through 30. A σ_i could not be obtained for the other gases because no charge-changing cross sections are known to have been measured for them to date. Also plotted are the cross sections predicted by Equation (6-2) for $Z_i = 1$, using the values of A and B obtained for these targets from proton measurements,[20] this amounts to just scaling out proton measurements by a factor of four in energy. These cross sections are labeled "Predicted from Experimental H^+; $Z_i = 1$" in the figures.

It is evident that the σ_i curves are indeed nearly parallel to the predicted curves above about 0.60 MeV. They run higher than the predicted curves by a factor of about 1.4 for helium, 1.5 for argon, 1.3 for hydrogen, and 1.5 for nitrogen.

Thus it is shown that the concept of an effective charge Z_i 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

$$Z_i \simeq \sqrt{1.4} \simeq 1.2$$

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

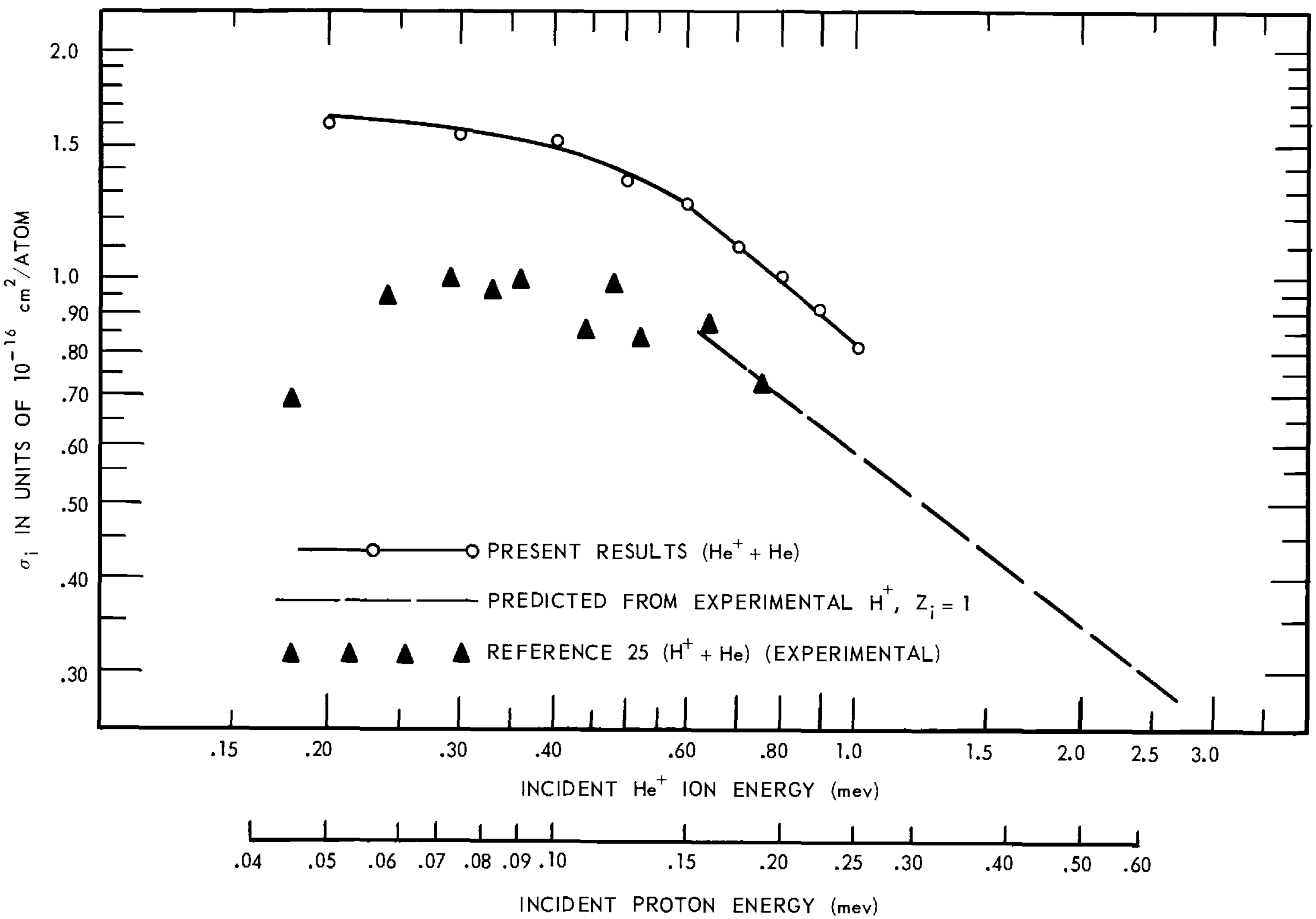

Figure 27. Comparison of Experimental and Theoretical Gross Ionization Cross Sections for He^+ Ions and Protons of Equal Velocity Incident on Helium.

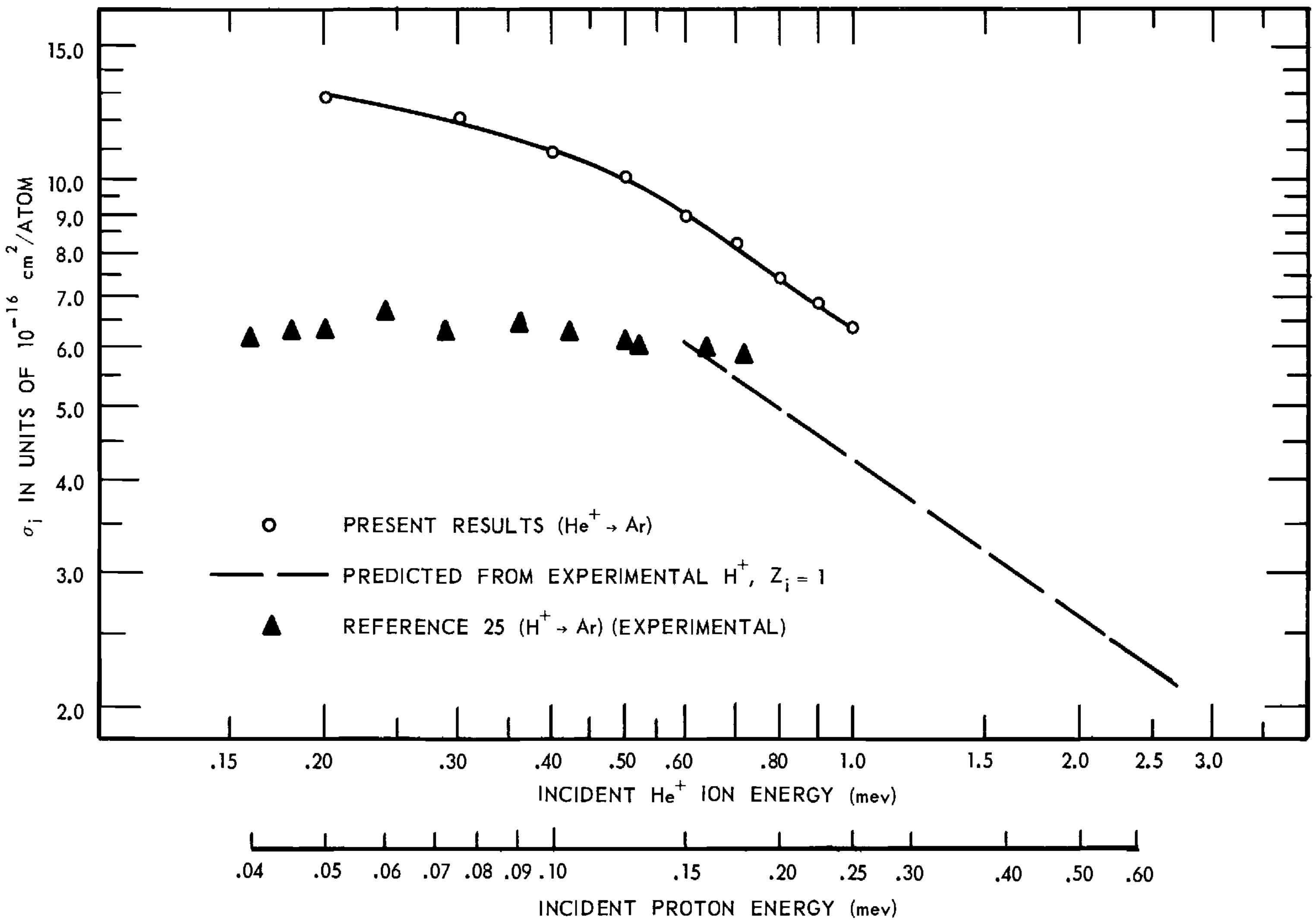

Figure 28. Comparison of Experimental and Theoretical Gross Ionization Cross Sections for He^+ Ions and Protons of Equal Velocity Incident on Argon.

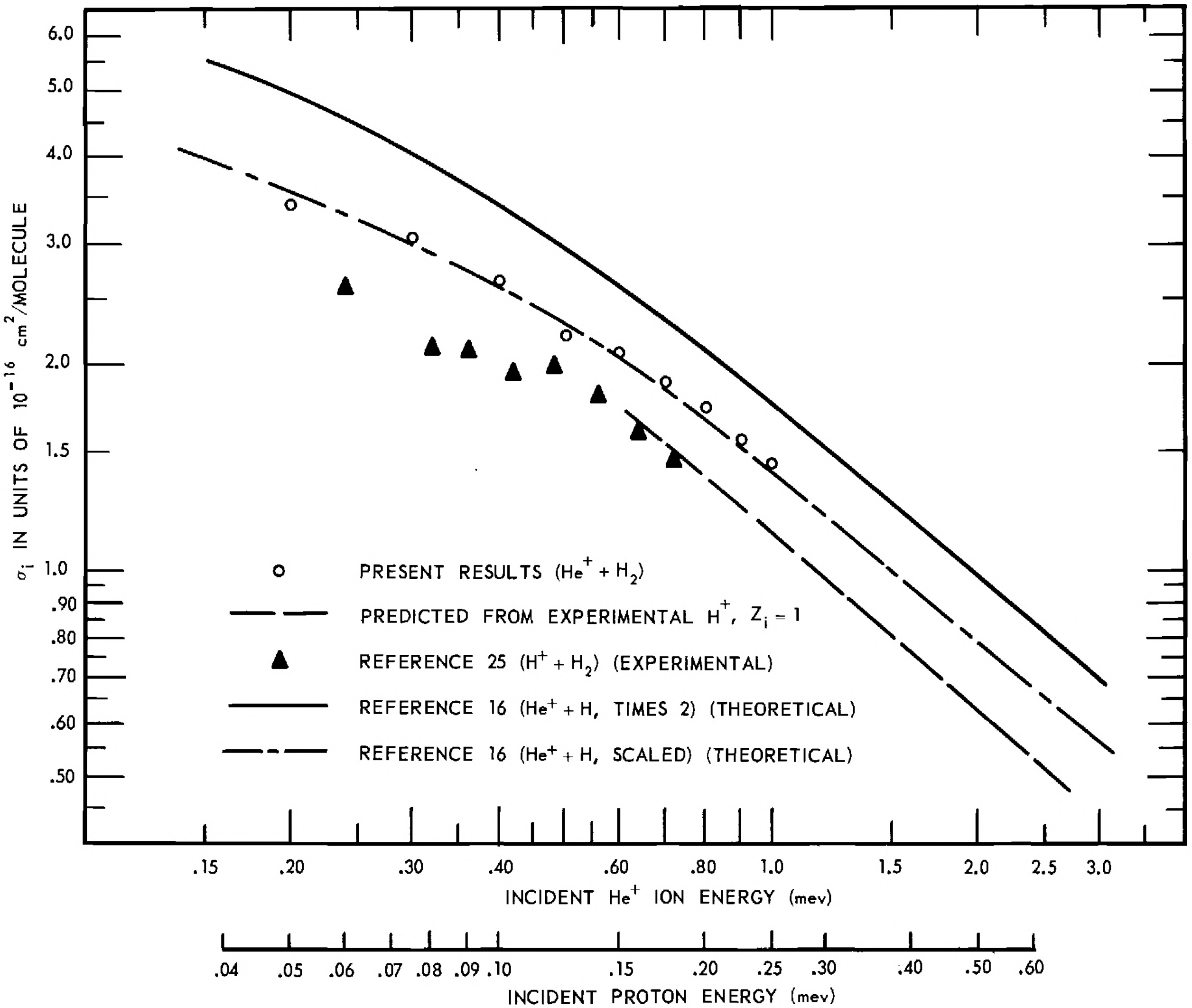

Figure 29. Comparison of Experimental and Theoretical Gross Ionization Cross Sections for He^+ Ions and Protons of Equal Velocity Incident on Molecular Hydrogen.

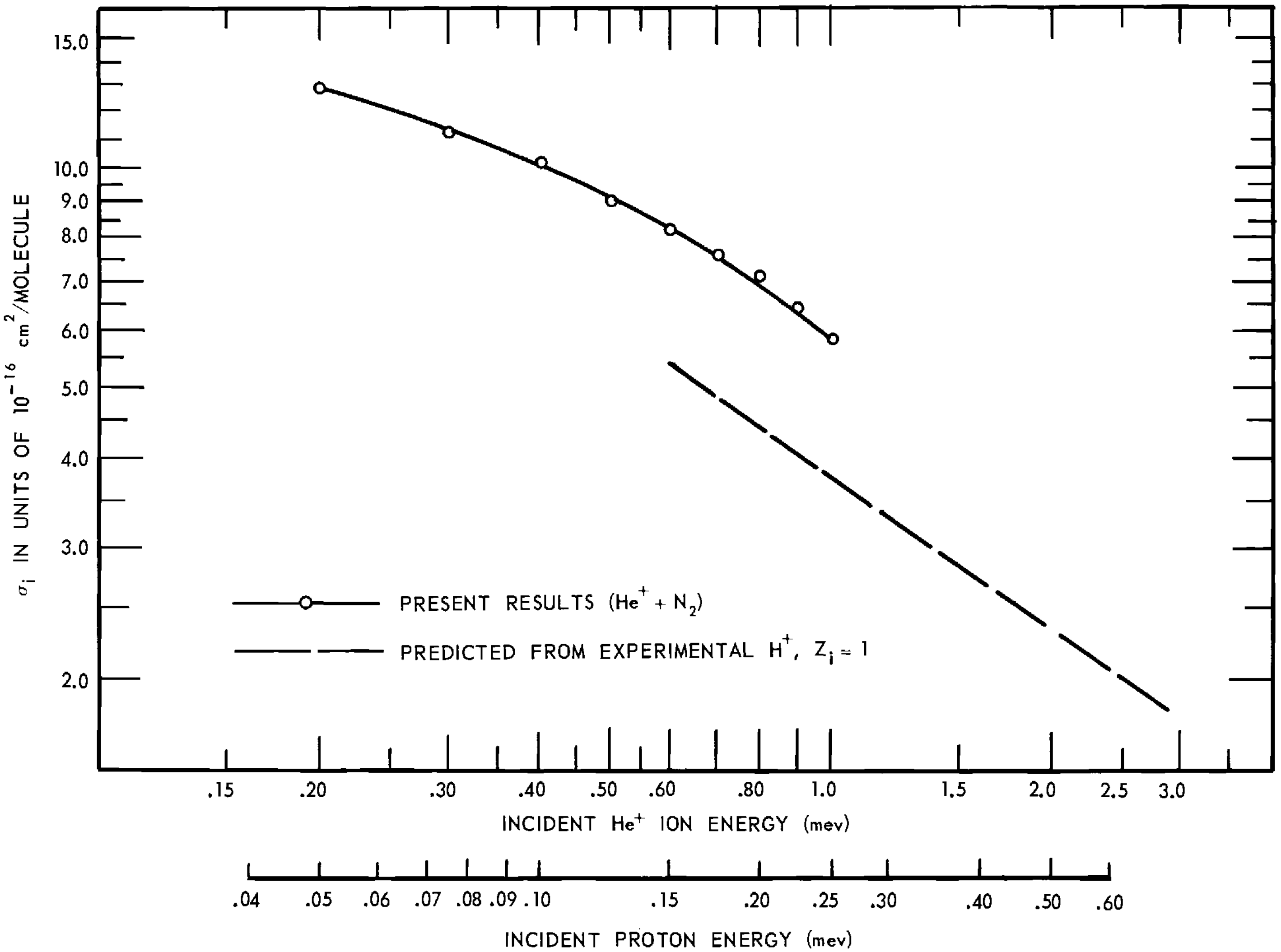

Figure 30. Comparison of Experimental and Theoretical Gross Ionization Cross Sections for He^+ Ions and Protons of Equal Velocity Incident on Molecular Nitrogen.

the neutral helium atom. This difference is not unexpected since the two cases are quite different, and may be most sensitive to quite different spatial regions of the wave function.

A theoretical calculation by Boyd et al. has been made for a bare nucleus plus one electron incident on atomic hydrogen.[16] It was suggested there that a doubling of the atomic cross section would produce the cross section for the molecular structure. This scaling was carried out and is presented in Figure 29. It appears that doubling the atomic cross section is just a first approximation for the molecular cross section. The doubled atomic cross section lies consistantly above the present results. Since this calculation was the same type as that of Bates and Griffing the scaling procedure described in Chapter III was made and the results of it agreed well with present results as is shown in Figure 29.

CHAPTER VII

CONCLUSIONS

The experimental values of the cross sections for the production of slow positive ions for He^{+} ions incident on helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide are presented for comparison in Figure 31, while the cross sections for the production of free electrons for He^{+} ions incident on the above mentioned gases are presented for comparison in Figure 32. The energy of the incident particles ranged from 0.133-1.00 MeV.

Theoretical calculations for ionization cross sections using the Born approximation have been made by Mapleton (He^{++} + He)[14] and Bates and Griffing (He^{++} + H)[13] for point-charge ions, i.e., completely stripped nuclei, and were found to agree well with the present results.

A general theoretical treatment[19] of high energy ionization by Bethe for incident point-charge ions was compared with both helium and hydrogen for incident He^{++} ions. This theory used known experimental proton ionization cross sections to determine needed constants. The agreement between this theory and present results is good. Also the estimated experimental ionization cross sections of several gases by He^{+} ions were compared with Bethe's calculations to examine the proposition that the Bethe treatment could be used for the case of an ion carrying bound electrons by using an "effective" charge Z_i lying between the nuclear charge and the actual net charge of the ion. To be a useful concept, the effective charge for a given incident ion must be found to be independent of

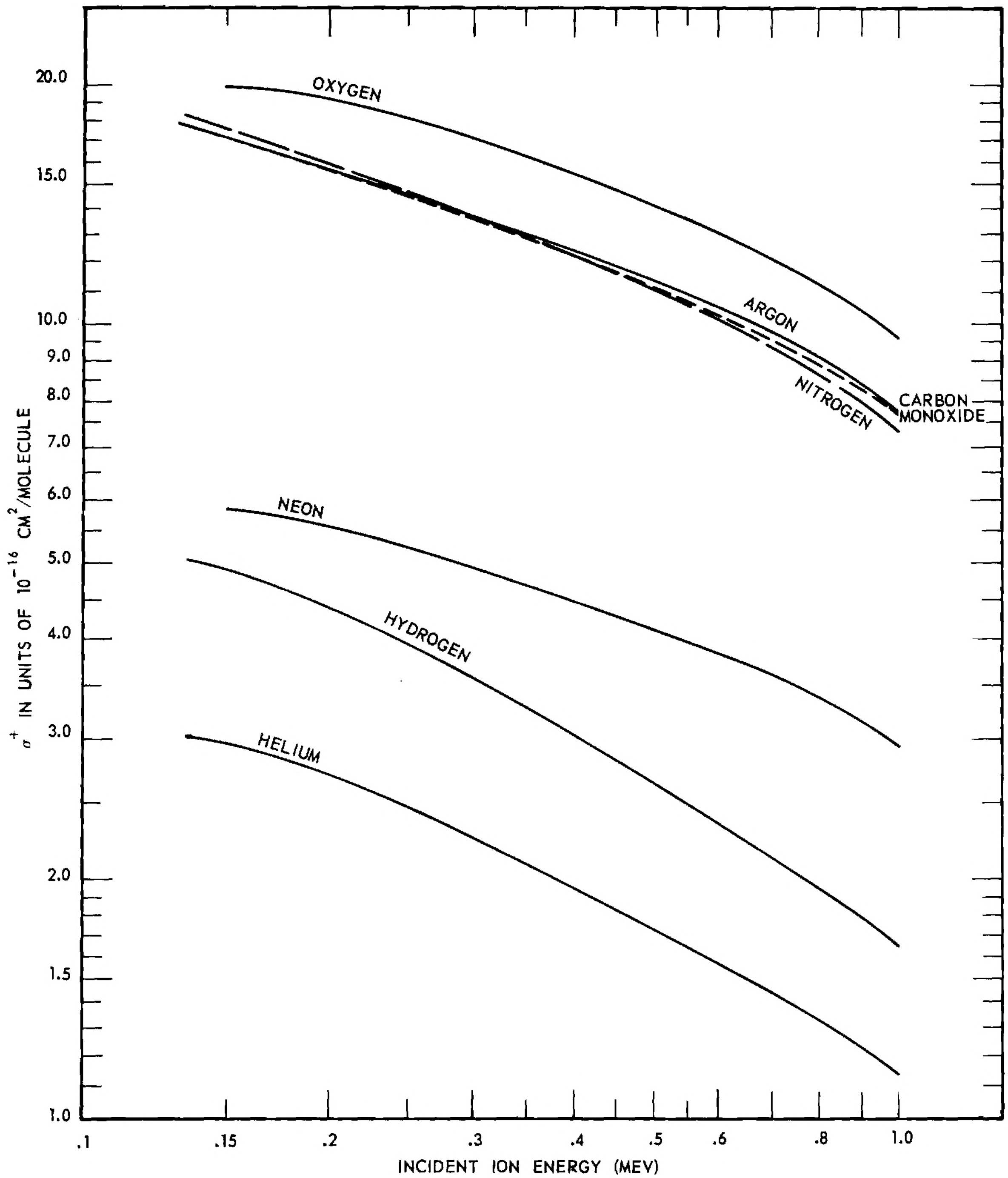

Figure 31. Cross Sections for the Gross Production of Positive Ions by He^+ Ions Incident on Helium, Neon, Argon, Molecular Hydrogen, Molecular Nitrogen, Molecular Oxygen, and Carbon Monoxide.

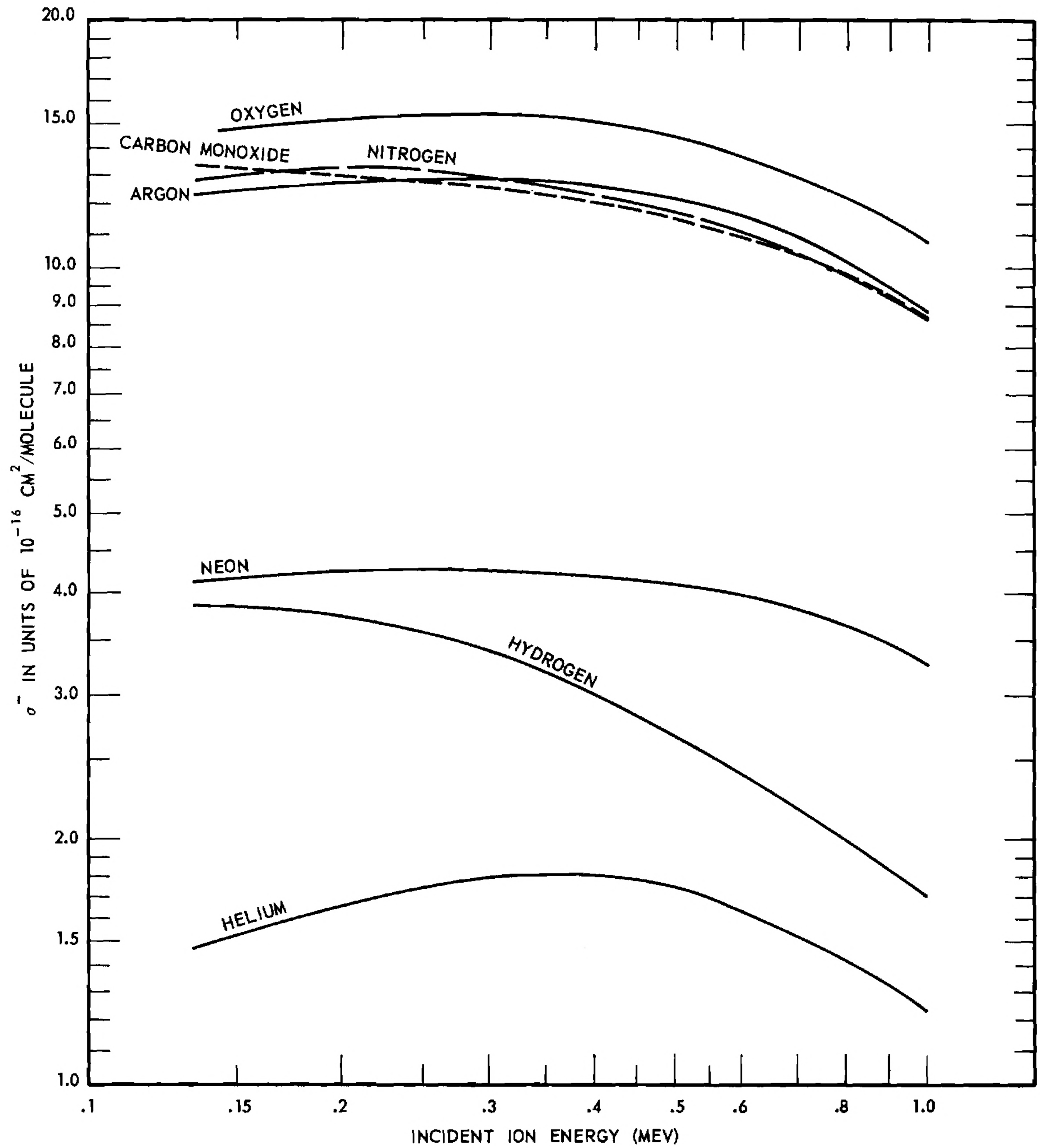

Figure 32. Cross Sections for the Gross Production of Free Electrons by He^+ Ions Incident on Helium, Neon, Argon, Molecular Hydrogen, Molecular Nitrogen, Molecular Oxygen, and Carbon Monoxide.

the target gas and of the incident ion energy. The theoretical calculations referred to here describe only "simple" ionization events in which the incident ion does not gain or lose electrons. Therefore the present experimental data on the total ion and electron production by He^+ had to be corrected for the appreciable contributions from charge-changing events encountered at high energies. With presently available information this correction can be made only approximately, even for those cases where the "stripping" cross section has been measured.[21,24] It was found that the estimated cross section for simple ionization was greater than that for incident protons of the same velocity by a factor that was very nearly independent of energy above 0.6 MeV, and varied only from 1.3 to 1.5 for the four gases hydrogen, helium, argon, and nitrogen. Thus the concept of an effective charge of about 1.2e for He^+ does seem to have at least a qualitative validity. It is noteworthy that this value is appreciably less than the effective charge 1.69e deduced in variation calculations of the ground state wave functions of helium. This difference is not unexpected since the two cases are quite different, and may be most sensitive to quite different spatial regions of the wave function.

A more exact theoretical treatment of He^+ incident on atomic hydrogen has been made by Boyd et al.[16] A doubling of the theoretically determined atomic ionization cross section to obtain the molecular cross section is suspect in that it leads to a cross section higher than the experimentally observed cross section. The scaling procedure described in Chapter III was applied to the theoretical calculations and agreement between the estimated experimental ionization cross section and the scaled theoretical cross section was excellent.

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_o 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:

$$-\frac{dN(x)}{dx} \sim N(x)n \qquad \text{(A-1)}$$

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

Let the constant of proportionality be represented by σ. Then:

$$-\frac{dN(x)}{dx} = \sigma N(x)n \qquad \text{(A-2)}$$

Integration of Equation (A-2) followed by evaluation of the arbitrary constant yields:

$$N(x) = N_o \, \varepsilon^{-n\sigma x} \qquad \text{(A-3)}$$

A knowledge of N_o, $N(x)$, and n leads to a determination of σ. It will be observed that the proportionality constant σ has the dimensions of $(\text{centimeters})^2$. Therefore σ 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, σ 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 for all possible types. Thus:

$$\sigma = \Sigma \, \sigma_n \qquad \text{(A-4)}$$

where σ_o, σ_1, σ_2, σ_3, etc. represent the individual cross sections. In general σ and all of the σ_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. The gross cross section for the production of free electrons can be determined by measurement of the electron current.

To construct a model for this experiment let n represent the number of target atoms per unit volume, σ_- 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_o 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:

$$f = \frac{A\ \sigma_-\ n\ dx}{A} = \sigma_-\ n\ dx \qquad (A\text{-}5)$$

This result is based on the assumption that the gas pressure is sufficiently low that the shielding of one target atom by another is a negligible effect.

$N_o\ \sigma_-\ n\ dx$ 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, $N_o\ \sigma_-\ n\ell$ 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 production cross section σ_-. The total number of electrons collected per unit time under the preceding conditions will be equal to $N_o\ \sigma_-\ n\ell$. The collected electrons will produce a current I^- equal to $N_o\ \sigma_-\ n\ell\ e$, where e denotes the electron charge.

Essentially 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:

$$\frac{I^-}{I_i} = \frac{N_o\ e\ \sigma_-\ n\ell}{N_o\ e} = \sigma_-\ n\ell \qquad (A\text{-}6)$$

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

$$\sigma_- = \left(\frac{1}{n\ell}\right)\left(\frac{I^-}{I_i}\right) \text{ cm}^2\text{/target particle} \qquad \text{(A-7)}$$

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

$$\sigma_+ = \left(\frac{1}{n\ell}\right)\left(\frac{I^+}{I_i}\right) \text{ cm}^2\text{/target particle} \qquad \text{(A-8)}$$

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VITA

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He attended public school in Athens, Georgia, and was graduated in 1955. He received the degrees of Bachelor of Science in Physics and Master of Science in Physics in June 1959 and June 1960, respectively, from the Georgia Institute of Technology.

Since 1959 he has been a Graduate Research Assistant at the Engineering Experiment Station. In 1963 he served as a Graduate Instructor of Physics at the Georgia Institute of Technology.

TECHNICAL STATUS REPORT NO. 16

PROGRESS REPORT

PROJECT NO. B-176

Covering the Period

March 1, 1963 to November 30, 1963

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By D. W. Martin
D. S. Harmer
L. J. Puckett

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

U. S. ATOMIC ENERGY COMMISSION
OAK RIDGE, TENNESSEE

1 December 1963

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

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Progress Report

I. Title

Ionization and Charge Transfer Cross Sections

II. Period Covered by Report

The period covered by this report is March 1, 1963 through November 30, 1963. This period corresponds to the first 9 months of the 12-month extension provided for by Modification No. 4 of Contract No. AT-(40-1)-2591.

III. Scope of the Research

A general study 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 has been in progress at this laboratory under this contract since September 1959. These cross sections have been measured under "thin" target conditions with 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.

A. Results Achieved

Prior to the present report period, measurements were made of the apparent ionization cross sections for protons incident on targets of He, Ne, Ar, H_2, N_2, O_2, 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 were 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 have been published in the open literature.[1-3]

Other results obtained prior to the period covered by this report included measurements of the cross sections for He^+ ions incident on targets of He, Ne, Ar, H_2, N_2, O_2, and CO. These results were summarized in the Annual Summary Report (Technical Status Report No. 14) of March 1, 1963. This report also included a detailed comparison of He^+ and proton ionization in which it was shown that the apparent ionization cross sections for the incident He^+ ions, at sufficiently high energies, corresponded to the values expected for a point-charge ion having an "effective charge" of 1.2e.

In the period covered by this report, experimental measurements of the apparent ionization cross sections for He^{++} ions incident on helium and hydrogen have been made for incident particles in the energies range 0.50 to 1.00 MeV. In this energy range the Born approximation should be valid and therefore it was of interest to compare the experimental results with those obtained from theoretical calculations based on this approximation.

The values of the cross sections calculated from theory by Mapleton (He^{++} + He°)[4] and by Bates and Griffing (He^{++} + H°)[5] were found to agree quite well with the experimentally determined values. In addition, using the general theoretical treatment of high energy ionization of Bethe,[6] with target gas parameters determined from proton measurements,[3] the cross sections for He^{++} point-charge ions were calculated. The agreement between these values and the present results was also found to be good. It had been shown[3] previously that the observed proton and electron ionization cross sections at the same incident particle velocity were the same at sufficiently high energy as predicted by this theory. The current He^{++} results show the observed cross section to be the ion charge squared times the cross section for protons or electrons of the same velocity incident on the same target gas, also in agreement with the form of the Bethe theoretical expression.

This agreement among the data for electron, proton and doubly-charged helium ionization cross sections lends credence to the use of the same theoretical treatment for the case of the He^+ ion in which the effective charge of the ion is taken to be 1.2e rather than 1.0e.

Excellent agreement was also obtained between the He^+ data for molecular hydrogen and the more exact theoretical treatment of He^+ on atomic hydrogen of Boyd, Moiseiwitsch and Stewart[7] if the theoretical values are modified by the known functional dependence[6] of the cross sections on the ionization potential of the struck atom and assuming the H_2 molecule acts as two atoms each with an ionization potential characteristic of the molecule. This scaling of the cross sections of atomic to molecular hydrogen had been shown previously to give good agreement in the case of ionization by protons.[1-3]

Details of the results for fast helium ions, including the above mentioned comparisons and details of the apparatus and experimental methods were given in the doctoral thesis of R. A. Langley which was published as Technical Status Report No. 15 (June 1, 1963). A summary of these results was presented at the Third International Conference on the Physics of Electronic and Atomic Collisions in London, 23-26 July 1963, and will be published in the Proceedings of this meeting by the North-Holland Publishing Company, Amsterdam. A more detailed report is in preparation for submission to the Physical Review.

B. Current Studies

After the measurements of He^{++} beams in H_2 and He targets had been completed and verified for presentation in the London paper, measurements of He^{++} beams in the heavier gases Ar and N_2 were begun, as had been anticipated in our proposal of December 1, 1962. As expected, the cross sections for these targets proved to be several times larger than for H_2 and He, and this necessitated operation with lower target gas pressures in order to maintain thin target conditions. After a series of measurements were made it became evident that inconsistent McLeod-gauge target-gas-pressure readings were causing serious discrepancies in the data. A new "extended range" gauge, Consolidated Electrodynamics Corp. No. GM-110, had been acquired in the latter part of the previous contract year, and had been used during the He^{++} measurements in H_2 and He. In comparison to the smaller GM-100A gauge used earlier, this gauge nominally can be read at a twenty-five times lower pressure with the same precision. However, this gain has proved to be partly illusory because of friction and sticking of the mercury columns in the smaller capillaries of this gauge. This problem had caused some difficulty even during the measurements in H_2 and He, and became so severe during the attempted measurements in Ar that the cross sections were uncertain by more than 20 per cent in some cases.

Following various efforts to improve the performance of the gauge, in consultation with the manufacturer, the gauge was returned to the factory for repair and calibration. It was damaged in transit when it was returned, and had to go back a second time for further repairs. It has been reinstalled only recently, and unfortunately the sticking problem is still rather severe. At the time of the present writing, a series of systematic observations of the behavior of the gauge is being conducted to determine whether the sticking errors are sufficiently reproducible to be evaluated and consistent corrections made for them. Otherwise it appears that the gauge must again be dismounted and a further effort made to clean the capillaries, which is quite difficult with this particular type of gauge. These difficulties certainly emphasize the point we have often made before, that the lack of a really good absolute way to measure gas pressures in this range is the largest single uncertainty in the measurement of accurate cross sections.

As a result of these delays with the McLeod gauge, no further final results have been obtained beyond the He^{++} measurements in H_2 and He targets that have been detailed previously in Technical Status Report No. 15. However, work has proceeded on the development of other new components of the apparatus required for the extensions of our measurement program that were scheduled for the present contract year, namely, extension to the case of incident neutral particles and the addition of e/m analysis of the slow ions formed.

C. Measurements with Incident Neutral Beams

The charge-changing gas cell and electrostatic fast-beam analyzer constructed during the previous contract year for the production of fast He^{++} beams was so designed that it can also be used to produce a beam of fast neutrals, as has been described in detail in Technical Status Reports Nos. 14 and 12. However, a detector for the emerging fast neutral beam is required and the development of a satisfactory device has been essentially completed at the time of this writing. A combination arrangement has been constructed which can serve simultaneously as a total-charge Faraday cup, as a total-beam-power thermal detector, or as a secondary emission detector. Choice of the function is selected solely by the external circuit connections without any physical changes of arrangement or position of the detector or its parts. The thermal-detector function may be readily calibrated against the total-charge-collection function by using a charged-particle beam, and the resulting calibration may be confidently applied to neutral beams on a priori grounds. Further, this calibration should be stable and independent of the particle type. Then the secondary-emission-detector function can be very easily calibrated, for each energy and type of particle, against the thermal-detector function. The ease with which this calibration can be made permits it to be made as often as necessary, so that any lack of long term stability in the calibration is of no great consequence. There are two principle reasons why the secondary-emission-detector function has been added, despite the extra calibration step required, and even though in principle we could use the thermal-detector function directly in routine measurements. First there is simply the greater convenience of measuring the secondary-emission current continuously with an electrometer as against the measurement of a thermocouple EMF with a potentiometer. Secondly, the secondary-emission current responds immediately to fluctuations in the incident particle flux, whereas the thermal detector response is necessarily more or less sluggish and this might prove to be a serious problem under the conditions sometimes encountered where the incident particle flux is not very stable.

An additional advantage of the arrangement chosen is that the immediate availability of the total-charge Faraday cup function allows us to continue our established practice of frequent checking of the entire measurement by means of periodic remeasurement of our well-established cross sections for incident protons.

The idea of such a three-way combination detector is by no means original, having been used previously by Barnett among others. However, explicit details of the construction of his detector were lacking, so that we have had to engage in our own trial and error development.

The thermal detector consists essentially of a small metal foil disc of sufficient size and thickness to intercept and stop all of the beam particles, which is partly isolated thermally so that the kinetic energy deposited in the disc by the beam particles will raise its temperature. The equilibrium temperture rise, measured with a thermocouple, is related to the total power, and hence the intensity at given kinetic energy, of the beam. In our device, the disc is attached to and mechanically supported by fine wires which constitute one side of the thermocouple, and also provide electrical and limited thermal conduction contact with a massive base ring. A separate dissimilar wire attached to the center of the disc forms the other side of the couple. The size and mass of the disc are kept as small as possible to minimize its heat capacity in the interest of rapid response, but the optimum supporting wire size must be determined empirically as a compromise between the sensitivity and response-time requirements. It is easily seen that increasing the size and conductivity of the wires will improve the response speed, but will also decrease the equilibrium temperature rise and hence the overall sensitivity.

The thermocouple first chosen for trial was the common pair chromel-alumel, with the chromel chosen more or less arbitrarily for the disc supporting wires. Using a small brass disc and 6-mil diameter wire, an excellent sensitivity was obtained--over 5,000 microvolts of thermal EMF for about 10^{-8} amperes of protons incident at 1 MeV, which indicated a temperature rise of over 60°C. However, the response speed was very poor, with a time constant of about 75 seconds. Increasing the wire size at first improved the response speed. However, beyond a certain point there was no further improvement in response speed, even though further increase in wire size continued to decrease the sensitivity. For example, with the same brass disc and 16-mil diameter chromel support wires, the sensitivity had decreased tenfold while the response time remained in excess of 20 seconds.

It was then realized that with the larger wire sizes, the heat capacity of the wires themselves was comparable to that of the disc, so that further increase in size added conductivity and capacity proportionately, with no net gain in response time. Accordingly, a "figure of merit" for the support wire material is the ratio of the thermal conductivity to the heat capacity per unit volume, i.e., to the product of the density and the heat capacity per unit mass. On the basis of this figure it was then realized that copper and silver far surpass all other common metals, with silver being almost 50% better than copper. In addition, a thermocouple of either one with constantan has just as large a thermal EMF as chromel-alumel, and a couple of either one with iron would be nearly twice as good. Evidently silver-iron is the best combination, although it seems certain that copper-iron would also be more than adequate. At the present writing, we are trying to locate a supply of fine silver wire, but we can try the copper at any time if the silver is not immediately forthcoming. At any rate, it appears clear that a completely satisfactory detector can now be assembled at any time with essentially no further development effort.

D. Slow-Ion e/m Analyzer

The major new addition to the experimental apparatus contemplated for the present period is a device providing charge-to-mass ratio analysis of the slow positive ions formed in the target gas by the fast beam particles. With such an analyzer the relative contributions of singly- and multiply-ionizing events to the total ionization can be determined, or in the case of molecular target gases, the relative frequencies of the formation of atomic or molecular ions. In either case, the general objective is to obtain more detailed information about the ionization collisions, in order that the results may be compared with available theoretical calculations or extrapolated to higher energies with fewer assumptions and greater confidence.

The analyzer could be of any of several general types, and considerable thought has been given to the selection of the type. High resolution is not at all necessary, since it is necessary to distinguish only between singly-, and doubly-, triply-, etc. charged ions of a given mass or between the atomic and molecular ions of a diatomic target gas. However, an important consideration is that a small fraction of the ions of each type may have initial kinetic energies of as much as 50 eV; the instrument chosen must either be insensitive to the initial energy or have sufficient resolution not to confuse a 50-eV ion of one e/m with a slow ion of any other possible e/m. The latter alternative offers the advantage that the slowest and the fastest ions may be examined separately if desired, to determine whether there is any material difference in the energy distributions of the ions of various e/m.

The dominant considerations are that the transmission efficiency of the analyzer be independent of the ion type, be either calculable or experimentally determinable, and finally, be as large as possible. Compactness, simplicity, and cost are of course also considerations.

The simple, familiar scheme of deflection in a magnetic field following electrostatic acceleration has been chosen, despite the fact that the "acceptance aperture" must be sharply restricted by slits to obtain adequate resolution. Due consideration was first given to two alternatives. One is the class of analyzers utilizing either radio-frequency or pulsed grids that are essentially time-of-flight analyzers. These may have relatively quite large acceptance apertures. However, ions may be admitted for analysis during only a small fraction of the time when the RF or timing cycle is at the proper phase. For a given resolution, this "duty cycle" must be small enough that the overall time-averaged transmission efficiency is not materially better than that of a comparable magentic deflection instrument. For some types there are also difficulties with the spurious transmission of ions of a given e/m for frequencies that are integral multiples of the proper frequency, which tends to confuse ions having e/m ratios that are integral multiples of each other. Since this is precisely the type of spectrum we wish to analyze, problems of this type would be most serious.

A second general class of analyzer considered was the relatively recently developed radio-frequency quadrupole analyzer. This type offers both a large acceptance aperture and a full time duty cycle. However, rather large radio-frequency voltages are needed, which have excellent stability and are continuously tunable over a wide range of frequency. No complete instruments of this type are known to be available commerically, and it is even likely that an adequate RF voltage supply is either not available or quite expensive. In any case it appeared that development of an instrument of this type would involve an extensive effort, and so further consideration of this type was reluctantly set aside, at least for the present.

The chosen magnetic deflection instrument may be tuned for ions with different e/m values by varying either the electrostatic acceleration field or the magnetic deflection field. The first alternative is attractive because it would permit the use of a permanent magnet. However, a maximum voltage of more than 10 kV would be required in order to cover a 40 to 1 range of e/m values and at the same time keep the voltage always large enough that the fractional energy spread of the accelerated ions due to their initial energies is small. Further, the slit widths and therefore the transmission would also have to be varied if the initial energy distribution is to be visible at every e/m, as mentioned above. It has, therefore, been decided that our purposes would best be served by an instrument with a continuously variable magnetic field. A permanent magnet with a variable shunt will be used in preference to an electromagnet if this proves to be feasible and compares favorably with respect to weight, bulk, and cost. This question has not yet been resolved but is now under study.

The Nier mass spectrometer employing a 60° deflection in a sector field has been chosen as the basic design type. A deflection radius of curvature of 5 cm and an accelerating voltage of about 300 volts have tentatively been chosen for the major design parameters, subject to possible modification if the resulting size of the magnet seems to be impractical. Actual construction of the device must await the completion of the magnet design.

The analyzer is to be mounted at right angles to the fast beam directly behind the present slow-positive-ion collector plate. An accurately machined slit in the center of the collector plate, also oriented at right angles to the beam direction, will serve as the entrance slit. The fraction of the slow ions drawn to the collector plate which enter the analyzer should then be equal to the ratio which the width of the slit bears to the length of the collector plate along the beam direction. The electrical connections will be such that gross measurement of the current of all ions reaching the collector plate and analysis of those ions which enter the slit can be performed simultaneously. Comparison of the total analyzer current for all values of e/m present with the collector plate current will then provide a measure of the transmission efficiency of the analyzer; hopefully it will be found to be possible to make this 100% for all ions which enter the slit. In this way the cross sections for the formation of ions of various e/m will be determined not only relatively but absolutely, with the simultaneous remeasurement of our now well established total ion production cross sections serving always as an automatic check of self -

consistency and accuracy.

E. Estimated Progress for the Remainder of this Period

In the proposal of December 1, 1962, covering the present contract year, it had been anticipated that all of the gross ion production measurements for beams of incident He^{++} and H^{o} would be completed within this period, that construction of the e/m analyzer would also be completed, and that measurements utilizing the analyzer would be well underway. As the details of the present status of the work given above indicate, the progress of the work is somewhat behind schedule at this time. The problems described above with the McLeod gauge used in determination of the target gas pressure have been a major source of delay. In addition, the level of activity during the summer months was somewhat curtailed by the lengthy absence of the Principal Investigator while attending the Paris and London conferences, and by preoccupation of the senior graduate student with preparations for major examinations in September.

The pressure determination problem is now receiving concentrated attention. Upon its resolution, the remaining He^{++} and H^{o} measurements will be resumed, and they may reasonably be expected to be completed within the remaining quarter of this period. Meanwhile, the construction of the e/m analyzer will be pressed. While it now appears to be unlikely that any substantial program of measurements utilizing the analyzer can be performed within this period, the construction itself should be largely completed within the time remaining. The level of effort during this time will correspond approximately to that originally specified for this period.

IV. Publications and Travel

Dr. D. W. Martin attended the Third International Conference on the Physics of Electronic and Atomic Collisions in London, 23-26 July 1963, and presented a summary of the fast helium ion results in a paper entitled "Production of Slow Electrons and Positive Ions in He, Ne, Ar, H_2, N_2, O_2 and CO by Energetic Helium Ions" at this meeting. The text of this paper will appear in the Proceedings of the meeting to be published by the North-Holland Publishing Company of Amsterdam. A more detailed account of the results is now in preparation for submission to the Physical Review.

V. Personnel

R. A. Langley received the degree of Doctor of Philosophy in Physics in July 1963 from the Georgia Institute of Technology and is now on active duty with the United States Air Force at the Air Force-Cambridge Laboratories. Mr. L. J. Puckett, who has been working on the project since January 1963, is now the senior graduate student with the project.

VI. Incident Report

There have been no incidents, as defined in Attachment "A" of letter of instructions dated November 5, 1963, during the performance of the research under this contract in the present reporting period.

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TECHNICAL STATUS REPORT NO. 17

PROGRESS REPORT

PROJECT NO. B-176

Covering the Period

December 1, 1963 to November 30, 1964

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By D. W. Martin
E. W. Thomas
L. J. Puckett
G. O. Taylor

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

U. S. ATOMIC ENERGY COMMISSION
OAK RIDGE, TENNESSEE

1 December 1964

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

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December 1, 1964

Technical Status Report No. 17, Project No. B-176

Progress Report

I. Title

Ionization and Charge Transfer Cross Sections

II. Period Covered by Report

The period covered by this report is December 1, 1963 through November 30, 1964. This period corresponds to the first 9 months of the 12-month extension provided for by Modification No. 5 of Contract No. AT-(40-1)-2591, plus the final 3 months of the preceding contract period.

III. Scope of the Research

A general study 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 has been in progress at this laboratory under this contract since September 1959. These cross sections have been measured under "thin" target conditions with electrostatic collection of the slow charged particles 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.

A. Results Achieved

We summarize first very briefly the earlier results achieved in this continuing program, up to the time of the last Progress Report of 1 December, 1963. The total apparent cross sections for the production of slow positive ions and free electrons had been measured for the following projectiles and targets, over the energy ranges of the incident particle indicated:

Protons into helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide, from 0.15 MeV to 1.1 MeV;

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Singly-charged helium ions into the same seven gases, from 0.133 MeV to 1.0 Mev;

Doubly-charged helium ions into helium and hydrogen, from 0.5 to 1.0 MeV.

Detailed comparisons have been made between these results and all other known experimental results of the same type, all of which are over lower energy ranges that extend into only the lower part of our energy range. Also, detailed comparisons have been made between our results and the available theoretical calculations, among our results for the various projectile particles into the several target gases, and between our results and the results of others for electrons into the same targets. For incident helium ions, further comparisons have been made between the differences of our positive ion and electron production cross sections and the measurements by others of the total charge changing cross sections.

All of the results and comparisons for incident protons had been published previously, as had an abbreviated summary of the helium ion results and comparisons, and these references have been given in previous reports. A detailed report of the helium ion results and comparisons was published in two papers in The Physical Review during the period covered by the present report. These will be found listed in the Publications Section.

The program for the present period contemplated first of all the extension of the He^{++} measurements to nitrogen and argon targets, and secondly measurements in several target gases for incident neutral atoms of hydrogen and helium. As this program proceeded, certain changes in the apparatus were decided upon and accomplished, as the need for them became apparent.

1. Extension of He^{++} Measurements to Lower Energies.

In earlier reports we have explained in some detail why the measurements for doubly-charged helium ions were restricted to energies greater than 0.5 MeV. Briefly, the apparatus as constructed was unable to provide a sufficiently pure beam of He^{++} of adequate intensity for lower energies, due to the energy dependence of the various charge changing cross sections. The nature of the previously reported results in the first two target gases showed that it would be worth some extra effort to try to extend this energy range lower. The log-log plot vs. energy of our estimates of the apparent cross sections for simple ionization (defined to mean collisions in which the incident fast particle does not change its charge state) has a decided curvature as the energy decreases toward 0.5 MeV. It appeared that the cross section might pass through its maximum value at an only slightly lower value of the energy, and it was judged worthwhile to try to locate the maximum. It further appeared that agreement between the experimental results and the theoretical calculations might be persisting to rather lower values of the incident particle velocity for He^{++} ions than for protons. However this observation could not be stated very emphatically because of the limited energy range of the He^{++} data.

Therefore, the beam apertures of the charge changing gas cell were changed from knife-edged holes to drilled channels 1/10-inch in diameter and $1\frac{1}{4}$-inches long. In addition, the pumping speed on the "vestibule" between the gas cell and the electrostatic analyzer was increased by mounting a 2-inch oil diffusion pump directly to this chamber through as short and wide a pumping line as possible. With these changes we have been able to use higher gas pressures in the charge exchange cell, while holding the pressure in the analyzer region and the following drift space below 2×10^{-6} Torr. Further study of the available information on charge changing cross sections for helium showed that there would be a slight advantage, for low energies, if nitrogen were used in place of argon in the gas cell.

With these modifications we have been able to obtain a sufficient He^{++} intensity to conduct measurements down to 0.18 MeV, and all subsequent work has been carried to this lower limit.

2. Target Gas Pressure Measurements.

It was indicated in the last report that we had been having some difficulties in obtaining satisfactory target gas pressure measurements with the large "extended range" McLeod gauge (CVC Model GM-110). A major part of the problem was due to sticking of the mercury columns in the very narrow (0.535-mm diameter) capillaries of this gauge. The self consistency of pressure readings was never much better than about 5% in using the gauge in the normal manner, even when the gauge was new and supposedly clean. Thus the "extended range" of this gauge was largely illusory. Several attempts were made to clean this gauge better, but no real improvements were effected. Experiments were then performed to see if more reliable measurements could be obtained by reading the simultaneous positions of both columns at several different positions, for each single pressure measurement. The hope was that the sticking errors would be consistent enough that they could be evaluated, from a study of the systematics of the several readings.

Despite considerable efforts of this kind that were invested in the problem, we were never able to obtain consistently reliable results with this gauge as it stood. It was finally concluded that the small capillaries were simply not practical. Therefore we have replaced them with larger capillaries made from a single length of precision 1.00-mm diameter tubing, which was first thoroughly cleaned, and then was carefully calibrated over its whole length.

Even with the new capillaries, we were not satisfied with the results obtained from single readings in the normal manner, i.e., raising the meniscus in the open capillary level with the end of the closed capillary, and then reading only the position of the meniscus in the closed capillary. We now follow a procedure of reading the positions of both columns for three different positions of the open column, computing a value of the pressure for each, and averaging these three results. This procedure has not proved to be too burdensome because our normal mode of operation of the experiment involves holding the target gas pressure constant while a complete run of cross section measurements are made over all or a large part of the energy range of the incident particle, a procedure that normally takes one or two hours. Several separate measurements of the pressure are made during this period, and the entire run is discarded if the self consistency is not adequate. Such runs are of course made for several values of the pressure to assure that there is no systematic dependence of the cross section values obtained on the pressure, which assures that thin target conditions prevail.

With these improvements we now find that the self consistency of our measurements has been much improved. In numerous spot checks we have found that we can usually reproduce a given previous cross section measurement within about 3% in absolute value.

During this period we first became aware of several papers in the vacuum technology literature dealing with systematic errors in gas pressure measurements with cold-trapped McLeod gauges, due to the pumping action of mercury vapor streaming to the trap (the Iishi or Gaede effect). Both theoretical and experimental evidence given in these papers indicated that the effect could produce rather appreciable errors; applying the formulae given to our own gauge, errors were predicted ranging from about 2% for hydrogen and helium up to about 12% for the heaviest target gas, argon, for the pressure range in which we work. On consulting with other workers in the cross section field, we found that at first there were some differences of opinion as to whether the effect could really be as large as this; certain aspects of the theory do seem to be open to question. Therefore we published our helium ion data without the correction, but put a note in the paper about it, including the magnitude of the correction for each target gas as given by the theory.

More recently, evidence has been accumulating in several laboratories which indicates that the existing theory of this effect may be essentially correct. We have not undertaken any direct experimental tests in our own laboratory, but we are making an effort to keep up to date with developments elsewhere. At the present time, the thinking is that probably all of our earlier published data should be modified by this correction, which takes the form of a uniform reduction of the cross sections at all energies by the percentages mentioned. We note however that our extensive previous comparisons with theory are essentially unaffected; these have involved only hydrogen and helium targets, and for these gases the correction is small. The affect on the validity of our comparisons with the experimental results of others is problematical. As far as is known all such other data was probably subject to a similar error, but because of differences between the dimensions of their gauges and ours, the magnitude of the corrections required may be different.

3. Background Corrections.

Steps have been taken to reduce the residual or background pressure in the collision chamber. Our precedure has always been to pass the beam through the chamber with the target gas supply shut off, but with all throttling valves in the pumping lines set exactly as they will be set when the target gas is being flowed through. It is assumed that the ionization currents observed under these conditions will be essentially the same as the contributions to the total currents due to the residual background gases when the target gas is present, so that the currents observed with no target gas are simply subtracted from the currents observed with the target gas. Since this assumption is surely not strictly correct, we set a rule that the target gas pressure must be high enough, or else the background level low enough, that the corrections do not exceed 10%. However, the target gas pressure is also constrained to be low enough that the target remains "thin", both with regard to the ionization cross section itself, and more particularly with regard to the charge changing cross sections (otherwise the incident beam would become appreciably contaminated with particles in other than the intended charge state).

As the equipment stood a year ago, these two constraints permitted us a range of only about a factor of two in the target gas pressure for He^{++} into hydrogen and helium; for the heavier target gases with their larger cross sections, the range was even narrower, so that it was deemed essential to accomplish a reduction of the background. The existing background was not simply due to gross atmospheric leaks in the chamber; these had been located and closed, and a measurement with the McLeod gauge of the background pressure normally gave an essentially zero reading. However, the ion gauge attached to the chamber would usually read in the mid 10^{-6} torr range. It appeared that our background was due largely to condensible type impurities coming from surfaces in the chamber or from gaskets, etc., since a cold trap in the main pumping line should have largely blocked the backstreaming of oil from the pumps. The chamber could not be made bakeable without extensive modifications or even complete reconstruction. Therefore, as a stopgap measure, a flask to hold liquid nitrogen was constructed to hang inside the collision chamber. The flask is located above the horizontal collector plate assemblies in such a position that the target gas in the active region cannot "look" directly at the cold surface; the port leading to the McLeod gauge "looks" directly into the collision volume between the plates, and also cannot "see" the flask directly. These precautions are necessary to prevent perturbation of the target gas temperature and hence the measurement of the target molecule density by means of the pressure measurement.

As a check, a fine thermocouple has been suspended in the chamber at various places in and around the active region, and these tests have shown no evidence that the gas temperature is altered appreciably by adding liquid nitrogen to the flask. Also, the addition of the flask has not affected our ability to reproduce cross section values obtained without the flask. It has very effectively reduced the residual background as intended. We now obtain background ion gauge readings in the low 10^{-7} torr range, and the background ionization currents have been reduced two orders of magnitude, so that they are now seldom any problem.

Presence of this large cold surface right in the collision chamber is of course still rather worrisome, despite the reassuring test results mentioned above. It is clear that a cleaner and bakeable chamber would be a much preferable alternative.

4. The Excess-Electron Problem.

Another matter given considerable attention in this period has been the problem, discussed in some detail in previous reports, of excess electron currents collected from the collision region under some conditions. These have been thought to be fast electrons from slit edges, etc, that enter the chamber with the incident beam. The extent of the trouble that we have with this matter tends to vary erratically from time to time, often for no apparent reason. Presumably this is due to slight shifts in the incident beam profile or location at the entrance collimator apertures. Such shifts could be caused by, among other things, aging of the Van de Graaff ion source and the erosion of its exit aperture by the beam. Whenever the problem becomes troublesome, we simply have to rework the alignment of the collision chamber and collimator assembly with the beam, and/or restudy the dependence of the collected electron currents on the voltages applied to the various electrodes in the chamber, to find a suitable plateau. Judgement of the adequacy of the plateau used is based upon the ability to reproduce the well known equality of the positive ion and electron currents for incident protons in any of our target gases for energies above 0.2 MeV.

During one particularly troublesome series of difficulties with this matter, the entrance collimator was dismantled for inspection for the first time in several months. Evidence was seen of a surprisingly large amount of beam "splash" around the second and third apertures of the collimator. Since then we have made the second aperture larger than the first, keeping it still small enough to completely hide the edges of the first aperture from the surfaces of the third aperture. We also put a small pair of brass deflector plates in the space beyond the second aperture, to which potentials of up to 100 volts could be applied, to sweep any fast electrons out of the beam before it reaches the third aperture. Optical alignment of the three apertures, on reassembly of the collimator, was done with a telescope rather than the naked eye as had been done previously. These measures have effected a considerable improvement in the excess electron problem. Because of the improved geometry and alignment of the collimator, we find that the application of up to 80 volts to the deflector has essentially no effect at all, when the overall alignment with the beam has been optimized.

The recurring problems we have had in this area illustrate the difficulty of obtaining absolute electron production cross sections. One can obtain reliable results, and know they are reliable, only by frequent checking of the optimization of the apparatus alignment and of the applied collection voltages. The generally rather good agreement we have been able to obtain between the difference of our positive ion and electron production cross sections and the measurements by other methods of the total charge changing cross sections is taken as evidence that our procedures have been adequate and that our final results have been good. It should be noted that these adjustments we frequently make to minimize the excess electron current usually have little or no effect on the values we obtain for the positive ion production cross section.

5. New results obtained.

Measurements have been completed for He^{++} ions incident on targets of nitrogen and argon, over the energy range 0.18 to 1.0 MeV. The internal consistency of these data is generally much better than that of the earlier measurements for He^{++} in hydrogen and helium, due to the improvements in apparatus and technique detailed above. In both of the present cases, agreement is excellent between the difference of our positive ion and electron production cross sections and the measurements elsewhere of the total charge changing cross sections.

B. <u>q/m Analyzer for the Slow Ions</u>

As has been discussed previously, the design chosen for this analyzer was the simple Nier type 60°-magnetic-deflection mass spectrometer, with a fixed accelerating voltage, a variable magnetic field, and a deflection radius of 5 cm.

An effort was made to find a suitable magnet for this instrument on the commercial market, but without success. Most of the available models are larger than desired, having usually a 4-inch pole diameter. Also, most are of the common rectangular frame design, which is bulky and awkward for a 60°-deflection instrument. Inquiries were made of several manufacturers of the possibility of having a special magnet made to our order, but it was found that this avenue would be prohibitively expensive.

Therefore we have constructed a homemade electromagnet which is tailored to our exact needs for this instrument. The steel yoke parts were machined in the Georgia Tech shops, and the windings were made in the laboratory. Our design appears to have worked out very well. A field of over 6 kilogauss is produced in the gap by a current that is well below the rating of the windings.

The addition of the analyzer to the apparatus in such a position that it samples from the same collision volume as does the total ionization measurement necessarily involves extensive physical modifications of the collision chamber. We have discussed above the generally unsatisfactory vacuum cleanliness of the present chamber. Also, in the present arrangement, the beam entrance collimator is located physically inside the beam entrance pipe, which is awkward at best, and does not provide as great a pumping speed to the space between the middle and last apertures as might be desired. We have worked out a design for a new chamber, in which the collision chamber proper is a small enclosure entirely within a larger vacuum enclosure, and in which the beam entrance collimator also lies inside this outer enclosure. The new design would accomodate the addition of the analyzer tube in a much more satisfactory way than would any modifications we have thought of for the present chamber, and would largely avoid the deficiencies of the old chamber stated above. We now propose to construct this new arrangement, as an alternative to the modification of the old chamber.

C. <u>Estimated Progress for the Remainder of the Present Period</u>

It is expected that the measurements for He^{++} in helium will be completed within a few days, and that measurements for He^{++} in hydrogen can be carried out in about two weeks. We will then begin the measurements for incident neutral H° atoms. The triple-function detector for neutrals described in the last report is ready for use, and no further construction is anticipated for these measurements to begin.

It remains to be seen whether the excess electron problem will prove to be much more serious for neutrals than heretofore, but this is surely a possibility. It may in the end prove to be impractical to try to obtain meaningful values of the total electron production cross section. However, no great difficulty is expected in obtaining the total positive ion production cross section, and for incident neutrals at high energies the latter is essentially the total apparent ionization cross section.

It is difficult to predict meaningfully at this time just how far these measurements should progress in the remaining time of the present contract period. It seems unlikely that we would get any further than the completion of measurements for H° in the four targets hydrogen, helium, nitrogen, and argon, but if these are finished we will then proceed with similar measurements for incident neutral He°.

Further substantial progress in the construction of the q/m analyzer must await a decision on our proposal to rebuild the collision chamber in the coming period. If approval is forthcoming, we will proceed with the construction of such small parts as can be financed within the present period.

Meanwhile, Dr. E. W. Thomas is proceeding with the detailed design of new apparatus required for the new program of excitation measurements that has been proposed for the coming period. Much of this design is already done, and this phase of the program should be ready to proceed rapidly as soon as funds for its support are in hand.

IV. Publications and Travel

A detailed report of the previous results for He^{++} into helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide from 0.133 to 1.0 MeV, and for He^{++} into helium and hydrogen from 0.5 to 1.0 MeV has been published in the following two papers in The Physical Review:

"Cross Sections for Ion and Electron Production in Gases by Fast Helium Ions (0.133-1.0 MeV). I. Experimental", R. A. Langley, D. W. Martin, D. S. Harmer, J. W. Hooper, and E. W. McDaniel, Phys. Rev. 136, A379-A385 (1964).

"Cross Sections for Ion and Electron Production in Gases by Fast Helium Ions (0.133-1.0 MeV). II. Comparison with Theory", D. W. Martin, R. A. Langley, D. S. Harmer, J. W. Hooper, and E. W. McDaniel, Phys. Rev. 136, A385-A392 (1964).

Dr. E. W. Thomas attended the 17th Annual Gaseous Electronics Conference held in Atlantic City, New Jersey, October 14-16, 1964. Dr. E. W. McDaniel attended the special Atomic Collisions Conference held at Culham, England, September 14-16, 1964. Drs. Thomas, McDaniel, and Martin attended the Cross Sections Conference held at AEC Headquarters, Germantown, Md. October 29-30, 1964.

V. Personnel

Dr. E. W. Thomas arrived from England on October 1, 1964 to join the atomic collisions group at Georgia Tech as an Assistant Research Physicist in the Engineering Experiment Station. Mr. L. J. Puckett, the senior graduate student assistant on the project, passed his comprehensive examinations in the fall and has been admitted to formal candidacy for the Ph.D. in physics. Mr. G. O. Taylor, a graduate student in the School of Physics, joined the project in June as a graduate assistant. Due to the press of other duties, Dr. D. S. Harmer has ceased essentially all active participation in this project.

VI. Incident Report

There have been no incidents for which a report is required during the performance of the research under this contract in the present reporting period.

TECHNICAL STATUS REPORT NO. 18

PROGRESS REPORT

PROJECT NO. B-176-001

Covering the Period

December 1, 1964 to November 30, 1965

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

By D. W. Martin
L. J. Puckett
G. O. Taylor

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

U.S. ATOMIC ENERGY COMMISSION
OAK RIDGE, TENNESSEE

1 December 1965

Engineering Experiment Station
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TECHNICAL STATUS REPORT NO. 18

PROGRESS REPORT

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U.S. Atomic Energy Commission
Oak Ridge, Tennessee

December 1, 1965

Technical Status Report No. 18 - Project No. B-176-001

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Technical Status Report No. 18, Project No. B-176-001

Progress Report

I. Title

Ionization and Charge Transfer Cross Sections

II. Period Covered by this Report

The period covered by this report is December 1, 1964 through November 30, 1965. This period corresponds to the first 9 months of the 12-month extension provided for by Modifications Nos. 6 and 7 of Contract No. AT-(40-1)-2591, plus the final 3 months of the preceding contract period.

The present report will be concerned only with the ionization and charge transfer phases of the total program, which were the subject of Part A of our proposal of January 4, 1965, covering this period. The excitation measurements phase of Part B are covered in a separate report issued the same date, designated Technical Status Report No. 1, Project No. B-176-002. It is believed that the issuance of separate reports will be somewhat more efficient, in that many potential readers will be primarily interested in only one or the other of the two phases.

III. Scope of the Research

A. Introduction

A broad program of absolute measurements of the cross sections for the gross total production of slow positive ions and of free electrons in gaseous targets by fast hydrogen and helium ions and atoms has been in progress at the Georgia Institute of Technology for several years. The energy range of the incident particles covered is from 0.15 to 1.0 MeV; this range extends to higher energies than those of any previous similar measurements elsewhere, and reaches well into the asymptotic energy region where theoretical computations in the Born approximation may be expected to be valid. Measurements for fast protons and for both singly and doubly charged helium ions have been completed in previous years. The results for protons and for He^+ ions have been published previously,[1-5] and the final results for He^{++} ions are presented in the present report. New results for incident fast neutral helium atoms are also presented in this report; recent measurements for neutral hydrogen atoms, which are not yet final at this time, are also discussed. Target gases studied have for all projectiles included the noble gases helium and argon, and the diatomic gases hydrogen and nitrogen, thus including both the simplest example and one heavier, more complex example of each type of target molecule. Additional measurements in neon, oxygen, and carbon monoxide targets were obtained for some of the projectiles.

A central interest in this program has always been a careful comparison of our experimental results with the results of such theoretical computations as are available. Unfortunately, a completely direct comparison has usually not been possible. All of the available computations[7-9] have been for simple ionization, in which the incident particle suffers no change of its internal state, and the target particle is left in the ground state of the singly charged positive ion. Our total slow ion and electron production cross sections contain contributions from "charge changing" collisions in which the fast particle gains or loses electrons, from multiple-ionization events that remove more than one electron from the target, from ionization-dissociation events in the case of molecular targets, and from ionization-excitation events that leave one or both of the collision partners in an excited state.

Information on the gross total probabilities for some of these types of events, from experiments of other types done elsewhere, does however exist for many of the sets of collision partners which have been observed here. In all cases, the nature of this information is not of such detail as to make possible a completely rigorous deduction of the simple ionization cross section from our data. However, in most cases we can, by making only quite reasonable assumptions about the relative importance of some of the detailed processes, arrive at an estimate of what we call the "apparent" ionization cross section. This quantity still includes contributions from multiple ionization of the target particle, but has been corrected approximately for the charge-changing events. This result has been compared with the theoretical computations of the simple ionization cross sections for the three cases where they exist (H^+ on H,[7] H^+ on He,[8] He^+ on H[9]). In all three cases the agreement has been remarkably good in the upper portion of our energy range. For both of the incident proton cases, marked divergence between the theory and the experiment toward lower energies begins at about 0.3 to 0.4 MeV. These results are the first to have verified the apparent high precision of the existing Born calculations at sufficiently high energy, and to have established the lower bound of the energy region for which they remain valid.

Although the detailed Born calculations are available for only the three cases mentioned above, the general properties of the Born approximation lead one to expect certain simple relationships to exist between the simple ionization cross sections at high energies for various projectile particles on a given target system.[10] We have made extensive comparisons of our estimated apparent ionization cross sections for incident helium particles in each of the several charge states with our results for incident protons of the same velocity, and with the best results from elsewhere of the results for incident electrons of the same velocity. The expected correspondence was observed for high energies between all the true "point charge" ions, i.e., electrons, protons, and doubly charged helium ions, and the break-down of the correspondence toward lower energies was also evident. Quite interestingly, singly charged helium ions could be fitted into the same correspondence scheme by regarding them as equivalent to point charge ions with an "effective charge" that had a nearly constant value of about 1.2e for each of several target gases. Similar correspondence attempted for the new neutral helium atom results, described in this report, have not produced any such simple picture.

Empirical values for the target-dependent coefficients in the $\frac{1}{E}\log E$ dependence expected for very high energies have been determined from our proton results for all of the target gases studied. Extrapolation to energies higher than those measured here can be made with some confidence from these numbers; from the general pattern of our results for several projectiles in several targets, reasonable estimates can also be predicted for the high energy cross sections for other projectile-target combinations that have not been measured. A full discussion of these comparisons and correspondences among the previously published proton and He^{+} results has been published in the open literature.[3,6] Further extension of the comparisons to include the complete He^{++} results and the new He^{0} results is given in the present report.

The current neutral measurements will thus round out a rather comprehensive unified program of measurements that presents a broad picture of the gross ionization of a variety of targets by several light ions and atoms. Already begun in the current period is an extension of this program in the direction of more detailed observations for some of the same projectile-target systems, rather than an extension of the old type of measurements to a greater variety of systems. We have called our old measurements total gross ion production cross sections. The total current of slow positive ions has been measured, without regard to what fraction may be due to multiply-charged ions. Only an estimate of the simple single ionization cross section could be made, utilizing fragmentary information available and some guesswork.

Progress Report

In the present period, we have been constructing a charge-to-mass ratio analyzer for the slow ions, to permit separate determination of the cross sections for production of each of the possible charge states of the slow ion. In the case of the diatomic molecular gas targets, the analyzer may also permit separate determination of the dissociative and the non-dissociative ionization cross sections, although there are complications in this case. Details of the analyzer design and its construction will be found below.

B. Experimental Results

We present first, in Figures 1-4, the results for the total gross positive ion and electron production by fast doubly charged helium ions in helium, argon, hydrogen, and nitrogen respectively. These results supercede our previously published results[4,5] for He^{++} in helium and hydrogen targets for energies only above 0.5 MeV; in the case of hydrogen they are essentially identical to the earlier results, but in the case of helium, the new results are systematically about 8% lower. The bulk of these results were actually obtained prior to the present report period, but they were not presented in the last report since they had not all been completed at that time. As has been our practice in the past, these results (and the following He^{o} results as well) are presented here without correction for the Gaede mercury pumping effect associated with the cold trap on our McLeod gauge.[11] The standard calculations of the effect for our gauge indicate a negligible correction for helium and hydrogen, and a downward correction of about 12% for argon and nitrogen. However, tests we have conducted here (see Technical Status Report No. 1, Project No. B-176-002, on Part B of this program, of the same date as this report) indicate that the correction may actually be less than half this large. Until these uncertainties concerning this correction are

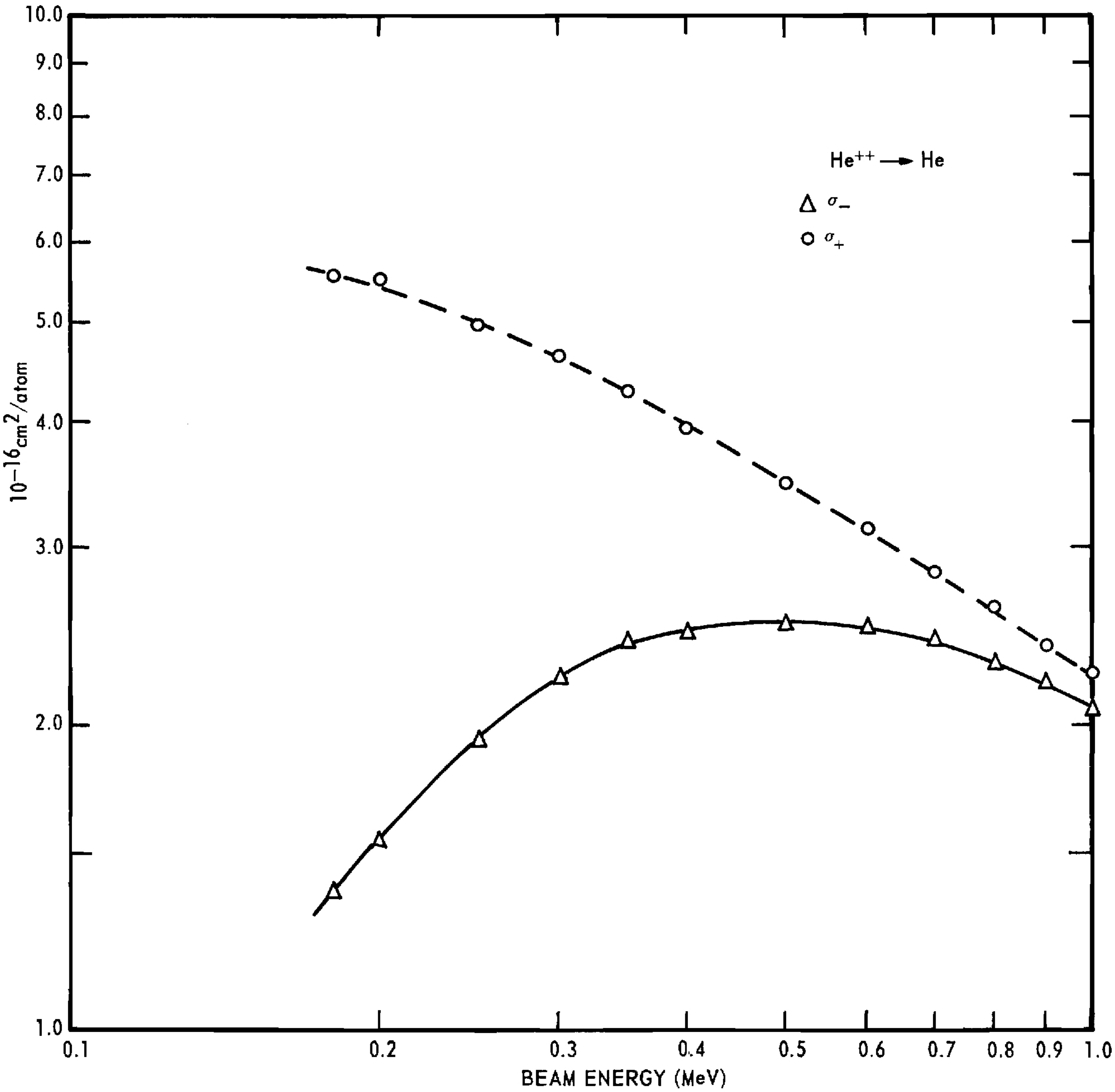


Fig. 1. Apparent cross sections for production of positive ions, σ_+, and of free electrons, σ_-, for He^{++} ions incident on helium.

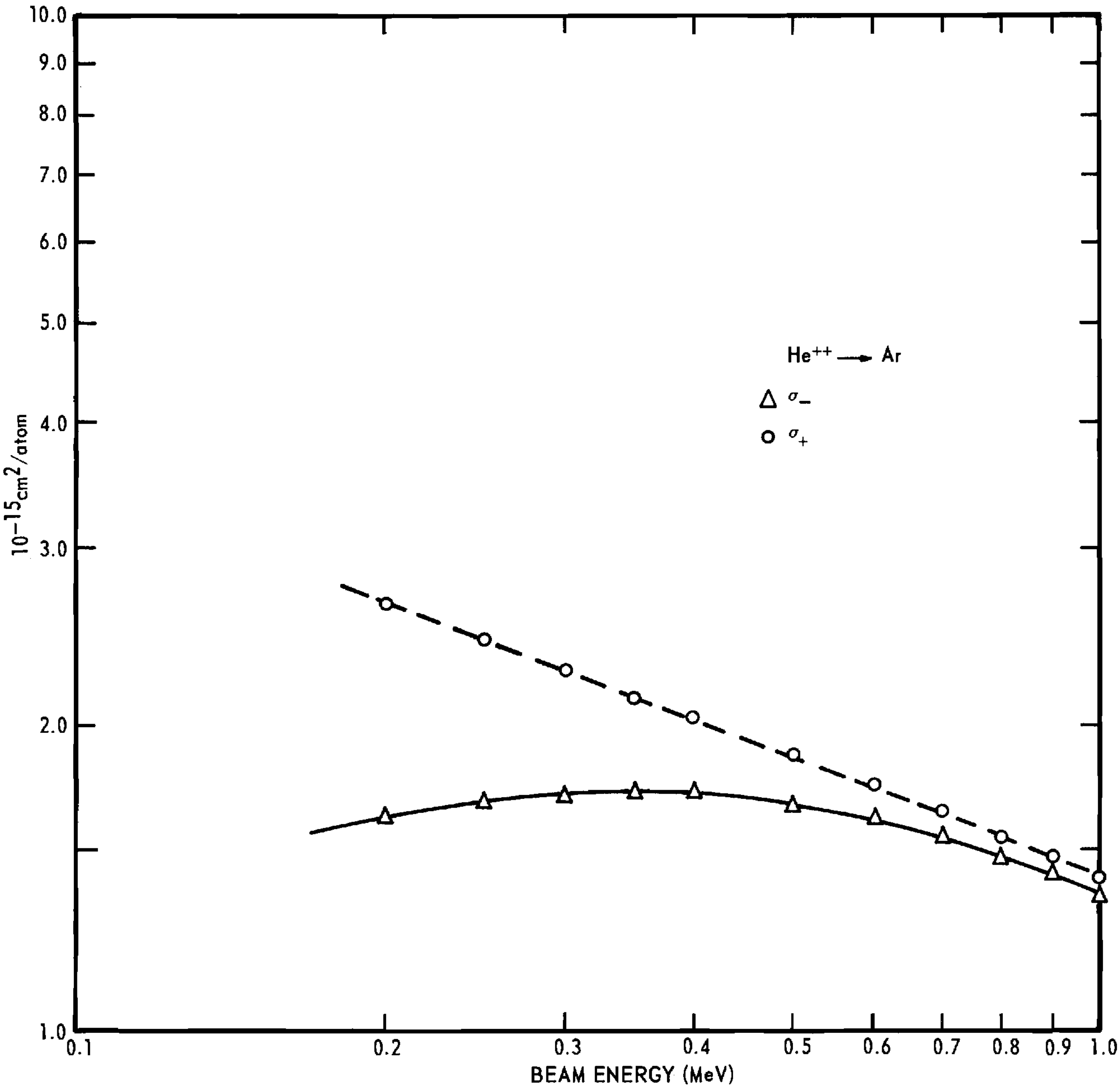


Fig. 2. Apparent cross sections for production of positive ions, σ_+, and of free electrons, σ_-, for He^{++} ions incident on argon.

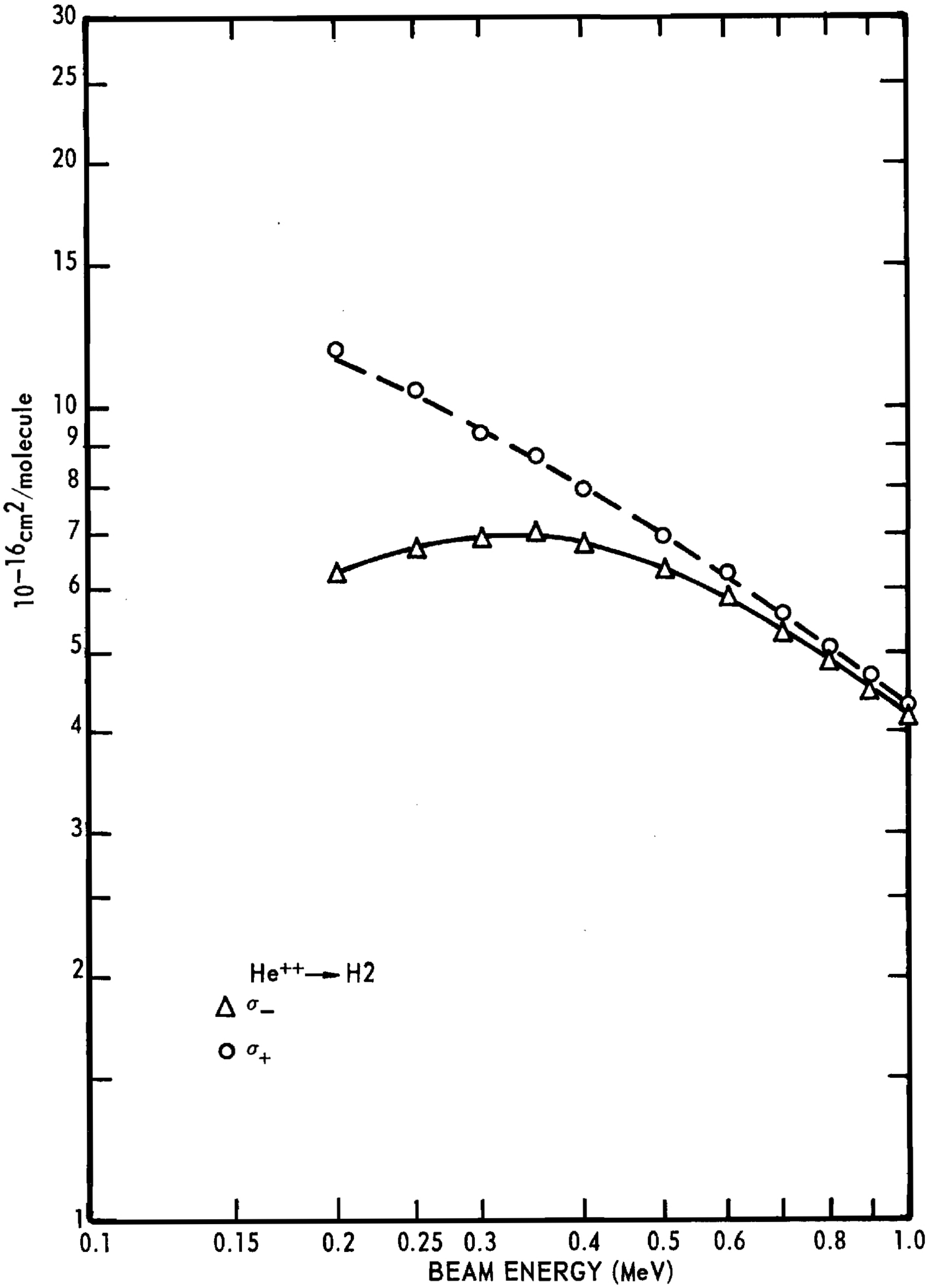


Fig. 3. Apparent cross sections for production of positive ions, σ_+, and of free electrons, σ_-, for He^{++} ions incident on molecular hydrogen.

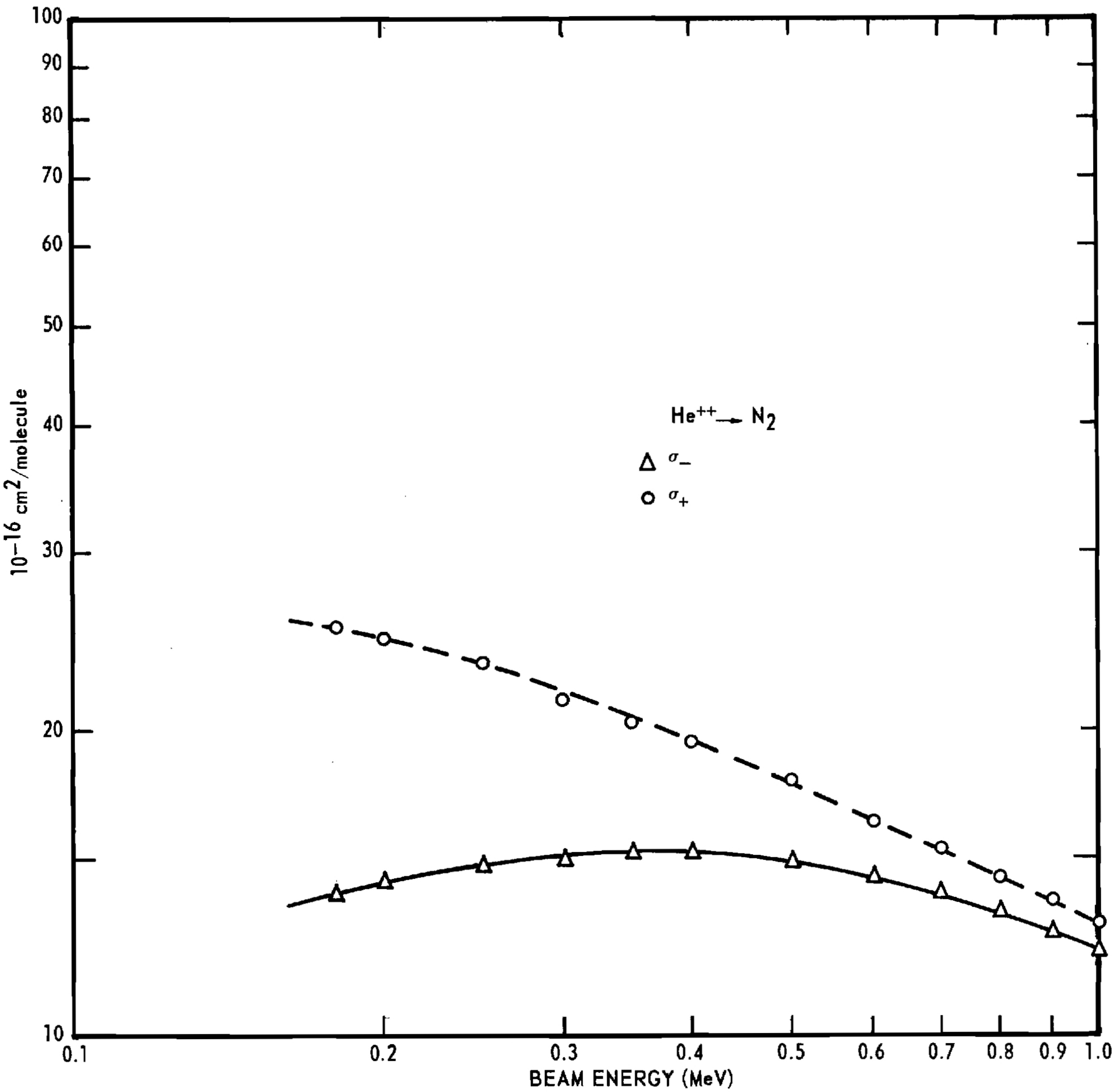
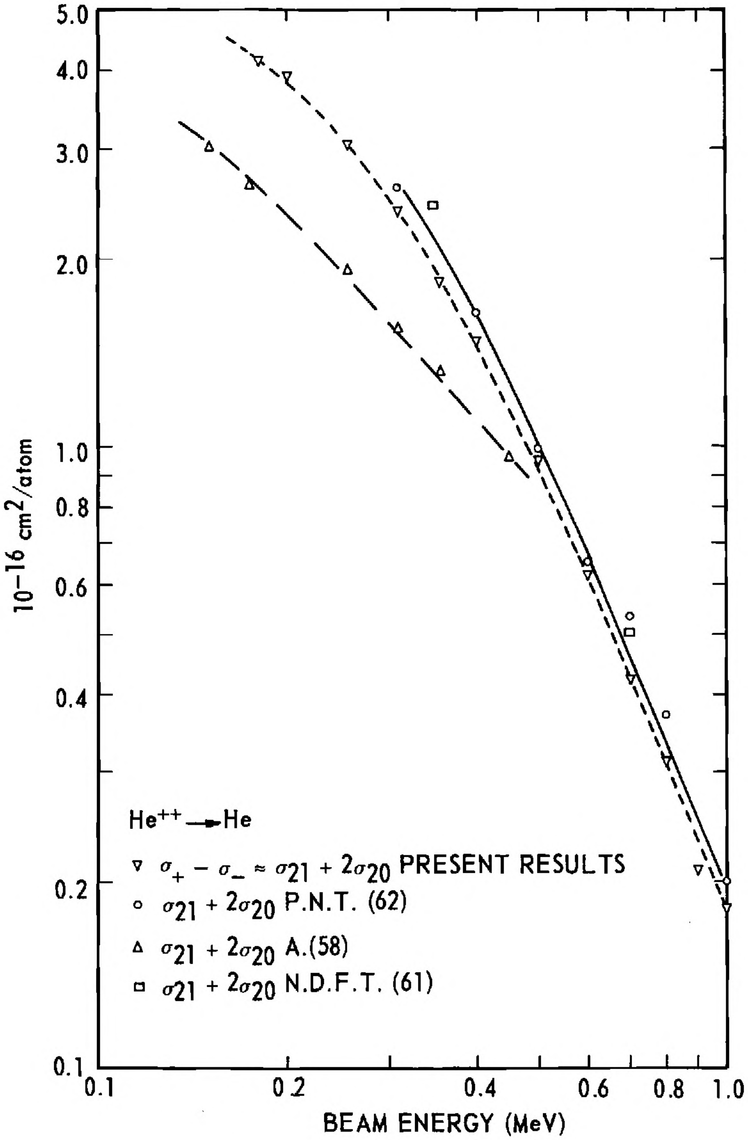


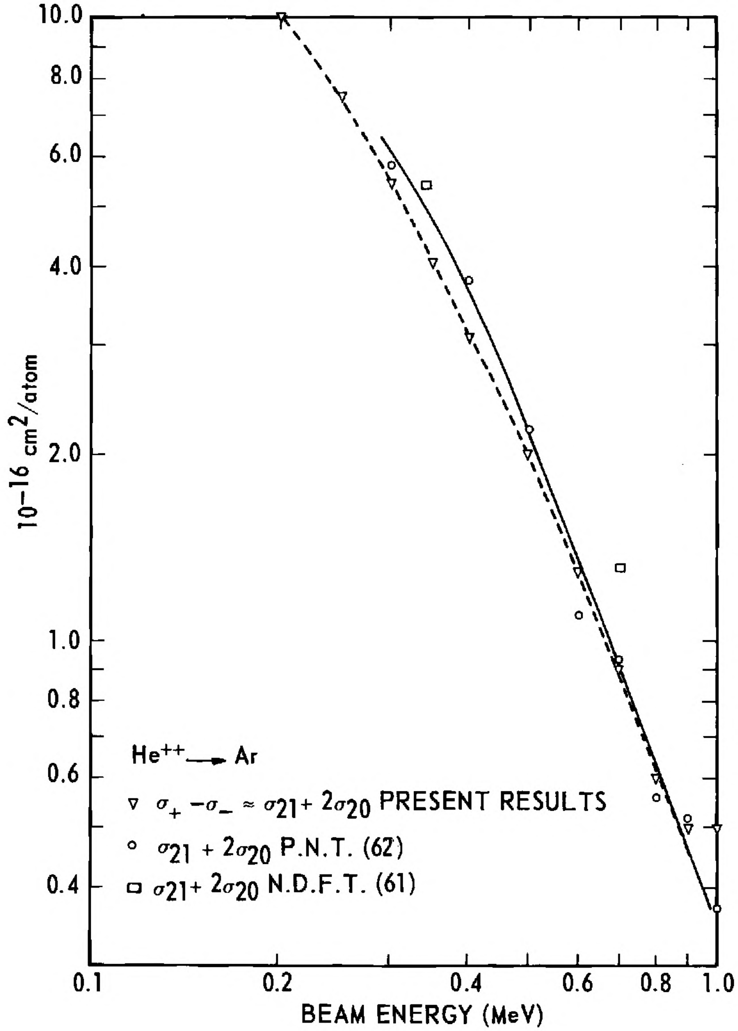
Fig. 4. Apparent cross sections for production of positive ions, σ_+, and of free electrons, σ_-, for He^{++} ions incident on molecular nitrogen.

removed, we feel there is nothing to be gained by applying the correction and have presented our data without it.

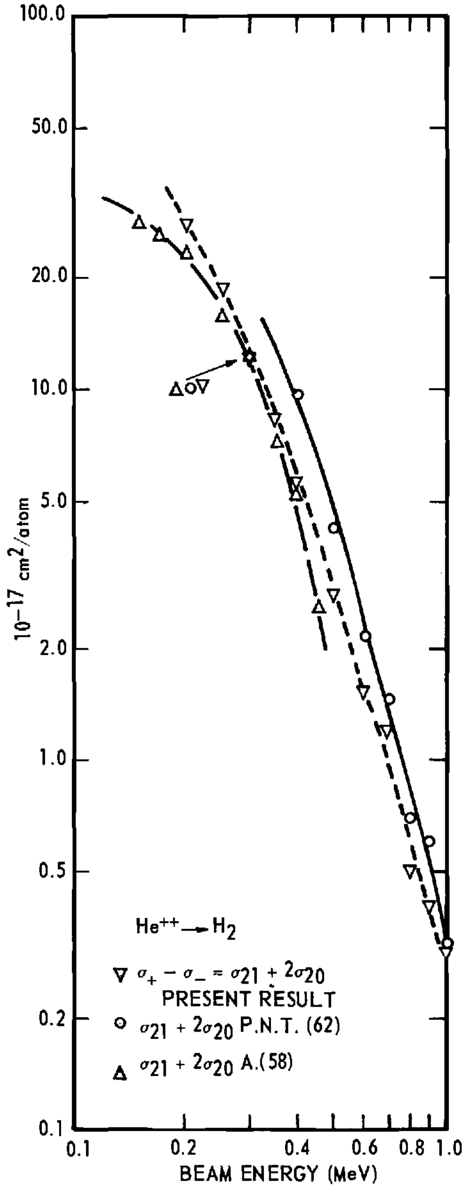
In Figures 5-8 we present for the same data comparisons of the difference $(\sigma_+ - \sigma_-)$ between our cross sections for positive ion and electron production, and the sum $(\sigma_{21} + 2\sigma_{20})$ of the total charge-changing cross sections of Pivovar, et al.,[12] of Allison,[13] and of Nikolaev, et al.[14] Both quantities represent a measure of the net excess positive charge deposited in the gas by the fast beam, and they should agree precisely without any assumptions. It is noted that the agreement is excellent in every case, providing a strong confirmation of the validity of both the gross ion production and the total charge changing cross section measurements.

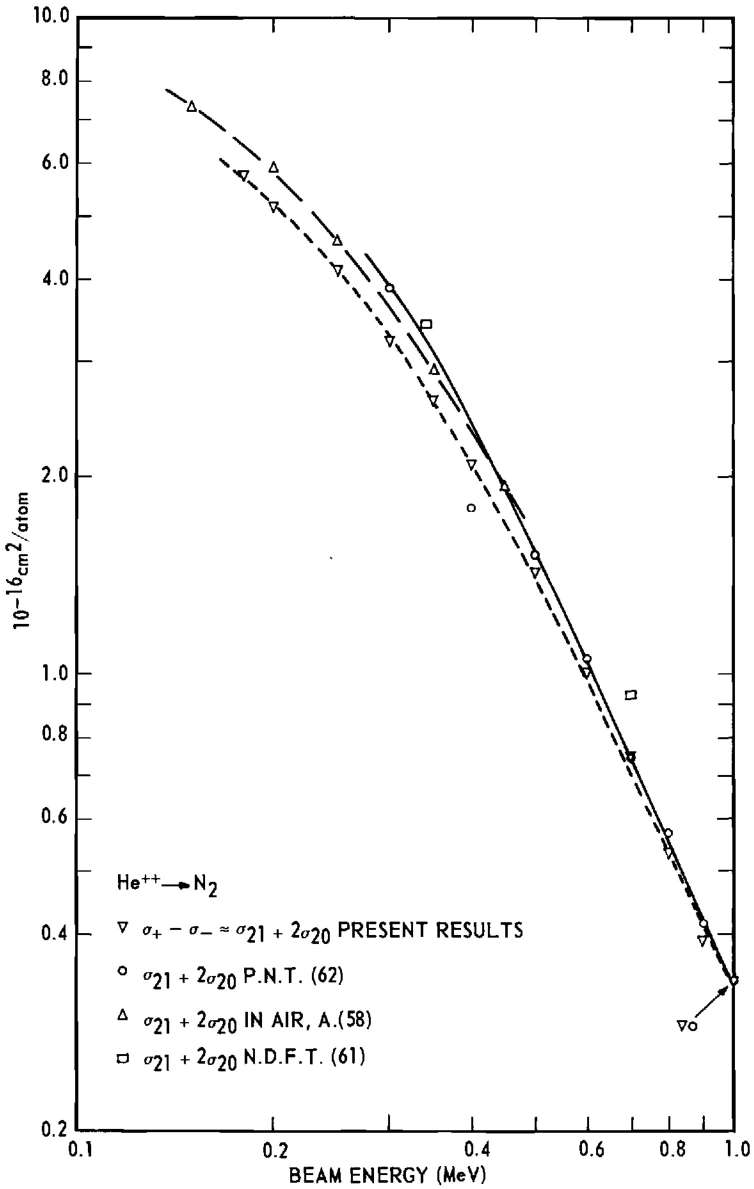
Complete and final results for the gross ion and electron production by incident fast neutral helium atoms, in the same four target gases helium, argon, hydrogen, and nitrogen, are presented in Figures 9-12. Also shown for comparison are the similar measurements of Solov'ev, et al.[15] extending up to only 0.18 MeV, and it is noted that the agreement is reasonably good. For neutrals at these high energies, the probability is very small that the fast particles will capture electrons to form negative ions. Therefore, the total positive ion production cross section is just the apparent ionization cross section, with no need for corrections for charge-changing collisions. Similarly, the difference between the total electron production cross section and the total positive ion production cross section is just the total cross section for the stripping of electrons from the fast neutrals. This difference is also plotted in each figure; for comparison we also plot the total stripping cross section results of Allison,[13] of Barnett and Stier,[16] and of Pivovar, et al.[17] It is immediately evident that our results are systematically some 40% higher than those of the latter three investigators, who are





Figs. 5 and 6. Cross correlation between the total apparent ion and electron production cross sections and the charge-changing cross sections for He^{++} ions incident on helium (Fig. 5) and on argon (Fig. 6). Key to references: P.T.N.(62), Pivovar, et al., (Reference 12); A(58), Allison, (Reference 13); N.D.F.T.(61), Nikolaev, et al., (Reference 14).





Figs. 7 and 8. Cross correlation between the total apparent ion and electron production cross sections and the charge-changing cross sections for He^{++} ions incident on molecular hydrogen (Fig. 7) and on molecular nitrogen (Fig. 8). Key to references: P.T.N.(62), Pivovar, et al., (Reference 12); A(58), Allison, (Reference 13); N.D. F.T.(61), Nikolaev, et al., (Reference 14).

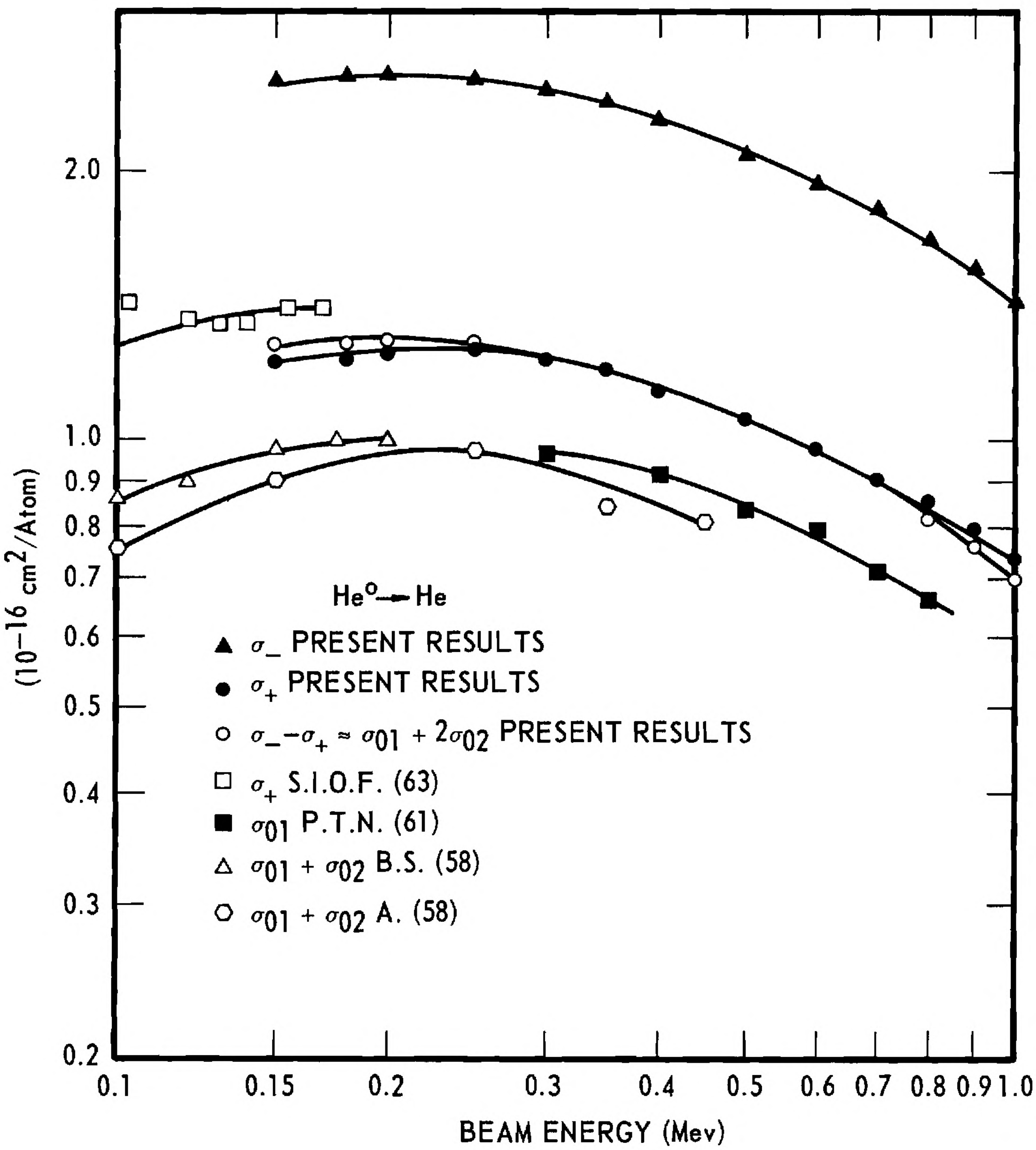


Fig. 9. Apparent positive ion and electron production cross sections, and the total apparent stripping cross section, for fast neutral He atoms incident on helium. Key to the results of other investigators: S.I.O.F.(63), Solov'ev, et al., (Reference 15); P.T.N.(61), Pivovar, et al., (Reference 17); B.S.(58), Barnett and Stier, (Reference 16); A(58), Allison, (Reference 13).

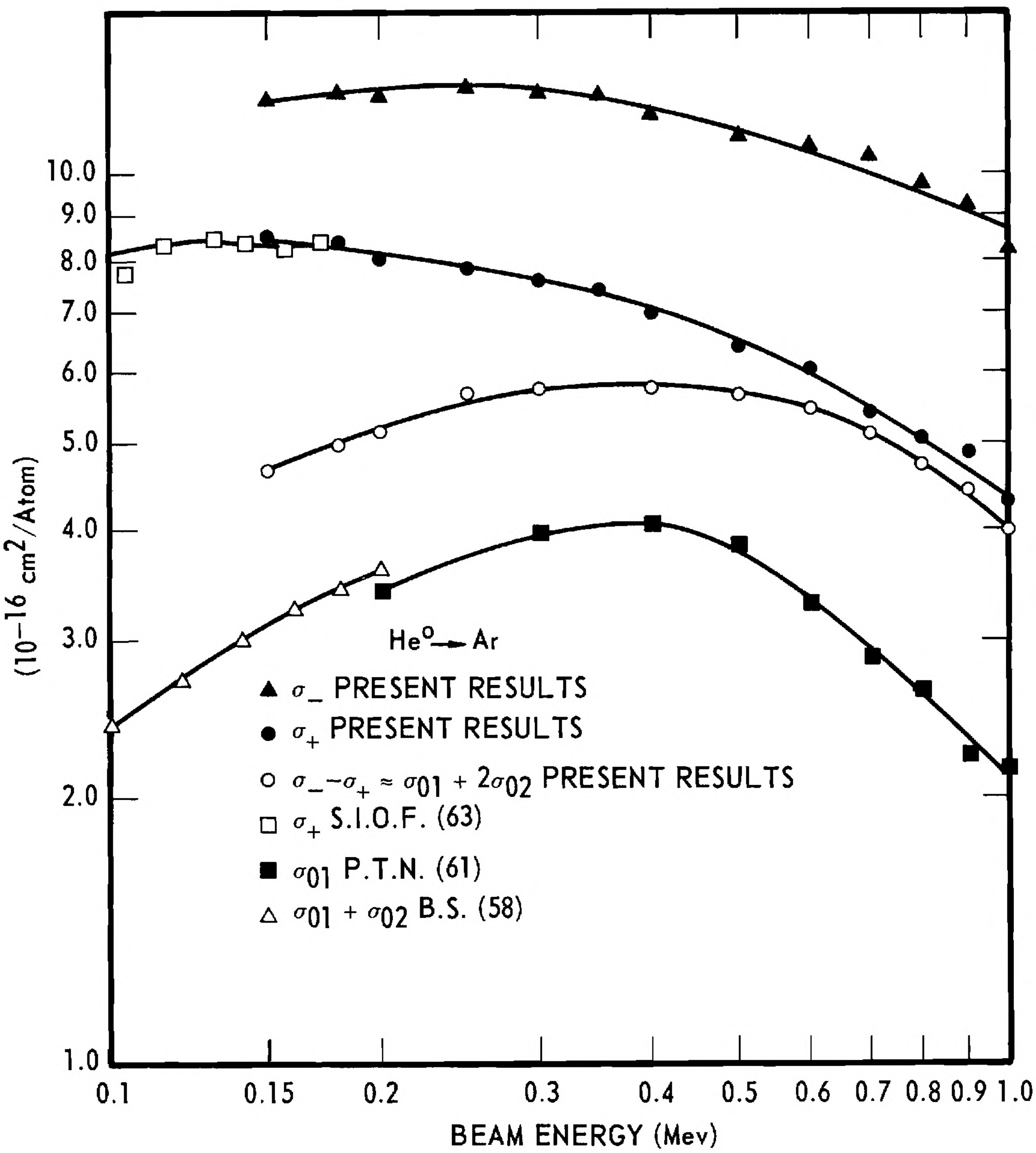


Fig. 10. Apparent positive ion and electron production cross sections, and the total apparent stripping cross section, for fast neutral He atoms incident on argon. Key to the results of other investigators: S.I.O.F.(63), Solov'ev, et al., (Reference 15); P.T.N.(61), Pivovar, et al., (Reference 17); B.S.(58), Barnett and Stier, (Reference 16).

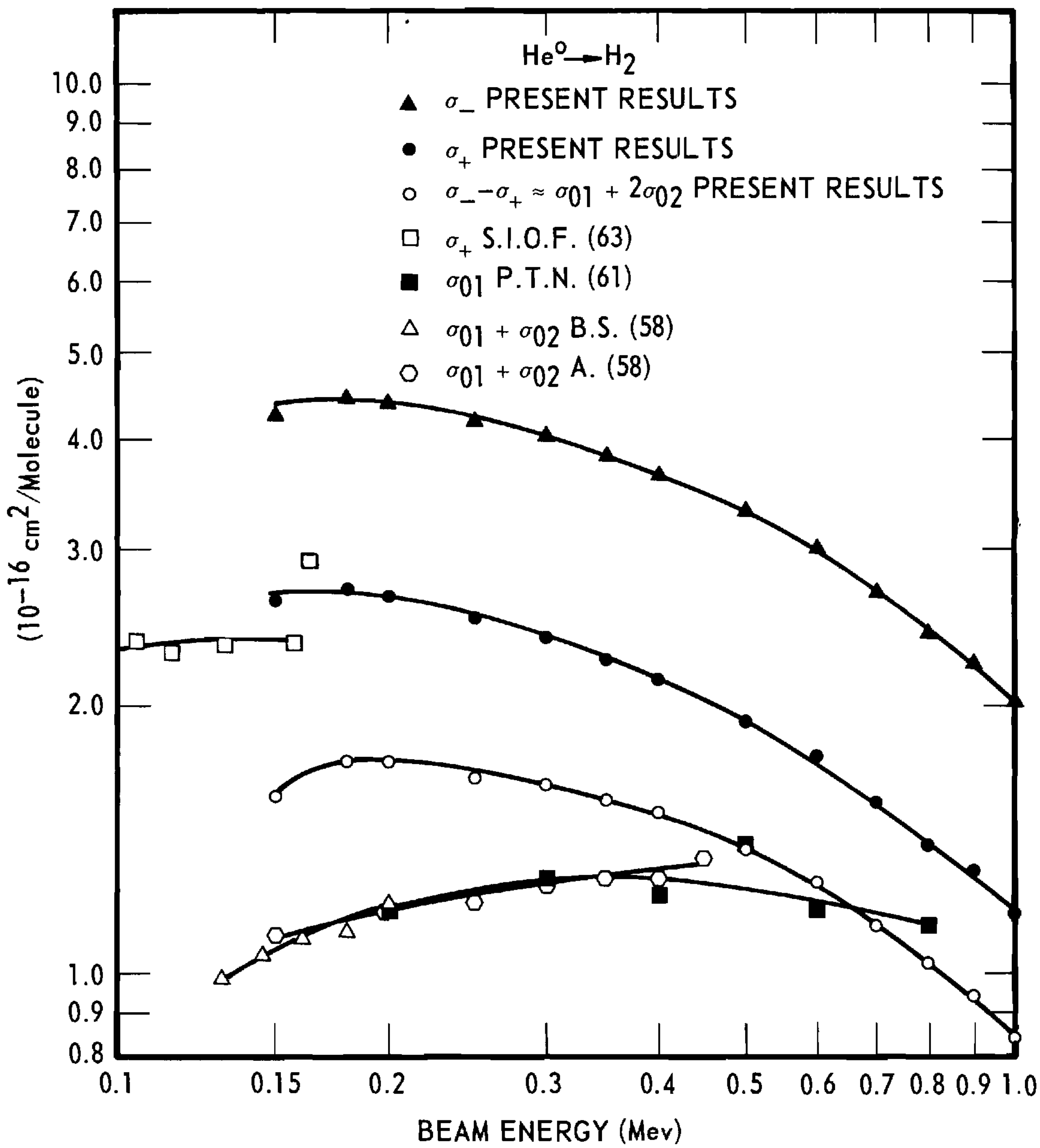


Fig. 11. Apparent positive ion and electron production cross sections, and the total apparent stripping cross section, for fast neutral He atoms incident on molecular hydrogen. Key to the results of other investigators:

S.I.O.F.(63), Solov'ev, et al., (Reference 15);
P.T.N.(61), Pivovar, et al., (Reference 17);
B.S.(58), Barnett and Stier, (Reference 16);
A(58), Allison, (Reference 13).

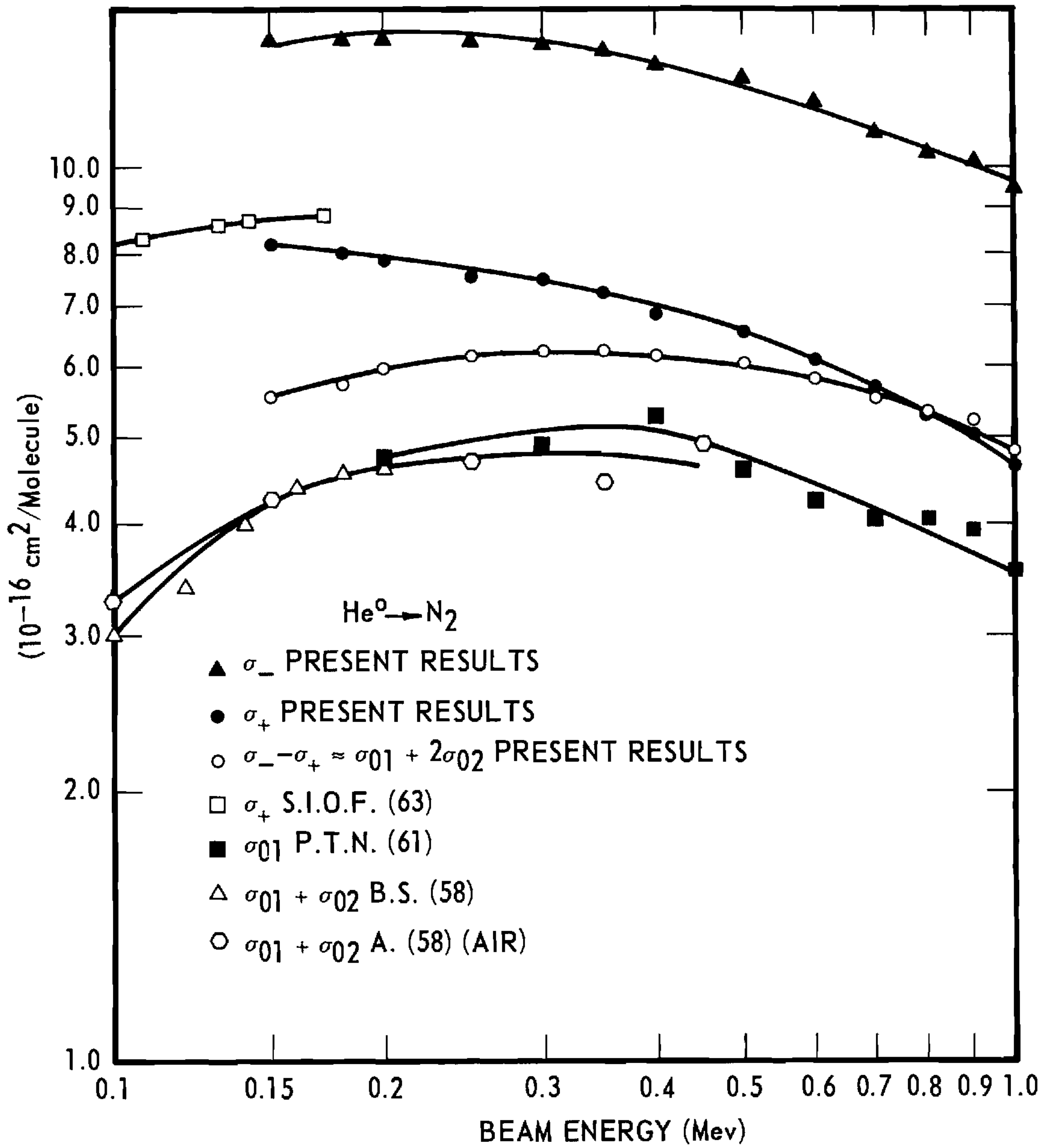


Fig. 12. Apparent positive ion and electron production cross sections, and the total apparent stripping cross section, for fast neutral He atoms incident on molecular nitrogen. Key to the results of other investigators:

S.I.O.F.(63), Solov'ev, et al., (Reference 15);
P.T.N.(61), Pivovar, et al., (Reference 17);
B.S.(58), Barnett and Stier, (Reference 16);
A(58), Allison, (Reference 13).

in generally good agreement with each other. It must be noted, however, that our result is not precisely the same physical quantity as is theirs. Since we collect all of the electrons formed in the target, we measure the single-stripping plus twice the double stripping cross section, i.e., $(\sigma_{01} + 2\sigma_{02})$. Two of the other workers,[13,16] in contrast, have measured the total attenuation of the neutral fast beam by either single or double stripping, with no attempt to distinguish these; hence, their result is simply $(\sigma_{01} + \sigma_{02})$. The observed differences then imply that

$$(\sigma_{01} + 2\sigma_{02}) \approx 1.4(\sigma_{01} + \sigma_{02})$$

hence

$$\sigma_{02} \approx \frac{2}{3}\sigma_{01} \ .$$

However, this inference is in contradiction to other findings elsewhere,[13] that σ_{02} is only perhaps 5% of σ_{01}. Thus there is a clear discrepancy here between the present ion production results and the total charge-changing cross section results; Solov'ev[15] has also pointed out this same discrepancy with respect to his results.

A major concern in this experiment is the possibility that the fast neutral beam, which is obtained through electron capture by fast He^+ ions in a gas cell preceding the collision chamber, has an appreciable contribution from atoms in metastable excited states. The magnitudes and even the ratios of the cross sections for most types of collisions would be different for such excited atoms than for ground-state atoms. If there are indeed many non-ground-state atoms in the beam, it would seem that the fraction of all beam atoms in such states should vary with the pressure and with the nature of the charge-exchange gas used in the cell. A search for such dependence in these neutral helium atom experiments gave a negative result. We normally operate the gas cell at around 7 microns, less than half of the pressure required to approach the equilibrium charge state distribution. We have varied this pressure by a factor of more than 1000 and have used different gases in the cell but have found no systematic changes in σ_+, in σ_-, or in their difference.

Another indication that our neutral fast beam is essentially all in the ground state is seen in Figure 9 for He neutrals into He target gas. Since the target and the projectile are identical, the total gross ionization of the target and the total gross stripping of the projectile should be equal, provided that both are in the same initial atomic state. (The latter is surely the ground state for the room temperature target gas atoms.) It is evident in Figure 9 that $(\sigma_- - \sigma_+)$ and σ_+ are in fact equal within the experimental errors; the small deviations from this statement at the lowest and the highest energies are within the errors, and are probably not significant.

In Figures 13-16 the new apparent ionization cross sections for He^o in the target gases helium, argon, hydrogen, and nitrogen are plotted together with the similar quantity estimated from the He^{++} ion results, and the previously published results[1-6] for protons and He^+ ions. (The energy axis for the proton results is shifted a factor of 4 to compare protons with helium particles of the same velocity.) The He^{++} results show quite precisely the expected correspondence (i.e., they are just 4 times the proton results) for the higher energies in helium and hydrogen and they appear to be approaching this correspondence at some higher energy beyond our range, perhaps 2 or 3 MeV, in the heavier targets. The He^o results appear to approach the same asymptotic energy dependence toward the upper end of the energy range as do the results for the other projectiles. However, in contrast to the He^+ ion results, for which the high energy end of the curve was found to be quite

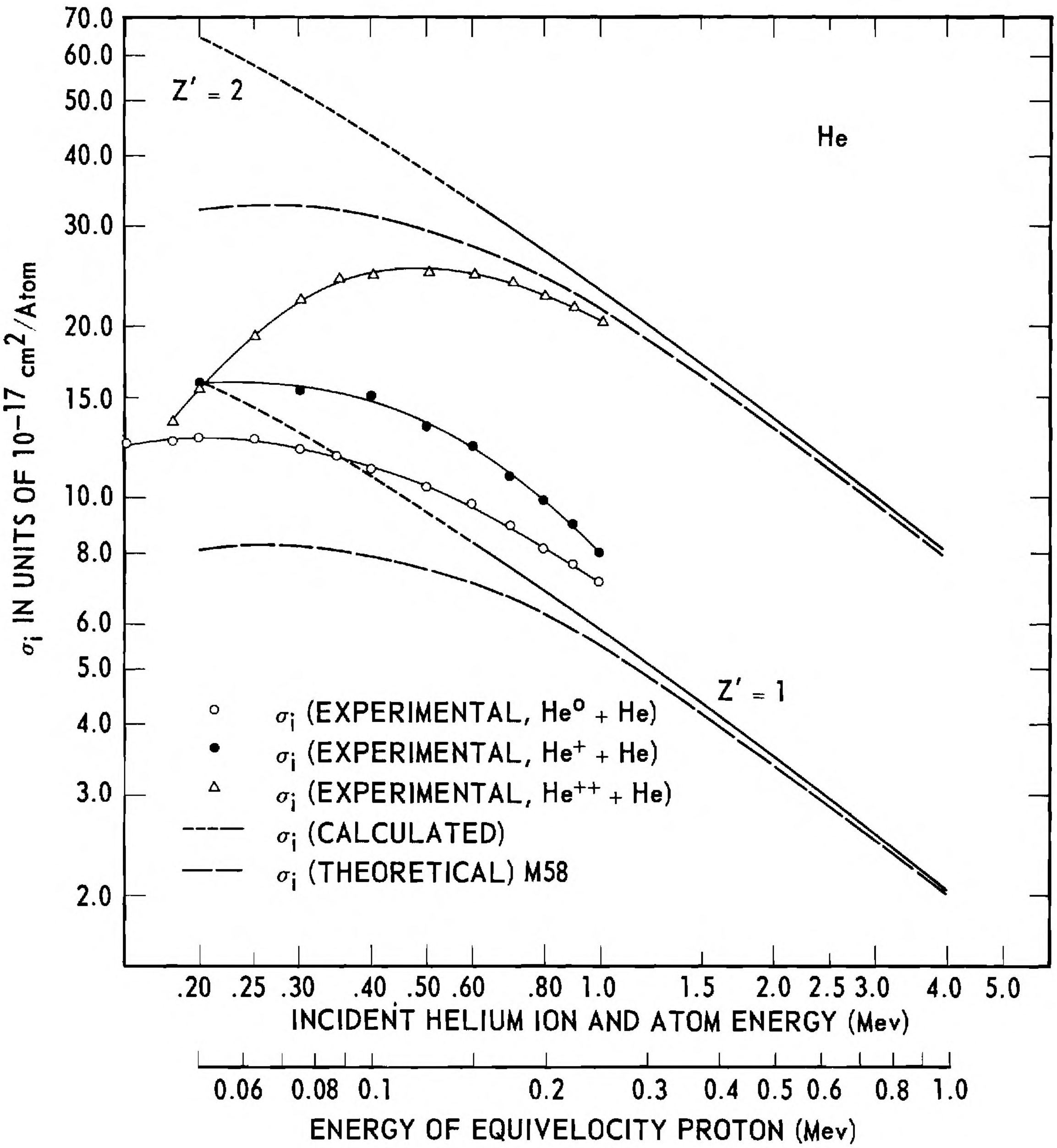


Fig. 13. Apparent ionization cross sections σ_i for helium ions and atoms incident on helium, compared with the calculated curve

$$\sigma_i = [A(Z')^2 M/E]\ln(BE/M)$$

with A and B evaluated from corresponding proton data (Reference 3), for $Z' = 1$ and $Z' = 2$. Also shown is the theoretical calculation for equivelocity protons on helium (Reference 8) for $Z' = 1$ and $Z' = 2$.

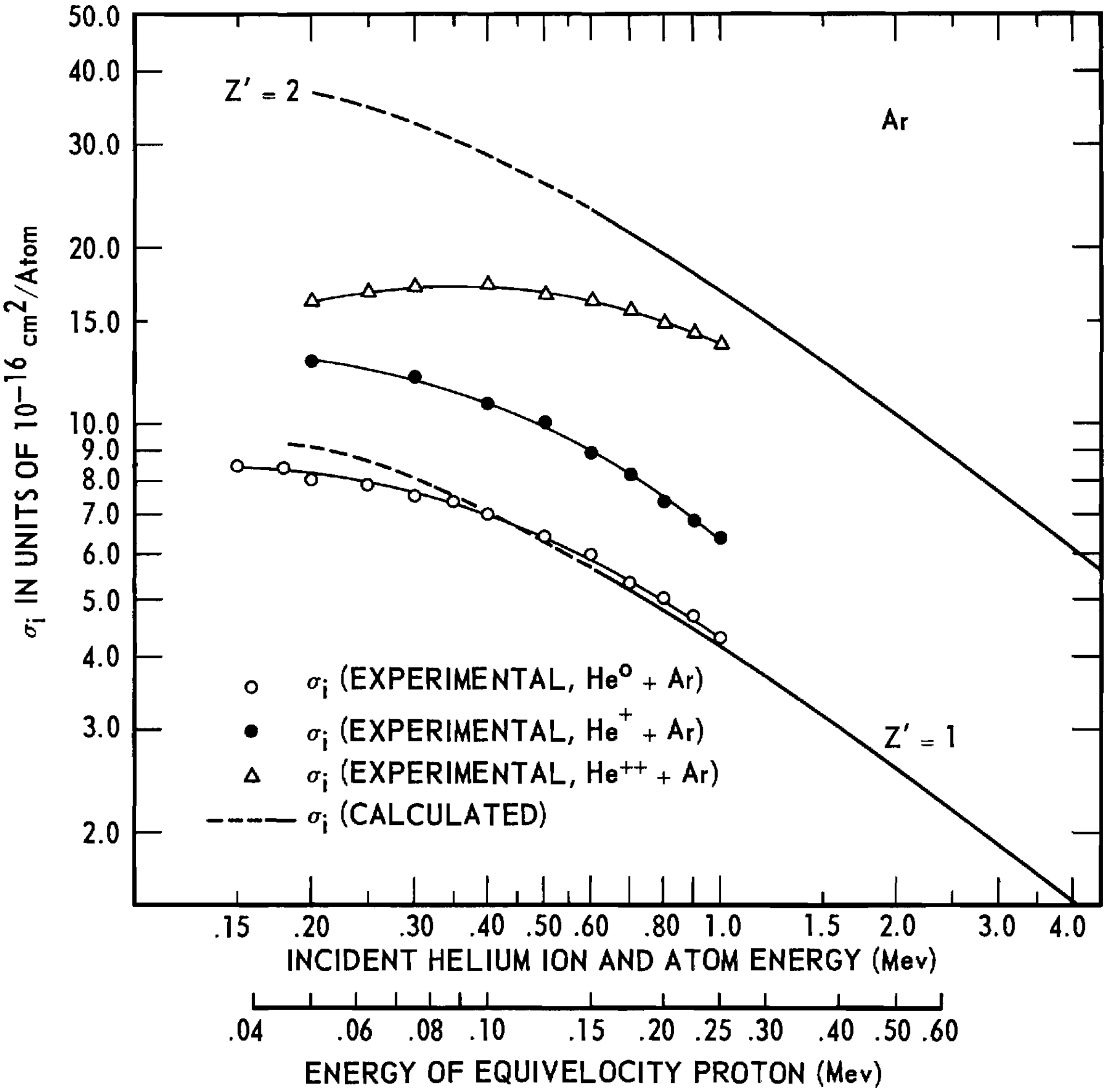


Fig. 14. Apparent ionization cross sections σ_i for helium ions and atoms incident on argon, compared with the calculated curve

$$\sigma_i = [A(Z')^2M/E]\ln(BE/M)$$

with A and B evaluated from corresponding proton data (Reference 3), for $Z' = 1$ and $Z' = 2$.

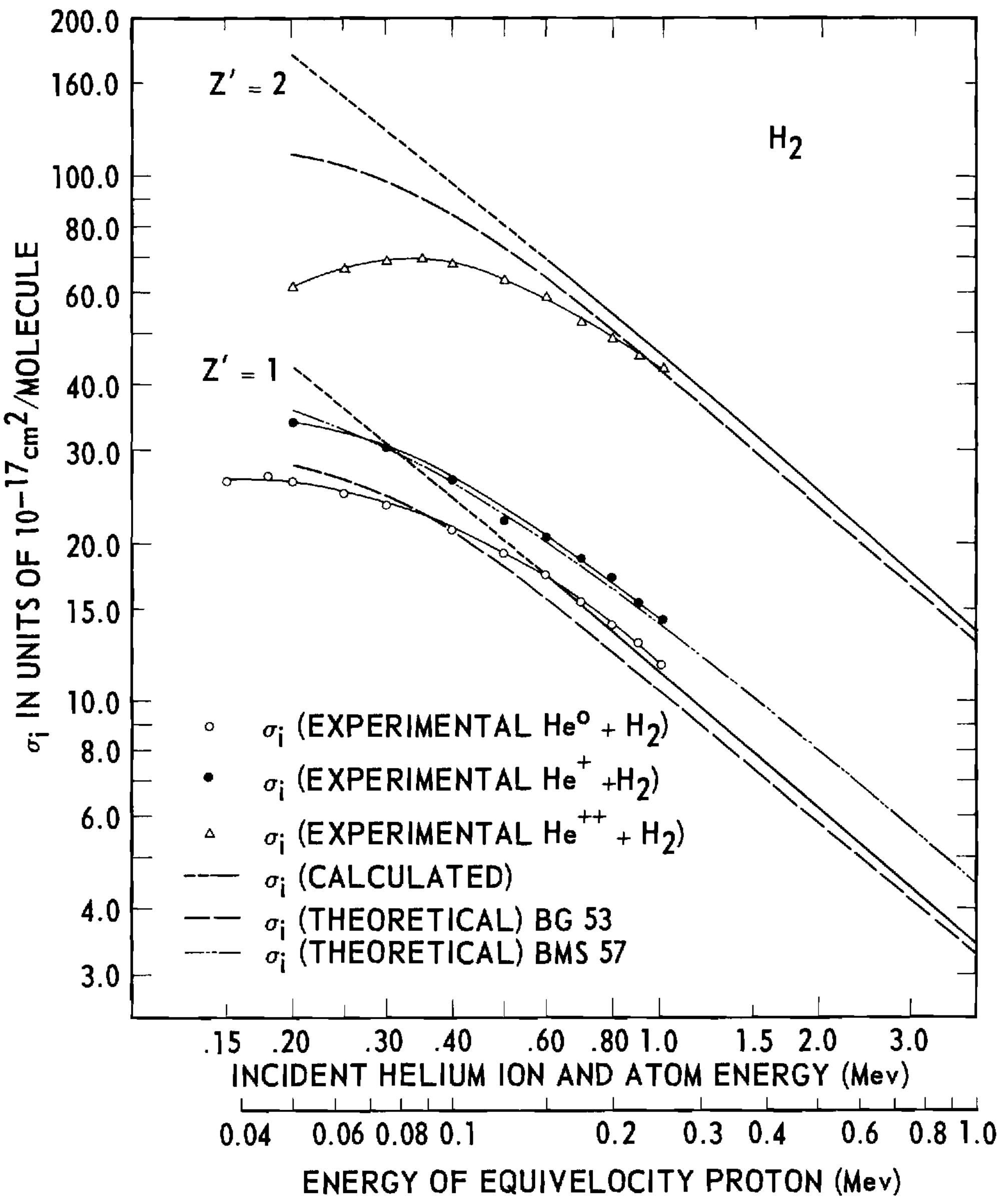


Fig. 15. Apparent ionization cross section σ_i for helium ions and atoms incident on molecular hydrogen, compared with the calculated curve:

$$\sigma_i = [A(Z')^2 M/E] \ln(BE/M)$$

with A and B evaluated from corresponding proton data (Reference 3), for $Z' = 1$ and $Z' = 2$. Also shown are theoretical calculations for atomic hydrogen targets, scaled to molecular hydrogen targets, for incident protons (BG 53, Bates and Griffing, Reference 7) for $Z' = 1$ and $Z' = 2$, and for incident He^+ ions (BMS 57, Boyd, Moiseiwitsch, and Stewart, Reference 9).

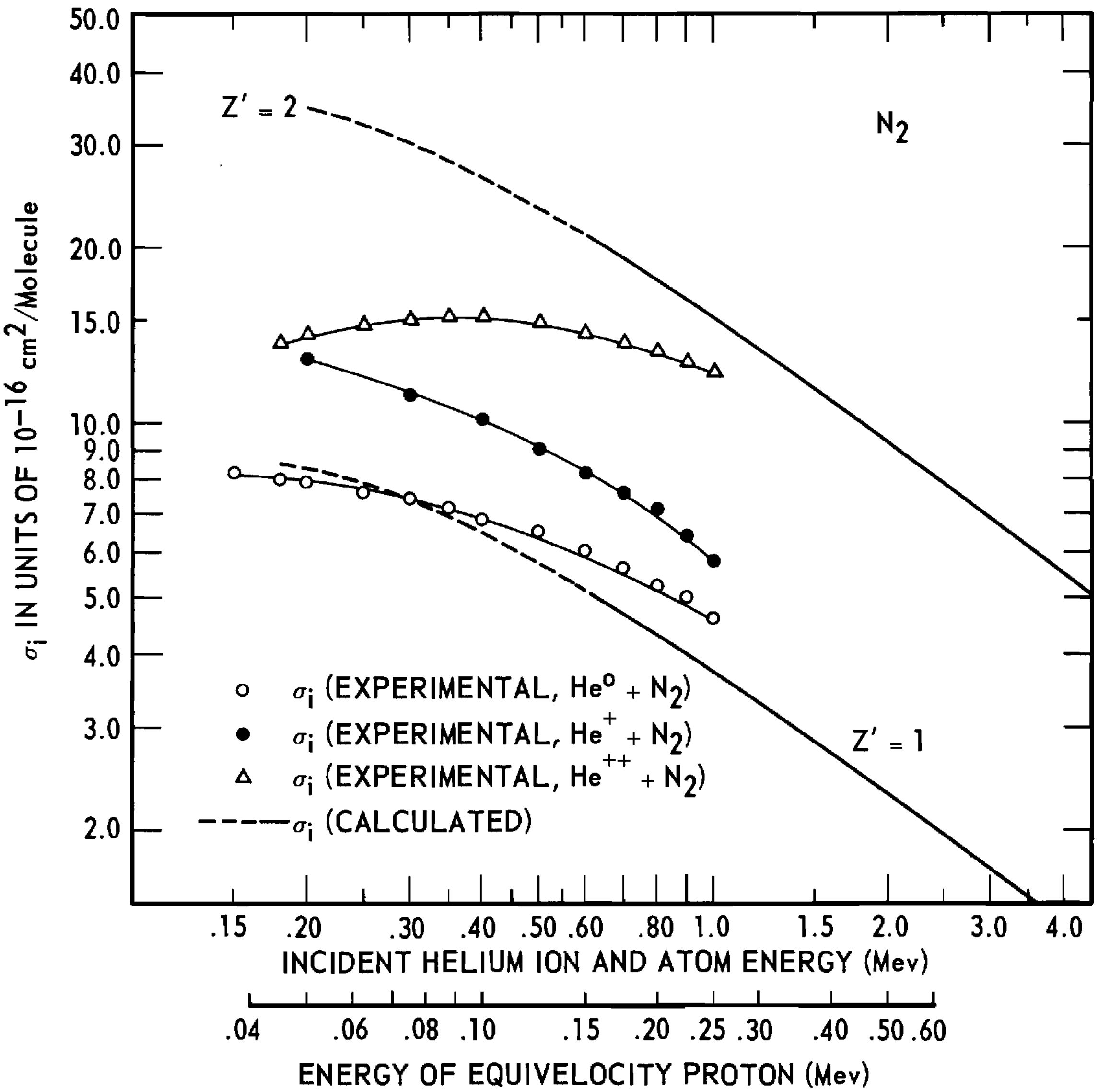


Fig. 16. Apparent ionization cross sections σ_i for helium ions and atoms incident on molecular nitrogen, compared with the calculated curve

$$\sigma_i = [A(Z')^2M/E]\ln(BE/M)$$

with A and B evaluated from corresponding proton data (Reference 3), for $Z' = 1$ and $Z' = 2$.

uniformly a factor of about 1.5 higher than the proton curve for all of the various target gases, the new He^{o} results show no such simple regularity; the He^{o} result is approximately equal to the proton result for both the lightest and the heaviest targets, i.e., hydrogen and argon, and to be greater than the proton result by a factor of about 1.2 for the other two cases. It thus does not appear to be possible to define an "effective charge" for He^{o}, independent of the target, representing the charge of a hypothetical point-charge ion of the same mass that has the same cross section for simple ionization at high energies.

Extensive similar measurements for incident fast neutral hydrogen atoms have also been carried out. In this case, the available energy range has extended up to only about 0.6 MeV because of low intensity of the neutral beam at higher energies. Results have been obtained for the targets He, Ar, and H_2, and measurements on N_2 targets are in progress. These H atom results have consistently displayed a much worse random scatter than usual, and they are in general in marked disagreement with the results of Solov'ev, et al.,[18] and Barnett and Reynolds.[19] (There is disagreement as to the energy slope of the cross section even more than there is disagreement as to absolute magnitude at any given energy.) Steps are now being taken to improve the stability of the Van de Graaff accelerator at low energies, which should increase the maximum beam deliverable into the collision region, and also reduce the statistical fluctuations. The results already obtained will be rechecked and may require some revision. Therefore, the present H^{o} results are not considered to be final, and they will not be presented in detail in this report.

C. Progress on Slow-Ion Analyzer

At the time of writing of the last renewal proposal, the conception we had of this analyzer was predicated on the assumption that no significant fraction of the slow ions would be formed with initial kinetic energies in excess of perhaps 100 eV. The analyzer was to be mounted so as to sample at 90° to the direction of the fast beam. Its entrance slit was to be cut in the "active" collector plate of our usual parallel plate collision region. The electric field normally applied to these plates to sweep to the active plate all of the slow positive ions formed in a well defined collision volume would simply sweep some of these ions into the analyzer entrance slit. If the width of the slit were made an accurately known fraction of the length of the active plate, this same fraction of all the ions formed in the collision volume should be swept to the slit. It was intended that analysis and measurement of the ion stream through the slit would be made simultaneously with measurement of the total current collected to the plate. Comparison of the ratios of these currents to the geometrical ratio would be a direct check on the collection efficiency of the analyzer, and the simultaneous measurement of our already well established total ion production cross sections would provide a continuous check on several of the more important factors in the measurement.

The mechanical design of the analyzer and of a new collision chamber, based on the conception described above, had been completed early in the present period. Before any actual construction was begun, however, further study was given to the adequacy of the underlying assumptions. The main aspects of these deliberations will be detailed below; the result was, however, a major decision to discard the concept of a fixed angle analyzer with a collection field in favor of an analyzer that is moveable in angle, and which samples with a narrow angular acceptance from a field-free collision region. The 60° magnetic-deflection type of analyzer was retained. This new system will perform measurements that are differential in the recoil angle, and will have sufficient momentum resolution to provide a moderate resolution scan of the energy spectra of the recoil ions. The magnet which was constructed previously will still be used. However, the original design for a new collision chamber had to be scrapped; the angular resolution that is desired has required a substantial revision of the design of the analyzer vacuum chamber as well. The new design uses an entrance collimator of very narrow acceptance angle; it and the ion acceleration electrode assembly must be very accurately and rigidly mounted with respect to the rest of the analyzer.

The principal technical reason for this change of plans was mounting evidence that a significant fraction of the recoil ions, particularly the multiply-charged recoil ions, are formed with substantial initial energies. Such energies would then require equally substantial values for the collection field voltages, to assure that all of the ions formed in a well defined collision region would reach the analyzer entrance slit. Details of the angular distribution of the initial motion could further influence the transmission efficiency of the ion optics of the analyzer, and require the use of still higher collection fields. Quite apart from any other difficulties this might entail, a large collection field would have the serious disadvantage of distorting the initial energy distribution. The incident beam has a finite spatial width; thus recoil ions would be formed over a region across which the electrostatic potential varies, and they would be given variable amounts of energy by the field as they were accelerated to the slit. Thus the recoil energy spectrum analysis for which the analyzer was designed would be obviated.

The evidence for substantial recoil energies comes partly from our own observations. On very careful examination, it has been determined that the slow ion current collected to the "active" plate of the parallel plate array in our present gross ion production collision chamber, as a function of the voltages applied to the plates, does not really "saturate" and become constant until the equal plus and minus voltages approach 200 volts or more. The 2 or 3 percent increase between 100 V and 200 V is small enough to be partially masked in the random errors in a single test, but the pattern of the increase over a large accumulation of data is unmistakeable. It follows that a small but significant fraction of the slow ions are formed with energies of more than 100 eV; it appears that the fraction having energies above 200 eV is too small to have a significant effect on the accuracy of our present gross total ion production cross sections. (We have normally used collection voltages of well over 200 V.) However, it does not follow that a similarly small fraction of all of the multiply-charged ions formed also have energies less than 200 eV, if the multiply-charged ions represent only a small fraction of the total ion current in the first place. Indeed, there is much evidence to the contrary.

Afrosimov and Federenko[20] have used a magnetic slow-ion analyzer which is rotatable about a field-free collision region and has a direction-defining collimator, to study the relative production of each slow ion charge state, differential in the recoil angle. The instrument had sufficient momentum resolution to provide a low resolution measurement of the recoil ion energy, and this was supplemented by a retarding potential feature for independent energy determinations. In studies of Ne^+ and Ar^+ ions of up to 0.15 MeV, in neon and argon targets, they found that quite appreciable fractions of the higher charge state recoil ions had initial energies of more than 200 eV. They remark that earlier non-differential studies in their own laboratory,[21] of the same collision partners, with a fixed angle analyzer and a collection field such as we had contemplated, were significantly in error for the higher multiply-charged recoil ions, particularly when the mass of the projectile was of the same order as the target mass.

Morgan and Everhart[22] have also studied the energy distribution of the recoil ions in Ar^+ on Ar collisions, at selected recoil angles that were well forward from 90°, corresponding to very hard collisions. They did indeed find recoil particles at these angles, particularly those of the higher charge states, with the energies of 1 keV and more expected for these angles. This particular paper by itself gives no absolute figures on the intensities of the recoils as a function of the recoil angle, to permit estimation of the relative contribution of such hard collisions to the total cross section, but it does verify that there are measurable numbers of recoils, particularly for the higher charge states, at these forward angles.

The evidence cited thus far for energetic recoil ions has in each case involved a heavy incident ion. The case of incident protons has been studied with fixed-angle analyzers using a collection field by the Leningrad group[18] and by Wexler.[23] The Leningrad measurements cover energies only up to 0.18 MeV, while Wexler's ranged from 0.8 to 3.75 MeV. Both groups have studied protons on He, Ne, Ar, and Kr targets. While their energy ranges do not overlap, a comparison of sorts can be made by extrapolation. There is an appearance of good agreement for the low charge states of the slow ions, but this really results from the fact that neither set of measurements was absolute. The Leningrad group normalized to their own total ion production measurements, while Wexler normalized to our total ion production results.[1,2] The apparent agreement thus really reflects only the rather good agreement between these two sets of total ion production measurements. Significantly, the agreement does not appear to be as good for some of the higher charge states of the recoil ion.

The conclusion to be drawn is that measurements of absolute or even only relative cross sections for the production of multiply-charged slow ions, using a fixed angle analyzer and relying on collection of the ions to the entrance slit by an electrostatic field, can quite possibly be substantially in error in some circumstances. On the other hand, an analyzer moveable in angle, capable of collecting within a well defined angular interval from a field-free collision region would produce results differential in the recoil angle. It goes without saying that this more detailed observation is of direct interest in itself. Integration of the result over the recoil angle to get the total production cross section for a given charge state should be more reliable than the simpler measurement, because the possible contribution from energetic recoils is evaluated directly.

Also relevant to our decision was the fact that we wished to construct this analyzer to be fully compatible with later evolution of a coincidence experiment, in which the final charge states of both of the partners from a single collision are determined. Originally, we also conceived of the coincidence experiment in terms of fixed-angle analyzers and a collection field. As such, the results would still be subject to the same possible errors due to hard collisions as described above. An experiment with moveable analyzers, differential in both the scattering and the recoil angles, would avoid this difficulty, while producing a more detailed result of intrinsic interest. In addition, if there is sufficiently good angular resolution, the inelastic energy loss in each collision is unambiguously determined from these two angles. The only atomic collision coincidence experiments that have been published thus far have in fact been designed with emphasis on study of details of the inelastic energy loss.[24-26] While our primary interest will be in the measurement of cross sections, it was concluded that a doubly-differential apparatus would be of sufficiently greater general utility as to represent the clearly preferable choice.

The slow ion analyzer as now designed will rotate about the collision region on a high precision bearing assembly, such that the point on the incident beam axis at which the collimator of the analyzer is aimed will hold steady to less than .001 inch. Collimator slits as narrow as .030 inch may be used, defining an acceptance cone whose width at the beam location is also about .030 inch. With these parameters, the angular acceptance range will be only ± 15 minutes in the recoil angle. Such high resolution would be required for energy loss determinations in a coincidence experiment; wider slits providing lower resolution can be used when desired.

Electrodes will be provided in the collision chamber to permit use of the analyzer at fixed angle with a collection field when desired, to allow direct measurement of a total non-differential cross section, whenever prior differential observations have verified that there will not be appreciable errors due to fast recoils. These electrodes will also be used to check the collection efficiency of the field free arrangement for very low energy recoil ions.

The analyzer will use an electron multiplier with post-analysis acceleration of up to 30 keV, for single-particle detection at close to 100% efficiency.

The mechanical design has been essentially completed at the present time. Materials for most of the major components are in hand, and the shop work on the precision-bearing support assembly is underway.

D. Plans for the Remainder of the Present Contract Period

The remaining measurements of total gross positive ion and electron production cross sections for incident fast neutral hydrogen atoms, and the rechecking of those already obtained, will be completed before the close of the present contract period on February 28, 1966. These results will complete our broad program of such measurements for hydrogen and helium ions and atoms in all of their several possible charge states (negative ions excluded). An article presenting the He^{++} ion results and all of the neutral results will be prepared for publication in The Physical Review.

It is anticipated that the construction of the slow ion analyzer will be completed at about the end of the present period. The initial study that will be undertaken with this facility will be of protons on helium. Separate cross sections, differential in the recoil angle and energy, will be measured for the production of both singly and doubly charged recoil ions.

IV. Travel and Publications

D. W. Martin and L. J. Puckett attended the 4th International Conference on the Physics of Electronic and Atomic Collisions held at Universite Laval, Quebec City, Canada, August 22-26, 1965. A paper presenting the incident neutral helium atom results was read. No publication of the papers, other than the abstract booklet distributed at the conference, is known to be contemplated.

D. W. Martin attended the 18th Annual Gaseous Electronics Conference in Minneapolis on October 20-22, 1965.

D. W. Martin presented a seminar talk on this research at the University of Nebraska on October 19, 1965.

V. Incident Report

There have been no incidents for which a report would be required within the period covered by this report.

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ORO-2591-19

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

PROGRESS REPORT NO. 19

Covering the Period

December 1, 1965 to November 30, 1966

By D. W. Martin
L. J. Puckett
G. O. Taylor

Report No. ORO-2591-19

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

U.S. ATOMIC ENERGY COMMISSION

OAK RIDGE, TENNESSEE

1 December 1966

School of Physics
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

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Ionization and Charge Transfer Cross Sections
Progress Report No. 19

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Ionization and Charge Transfer Cross Sections
Progress Report No. 19

The period covered by this report is December 1, 1965 through November 30, 1966. This period corresponds to the first 9 months of the 12-month extension provided for by Modification No. 8 of the contract, plus the final 3 months of the preceding period.

This report will be concerned only with the ionization and charge transfer phases of the total program at Georgia Tech, which were the subject of Part A of our proposal of December 1, 1965, covering the present period. The excitation measurements of Part B are covered in Report No. ORO-2591-23 of this same date. We are continuing the practice of issuing separate reports for the two segments of the program because they are relatively independent, and it is likely that many potential readers will be primarily interested in only one segment or the other.

I. INTRODUCTION

A broad program of absolute cross section measurements for fast hydrogen and helium ions and atoms in gaseous targets has been in progress at the Georgia Institute of Technology for several years. The energies of the incident particles, obtained from a 1-MV Van de Graaff positive ion accelerator, lie in the range 0.15 to 1.00 MeV. This range extends to higher energies than those of most previous similar measurements elsewhere, and reaches well into the range where theoretical computations in the Born approximation may be expected to be valid.

Detailed comparison of the experimental results with the results of such theoretical computations as are available has always been a central interest in the conduct of this program. Unfortunately, completely direct comparisons have quite often not been possible in the field of atomic collisions. Most types of theoretical computations involve the calculation of a transition probability from an explicit initial state to an explicit final state of the entire colliding system. Often the results are summed, or integrated in the case of continuum states, over all of the final states of a more or less broad class. For example, in the case of simple ionization, the results are typically summed over all energies and directions of motion of the ejected electron, and over the energy and direction of motion of the recoil of the target atom, to give the total cross section for collisions leaving both of the collision partners in specified states of internal energy and charge. Most types of experiments have not been this specific, however, since any information at all of the final internal state has usually been obtained for only one or the other of the collision partners. The cross section obtained for collisions producing a specified state of the one partner may thus contain contributions from events which leave the other partner in any of several states. A qualitative comparison may be possible, however, if some information is available from other sources on the relative probabilities of the various states of the unobserved partner, or if there are other grounds for arguing that only one of the possible processes is important. Much of the previous comparison between theory and experiment in the field of atomic collisions has involved reasoning of this sort, and thus has been to some degree on unsure ground.

Only quite recently have there been any coincidence experiments performed in this field, in which information is obtained simultaneously on the states of both of the partners from a single collision. Only with such methods may one single out for study individual collision processes which are as explicitly defined as are the theoretical calculations, and be enabled to make comparisons in greater detail.

Prior to the present report period, all of the ionization measurements in the Georgia Tech program have been restricted to what we have called σ_+ and σ_-, the gross positive ion and electron production cross sections. All of the electric charge of both signs produced or deposited in a thin gas target by passing through fast ions or atoms in a known initial charge state were simply collected by means of electrostatic fields, and the resulting currents were measured. No measurement was made of the fraction of the positive ion current attributable to multiply-charged ions, or of any fraction of the negative current that might be attributable to negative ions rather than to free electrons, and no analysis was made of the charges or energies of the fast particles after collision. However, care was taken that the targets were "thin" enough that essentially no fast particles suffered more than one collision, so that the initial charge states of both collision partners were known.

The difference between σ_+ and σ_- was a measure of the net charge deposited in the target in collisions in which the fast particles lost or gained electrons, and could be compared with other measurements performed elsewhere, involving observations of only the fast collision partners, of what have been called the "charge-changing" collision cross sections. For the most part, such comparisons were found to produce excellent agreement, which is considered to be strong evidence that both types of measurements were free of any gross errors.

From the gross ion and electron production cross sections and the gross charge-changing cross sections it was possible, with certain reasonable assumptions about the relative importance of certain of the possible detailed processes, to arrive at estimates of the "apparent ionization" cross section, σ_i. The latter is defined to include all ionization events in which the fast particle does not change its charge state; it is called "apparent" because it may still contain weighted contributions from events in which the slow ions formed are multiply-charged. For many of the cases studied it was known, however, that only a small fraction of all the slow ions produced by events of all types were multiply charged. Therefore, the estimated apparent ionization cross sections could realistically be compared with theoretical calculations of the simple ionization cross sections. The latter had been calculated in the Born approximation for a few of the cases studied, and the results have been compared with our measurements. Generally very good agreement has been obtained in these cases for the higher energies in our range, and the onset of substantial disagreement with decreasing energies of the fast particles has been established.

The Georgia Tech program of gross production cross section measurements has included as the fast projectiles atomic hydrogen and helium neutrals, H^o and He^o, as well as all of the positive-ion states of these particles, e.g., H^+, He^+, and He^{++}. Target gases have in all cases included both a light and a relatively heavy noble gas, e.g. helium and argon, and both a light and a somewhat heavier diatomic molecular gas, e.g. hydrogen and nitrogen. For some of the listed projectiles, measurements were made for certain additional target gases as well. These data form a substantial unified body of results for a sufficient variety of cases to provide a comprehensive view of the systematics of the ionization of gas targets by fast, light atomic projectiles, and several interesting generalizations have been drawn from them.

All of our results except those for H^o projectiles have been presented in previous reports; the H^+, He^+, and parts of the He^{++} results have also been published[1-6]. Included in these presentations have been comparisons with all of the then known data from other sources. Recently, de Heer, et al., have completed new measurements for incident protons and singly-charged helium ions[7], for lower energies extending up to 0.14 MeV. This range immediately abuts ours, so that comparison of the results can be made on the basis of how smoothly the curves join on to each other.

For the proton measurements, the general situation is that a reasonable extrapolation of de Heer's results for σ_i would come into good agreement with ours by about 0.25 to 0.30 MeV, but would run somewhat lower than our lowest-energy points. That is, his results suggest that ours should have fallen off somewhat, at our lowest energies, from the straight line log-log plots which we obtained. For protons, σ_i is simply equal to σ_-; however, we found that σ_+ and σ_- seemed to be equal in all of our targets at even our lowest energies. Therefore, only one quantity was plotted, which we called σ_i, but which actually was our σ_+ rather than our σ_-.

Equality of σ_+ and σ_- implies that the charge exchange cross section $\sigma_{10} = (\sigma_+ - \sigma_-)$ is negligible compared to σ_i. This conclusion was consistent with other measurements[8] of σ_{10}, in all of these targets, at the higher energies, and for the case of the hydrogen target, this was true even down to 0.15 MeV; we had been under the impression that the latter statement was also true for the other targets as well. De Heer points out that we have been mistaken in this; his own new measurements and the older results of others[8] both agree that σ_{10} becomes appreciable, compared to σ_i, by our lowest energy of 0.15 MeV, in the case of every target except hydrogen. It amounts to only around 5% in argon, nitrogen, and oxygen, but becomes 20% or more in helium and neon. These are just about the amounts by which our σ_i should fall off from the straight line, at our lowest energies, in order to join smoothly with de Heer's results.

The weight of the evidence suggests that de Heer is correct in this case, that the straight lines we obtained all the way to the low-energy end of our range are probably correct for σ_+, but that $\sigma_i = \sigma_-$ should fall below these lines at 0.15 MeV by amounts that range from about 2% in hydrogen, to around 5 % in argon, nitrogen, and oxygen, and to over 20% in helium and neon. We cannot explain how we happened to be misinformed about the expected magnitude of the charge exchange cross section. As to our observation that σ_- seemed always to be equal to σ_+, the low end of the energy range was at that time always the most difficult to work in, because of accelerator stability problems. Also, it has always been relatively more difficult to be sure of the values obtained for σ_- than of those obtained for σ_+; since we expected them to be equal, and it appeared that this was at least roughly so, we therefore normally plotted the values of σ_+, because they seemed to be the more reliable.

De Heer's new results for He^+ differ more drastically from ours than do his proton results. He finds our σ_i to be too large in every case except that of the helium target, by 20 to 30% in most of the cases, but by up to 50% or more in nitrogen and oxygen. In this case, we do not accept the fault for the disagreement, and have no ready explanations to offer. De Heer's method differs from ours, and he does not obtain his σ_i from his measured quantities in exactly the same way that we do. We have not as yet satisfied ourselves that de Heer has used our results properly in making comparison with his own. It must simply remain, for the present, that there appears to be substantial disagreement between his results and ours for He^+.

The gross production cross section phase of the program was brought to completion within the final three months of the preceding contract period, since the issuance of the last annual Progress Report. The program has now moved into a new phase aimed toward the development of a full coincidence experiment. The construction of a magnetic-deflection analyzer for the charge state, recoil energy, and angular distribution of the slow positive ions was completed in the early part of the present contract period, and preliminary measurements for a few of the same collision partners studied in the older phase have been carried out. An electrostatic analyzer for the charge state and scattering angle distribution of the fast collision partner has been designed and is presently under construction. Suitable detectors and electronic circuitry for the coincidence experiment are being selected and procured. It is anticipated that assembly of the coincidence apparatus will be completed by the end of the present contract period.

A lengthy Technical Report presenting in detail all of the new results from about the last two years is presently in preparation, and will be issued within about a month of the date of this Progress Report. Because of this fact, the new results since the last Progress Report will be discussed only briefly and in rather general terms here. Details of the slow ion analyzer design, as well as the preliminary results obtained with it, will also be covered in detail in the Technical Report, so they will also be dealt with only briefly here. Finally, the status of the construction of the fast beam analyzer and of the remainder of the coincidence apparatus will be reviewed.

II. NEW EXPERIMENTAL RESULTS

A. Gross Ion and Electron Production Cross Sections.

The final group of measurements in the gross production cross section phase of this program were those for neutral atomic hydrogen projectiles, and these are the only results in this phase that were not yet presented in detail in the last annual Progress Report. Measurements for the usual four target gases, helium, argon, hydrogen, and nitrogen were completed within the final three months of the preceding contract period, but only over the restricted range 0.15 to 0.40 MeV in the energies of the incident particles. Measurements to higher energies did not prove to be feasible by the methods used because of the low intensity available in the neutral beam. The electron "pickup" cross section for protons decreases very rapidly with energy above about 0.3 MeV, compared to the "stripping" cross section for hydrogen neutrals, so that the neutral fraction obtainable from even an effectively infinite thickness of gas target in the charge exchange cell decreases rapidly with increasing energy. The limiting intensity tolerable in our measurements was determined by the sensitivity of the neutral beam detector and the noise and zero-drift levels in the electronic instruments used to measure its output. Considerable effort to optimize the several factors involved was required to cover even this restricted energy range, and it was clear that no really significant extension of the range toward higher energies would be possible without changing to a completely different detection scheme.

Despite difficulties, results of quite satisfactory self-consistency were obtained over the reduced energy range, although we were obliged to assign somewhat larger limits of possible error that for most of the previous results. As previously mentioned, the results will not be presented in great detail here, in view of the forthcoming Technical Report.

One general feature of the H^o results should particularly be mentioned here. For incident neutrals at these energies, the apparent ionization cross section σ_i is quite simply equal to the total positive ion production cross section σ_+, because the charge-changing cross section to form negative fast ions is known to be negligible. In our previous comparisons[6] of σ_i for the various projectiles we have studied, it had been noted that σ_i for He^+ projectiles was rather uniformly about 1.4 to 1.5 times that for protons of the same velocity in the same target, for six quite different target gases. Thus it appeared to make sense to say that as far as simple ionization at high energies (above 0.6 MeV) is concerned, the He^+ ion is equivalent to a point-charge ion with an "effective charge" equal to $\sqrt{1.45}$ e, or about 1.2 e.

As was noted in the last annual Progress Report, no similar conclusion could be drawn with respect to the results for He^0 projectiles. For this case, σ_i was found to be 1.0 times the equivelocity proton results in two of the target gases, and about 1.2 times the proton results in two others. There was no evident correlation of the value obtained with the weight or molecular type of the target gas.

However, in the new results for H^0 projectiles, we have again found that the concept of an "effective charge" seems to be applicable. For all four of the target gases studied, σ_i for H^0 was very nearly 0.65 times σ_i for equivelocity protons, at the upper end of the energy range covered, and the energy dependence appeared to be the same. A value of the "effective charge" of $\sqrt{0.65}$ e, or 0.80 e, is thus indicated For whatever it may be worth, it should be noted that H^0 is "isoelectronic" with He^+.

B. Charge Analysis of Slow Ions

As was explained in the last annual Progress Report, the slow-ion analyzer was designed to be part of a coincidence apparatus, that will provide for observations that are differential in the scattering angle of the fast particle and in the recoil angle of the slow particle. It is to be capable of high angular resolution and accuracy in both angles, so that determination of the inelastic energy loss from the geometry of the collision is possible. A support assembly has been constructed having two massive, counterweighted arms, one to carry the slow-ion analyzer and one for a fast beam analyzer. The arms can be rotated independently on precision bearings about a common axis. A third, fixed arm to carry the incident beam collimator is mounted to the same axis. In a coincidence experiment, the effective collision volume is that volume common to all three of the "acceptance cones" of the three direction-defining collimators, one for the incident beam and one for each of the analyzers. High precision in the relative positions of these three cones is necessary to make this volume a well-defined function of the angular positions, if any meaningful cross section values are to be obtained. The assembly has been constructed to maintain these positions to the required accuracy.

The collision chamber is a cylinder mounted on the top end of the rotation axis shaft and free to rotate about that axis. It is joined to each of the three arms by a flexible bellows, and is allowed to seek its own angular position so as to minimize the total stresses in the three bellows. A machined metal cone projects from each of the three arms through the connecting bellows into the collision chamber, ending in an accurate round hole of 3/8-inch diameter about 1/2 inch from the rotation axis. A small metal button in which the actual beam-defining aperture is cut fits into this hole, and may be made to extend closer to the axis if desired. The entire interior of the chamber, and all surfaces of the cones and buttons, have been rhodium plated to provide clean, uniform, conducting surfaces and to minimize contact potential differences, so that the collision chamber volume and the regions within the beam-defining collimator cones may be kept free of unwanted electric fields that might distort the energy or angular distributions. A cryogenically trapped mercury diffusion pump evacuates each of the arms, and a small Vac Ion pump is used to clean up the collision chamber before the target gas is admitted. This pump is shut off and its magnet is removed when the experiment is in operation. All gaskets immediately on the collision chamber are metal, so that it can be baked moderately with the use of electrical resistance heating tapes.

The slow-ion analyzer is of the 60-degree magnetic deflection design, with a 5-cm radius. Its machined aluminum vacuum chamber is electrically isolated from its grounded collimator cone, from its support structure, and from the magnet, so that slow ions emerging from the collimator may be accelerated into the chamber, through a focusing electrode structure, by a negative potential of the order of 2 kV applied to the chamber.

The detector used thus far has been a nude, 14-stage secondary electron multiplier with Cu-Be surfaces, mounted to the chamber through an insulating extension made of Delryn plastic. The entire multiplier is floated at a negative potential of more than 15 kV (a 30-kV supply was obtained for this purpose), so that the ions emerging from the analyzer exit slit are further accelerated into the first dynode, for most efficient detection. This arrangement has proved to be rather troublesome, because the signal then originates at a high voltage point. Noise from the high voltage supply, and from any corona or arcing in the dividing resistor bank is coupled out to the signal detection circuits, and can cause large "background" count rates. A number of rather empirical measures were necessary to reduce these effects, including the addition of a smooth face cap to the forward end of the multiplier to reduce ionization of the residual gas by corona between the multiplier and the analyzer chamber exit slit assembly. Despite all efforts, it has never proved possible to use a post-acceleration potential greater than about 22 kV without creating excessive noise, and it is usually difficult to get much beyond around 18 kV. However, it has been shown for both He^{+} and He^{++} ions that the count rates reach a saturation level by about 15 kV, indicating that very nearly 100% of the particles are detected at this potential. However, further work on the detection system and consideration of alternative methods will continue to be a major concern.

The slow-ion analyzer and support structure were assembled in the early part of the present contract period, and will be described more fully in the previously mentioned Technical Report. Following the studies of the detector alluded to above, non-coincidence measurements of slow-ion charge state distributions have been undertaken, using, in place of the fast beam analyzer and its collimating cone, a guarded Faraday cup, to measure the intensity of the incident beam. The results obtained will also be presented in detail in the Technical Report, but the effort will be described briefly here.

For a proton beam into a helium target, both He^{+} and He^{++} slow ions were detected emerging from the field-free collision region. However, to our initial surprise, there was no discernible dependence of the count rate for either ion on the angular position of the analyzer, over the range from 70° to 90°. This result was taken to indicate that most of the slow ions are formed with even lower energies than was expected; certain other preliminary tests indicated that it was less than 1 or 2 eV. Even so, it might have been supposed that such ions should be peaked very sharply at 90°. However, Everhart has recently pointed out to us that his analysis[9] of the effects of thermal motion of the target atoms should be considered, and would probably predict almost complete "washing out" of the angular distribution for slow-ion energies as low as 1 eV. This conclusion does not follow completely trivially for our situation from the existing analysis, however, and it still remains to be checked in detail.

Meanwhile, similar tests were run for a proton beam into an argon target. Despite the larger mass of the target atom, the fraction of all collisions producing a substantial transfer of momentum to the target atom would be expected to increase substantially, because of the larger atomic number Z of the target atom. Ar^{n+} ions with n = 1 to 6 were detected emerging from the collision region, but again there was no discernible angular dependence. Quite recently, similar tests were made for a Ne^{+} beam into an argon target, a case for which sharply peaked angular distributions had previously been seen[10]. However, the distributions initially observed for both Ar^{+} and Ar^{2+} were at most only weakly dependent on angle, bearing little resemblance to the previously published distributions, or to the similar results for Ar^{+} into argon published by Everhart[11].

It was then pointed out to us by Everhart that the analyzer he had used in obtaining his distributions had been specifically designed to be insensitive to very low energy ions, since he had been interested only in the expected "hard" component. Thus, it was not necessarily inconsistent that we could not readily discern the same distributions above the nearly isotropic sea of very low energy ions that seemed to be present, and to which our analyzer is sensitive. To verify that this was an accurate assessment of the situation, we have in the days just preceding the present writing conducted a test in which a positive "retarding potential" was applied to one of the electrodes of the focusing assembly leading into the analyzer, to "bias out" the very slow ions. With an applied potential of only 1 to 4 volts, the slow ion count rates at most angles dropped off dramatically, leaving a well defined peak at about 86° that was of roughly the expected width and shape.

This test was conducted for Ne^+ into argon, and it appears to have established that for this case the great bulk of the slow ions are formed with energies of at most a few eV, and that these have an almost isotropic angular distribution in the laboratory reference frame. The latter feature will, we believe, prove to be attributable to the effect of the thermal motion of the target molecules.

There is little doubt that the same situation will be found to exist for the case of incident protons, with perhaps an even larger fraction of the slow ions in a group of even lower energy. Results that have been completed at the time of this writing are too preliminary to provide a realistic estimate of this fraction. For one thing, the retarding potential geometry being used is far from optimal, utilizing as it does an electrode assembly designed for a different purpose. This assembly must be modified, and the same type of tests must be extended to the incident proton cases.

Meanwhile, and prior to these recent tests with the Ne^+ beam, it had been tentatively concluded that for the proton cases, all but an essentially negligible fraction of the slow ions had energies of no more than a few eV, whether singly or multiply charged. Therefore, for measurement of the total production of the various charge states of the slow ions, it should be possible to make use of a parallel-plate collection field to sweep the slow ions to the entrance slit of the analyzer, without introducing significant errors due to discrimination effects for the higher charge state ions.

Accordingly, a small parallel plate assembly was fitted to the end of the analyzer cone, and the total production of the various slow-ion charge states has been observed for protons into helium and argon. The geometry of the assembly permitted only relative rather than absolute cross section determinations, so the results have been normalized to our own previous measurements of the total apparent ion production.

In helium, our results for He^{++} production at the lower end of our range agree very well with the results of Fedorenko[12], available up to 0.18 MeV. At the high end of our range, our results were a factor of 2 below those originally published by Wexler[13] in the range 0.8 to 3.75 MeV. However, we have since discovered that Wexler found an error in his published results, and has published an Erratum[14] reducing his He^{++} results by a factor of 2. These revised results are in very good agreement with ours in the region of overlap; however, our energy slope is markedly steeper than his.

An interesting correspondence has been noted with the measurements of excitation by protons, in the other part of the Georgia Tech program, reported concurrently in Report No. ORO-2591-23. It has been noted that, whereas the cross sections for "allowed" excitations generally have an energy dependence very similar to that of the apparent ionization cross section, those for the "forbidden" excitations invariably are steeper and approximate a straight-line 1/E dependence, as is predicted by the Bethe-Born approximation. The statement seems to hold even when the "forbiddenness" involves a two-electron excitation rather than simply an angular momentum selection rule. In particular, in the study of protons on helium, the excitation of one line of He^{+} was studied. Here the collision involved simultaneous ionization and excitation, is thus a "two-electron" transition, and it shows the characteristic "forbidden" energy dependence. It was noted that the cross section for double ionization of helium also shows very nearly this same energy dependence.

In the case of protons into an argon target, preliminary measurements have been made of the relative cross sections for the production of Ar^{+}, Ar^{2+},

Ar^{3+}, Ar^{4+}, and Ar^{5+}. The relative measurements were again normalized to our previous total apparent ionization measurements. For the Ar^{+} production, agreement with Fedorenka's results at lower energies[12], and with Wexler's results at higher energies[13], follows automatically from the normalization. For Ar^{2+}, there is also reasonably good agreement with the other results at both ends of the range. However, for Ar^{3+}, while there is good agreement with Wexler at the high end, agreement with Fedorenko's results at the low end is poor. It appears that the latter may be quite substantially in error, by as much as a factor of 8 at 0.15 MeV.

These comparisons will be given in greater detail in the forthcoming Technical Report; also presented there will be some rather interesting comparisons with other results for multiple ionization by electron impact.

C. Progress on the Fast Beam Analyzer and the Coincidence Experiment

The design of the fast beam analyzer is complete in all details. The vacuum chamber is now under construction, with delivery expected within two weeks. The additional mercury diffusion pump that will be required has been ordered, and some of the electronics components are in hand. A delayed pulse generator was obtained on loan some time ago, to allow evaluation of its suitability to provide the delay which compensates for the transit time of the slow ions. The borrowed unit was determined to be satisfactory for this purpose, and an identical unit has been ordered. Final decisions are now being made regarding the solid-state detector and the remaining electronics components, and orders will be placed soon.

III. PLANS FOR THE BALANCE OF THE PERIOD

As mentioned earlier, the focusing electrode assembly of the slow ion analyzer must be modified to provide a better arrangement for applying a retarding potential to "bias out" low energy ions. Careful study of the slow ion energy distributions will be made, to determine quantitatively (a) the fraction of the slow ions that are of such very low energy as to have essentially isotropic angular distributions, and (b) the fraction that are of too high an energy to be collected with a known and constant efficiency by a parallel-plate extraction field. It appears to us at present that, in order to obtain the desired coincidence cross sections, it may prove necessary to use a combination of, on the one hand, field free collision chamber measurements with a retarding potential and with angular distributions, and on the other hand, of total measurements at fixed angle with the use of a parallel-plate extraction field. The energy distribution studies described here will be necessary to decide the details of the procedures.

The fast beam analyzer should be completed before the end of the contract period. It appears likely, in view of the complication of the isotropic low energy ions, that the measurements to be pursued at first will have to be selected according to their usefulness in the test and evaluation of the method. It is expected that the first case to be dealt with will still be that of protons into helium, as originally planned. However, the testing requirements may dictate that some observations of other cases involving higher atomic numbers will be more profitable than would an immediate attempt to complete the study of protons into helium.

IV. TRAVEL AND PUBLICATIONS

Project personnel have on about three occasions travelled to Oak Ridge

National Laboratory, at least partly for the purpose of conferring with staff members there about various experimental problems, notably in the area of detectors. There has been no other travel within this period. However, the 19th Annual Gaseous Electronics Conference was held on the Georgia Tech campus in October, and an oral paper was presented there on the cross section measurements for incident neutral H^{o} and He^{o}, as well as for He^{++}.

An article presenting the same results will be prepared for submission to the Physical Review as soon as possible.

V. INCIDENT REPORT

There have been no incidents for which a report would be required within the period covered by this report.

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IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

PROGRESS REPORT NO. 20

Covering the Period
December 1, 1966 to November 30, 1967

by D. W. Martin
G. O. Taylor

Report No. ORO-2591-34

Contract No. AT-(40-1)2591

U. S. ATOMIC ENERGY COMMISSION

OAK RIDGE, TENNESSEE

1 December 1967

School of Physics
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

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Ionization and Charge Transfer Cross Sections
Progress Report No. 20

The period covered by this report is December 1, 1966 through November 30, 1967. This period corresponds to the first 9 months of the 12-month extension provided for by Modification No. 9 of the contract, plus the final 3 months of the preceding period.

This report will be concerned only with the ionization and charge transfer phases of the total program at Georgia Tech, which were the subject of Part A of our proposal of December 1, 1966, covering the present period. The excitation measurements of Part B are covered in Report No. ORO-2591-33 of this same date. We are continuing the practice of issuing separate reports for the two segments of the program because they are relatively independent, and it is likely that many potential readers will be primarily interested in only one segment or the other.

I. INTRODUCTION

A. General Objectives of This Program

A broad program of absolute cross section measurements for charge rearrangement collisions of fast hydrogen and helium ions and atoms in gaseous targets has been in progress at the Georgia Institute of Technology for several years. The program has included studies with all of the five incident-particle states H^o, H^+, He^o, He^+, and He^{++}. The energies of the incident particles, obtained from a 1-MV Van de Graaff positive ion accelerator, lie in the range 0.15 to 1.00 MeV. This range extends to higher energies than those of most previous similar measurements elsewhere, and reaches well into the range where theoretical computations in the Born approximation may be expected to be valid, if they are properly formulated and make use of sufficiently accurate wave functions.

Exact wave functions are of course available for all of the simple projectiles used here, with the exception of the neutral He^{O} atom, but exact functions are not available for any molecule that is stable in a static gas at room temperature. Born calculations actually exist for only a few of the simplest possible target molecules, and, for the most part, only for the simplest rearrangement processes, in which only one electron in the whole projectile-target system changes its state. Although for some cases the results are rather confidently expected to be valid for sufficiently large energies, it has not really been possible to predict theoretically the minimum energy, below which the approximations will become inadequate. It is clear that progress in the fundamental understanding of rearrangement collisions requires that every new development in theory be subjected to detailed experimental examination, to establish the bounds of its validity, and point the way for further developments.

It has always been one of the main objectives of the present experimental program to perform just this kind of role, including target molecules for which some theoretical work has been done, and attempting to determine, as far as possible, the cross sections for single, well-defined, and simple rearrangement processes. In addition, we have sought to cover systematically a sufficient variety of cases to reveal any general patterns in the dependence of the cross sections on the general properties of the projectile and target particles, and to provide an empirical basis for extrapolation, for the estimation of probable cross section values for a larger variety of cases. This was the basic idea behind the use as projectiles of both hydrogen and helium, in all of their possible charge states, and in the choice of the array of target gases studied. The latter has included He and Ar, as both the simplest noble gas molecule and one heavier and more complex one, and H_2 and N_2, representing the simplest diatomic molecule and one heavier one. A few additional target molecules have been included in the studies involving some, but not all, of the five different projectile states.

B. Earlier Work in This Program

In the first phase of the present program, the quantities which were directly measured, by a simple total-charge-collection method using a parallel-plate geometry, were the cross sections for the gross total production by the fast projectiles of slow positive ions and of free electrons and/or negative ions. From our results and from such information as was available on the same cases from elsewhere on the cross sections for (a) electron stripping from the fast projectile, (b) electron capture by the fast projectile, and (c) the relative production rates of multiply-charged recoil ions, we made estimates of the cross sections for pure ionization collisions. These results were compared with all available theoretical results, with similar experimental results from elsewhere, and with experimental results for electron bombardment of the same targets; finally, the results were further compared with each other, for all of the several projectile states and target molecules studied. Certain useful empirical patterns did indeed emerge from these comparisons, as anticipated.

All work on this first phase of the program was completed prior to the period covered by this report. Many of the results have been published previously, and a final manuscript covering the remainder (all of the neutral-projectile work and portions of the He^{++} work) is in preparation for submission to The Physical Review. A Technical Report, including this same material as well as early portions of the next phase, to be discussed below, is being issued concurrent with this progress report. (See Sec. IV).

C. Objectives of the Present Phase: The Coincidence Experiment

The "pure ionization" cross sections referred to above were actually called "apparent" ionization cross sections because our method, in which only the total current of the slow positive ions produced was measured, did not distinguish the fractions of this current due to doubly-charged, triply-charged, etc., slow ions, and hence the cross section obtained was a weighted sum of the true cross sections for the ionization events producing slow ions of various charges. In addition, quite apart from the matter of experimental errors, our method could produce only an estimate of even the apparent ionization cross section. The reason is that, in subtracting from the total (positive or negative) ion production that part due to charge-changing collisions, in which the fast projectile either gained or lost electrons, it was never known from the available information (except within certain limiting bounds) what fraction of the charge-changing events were accompanied by the simultaneous ejection of extra electrons from the target. The extra contribution to the total ion currents from any such events should also be subtracted, if the remainder was to represent even the pure apparent ionization, as defined above. Except for upper bounds that could be set from measurements of the total production cross sections for multiply-charged slow positive ions, information on the cross sections for simultaneous ionization and charge transfer, or simultaneous ionization and projectile stripping, can be obtained only through an experiment in which one determines the final charge states of both of the partners from a single collision. This obviously requires a coincidence experiment.

Until quite recently, there was no experimental information whatever of this type. Furthermore, existing theory was of little assistance regarding these multielectron transition processes, an area in which very little work has been done. Although the uncertainties in our results from these types of processes were probably less than the experimental errors in many of the cases, it was by no means certain that this was true in every case, especially in the cases involving He^{+} and He^{++} projectiles.

The construction of a coincidence analyzer apparatus, capable of determinating in coincidence the final charge states of both of the partners from a single collision, was started under this program some time ago. The first goal of this effort was simply to measure the cross sections for well defined charge rearrangement collisions, as a logical extension of our own earlier gross ion production measurements. Particular interest attached to the determination of the fraction of the single-charge-transfer events in which one additional electron was ejected, leading to the production of a doubly-charged recoil ion, and to the fraction of the single-electron-stripping events in which a slow recoil ion was also formed. These were the two particular classes of events that had produced the largest uncertainties in our attempts to estimate pure ionization cross sections, and we wished to make a direct determination in order to clarify our own previous results. However, it was always intended that we would not restrict attention to these particular processes; relatively little was known of multiply-charged ion production in general, and nothing was known of the contribution of events involving charge transfer, and essentially any of these multielectron processes are of *a priori* interest as extensions of the detailed knowledge of atomic collisions in general.

The apparatus has, however, also been designed to have certain capabilities beyond those required just for cross section measurements. Both the recoil-ion analyzer and the analyzer for the scattered fast projectile are movable in angle, and have direction-defining collimators which can be set for high angular resolution. This feature was incorporated, first of all, because it was believed it might prove essential just to get proper values of the total cross section, for those rearrangement collisions involving the formation of multiply-charged recoil ions. If any significant fraction of such recoil ions emerged from the collision with appreciable kinetic energies, they could not all be collected except by an analyzer that could scan in the recoil angle, determining a differential cross section that could be integrated over the angle to obtain the total cross section. At the same time, the sensitivity of the system for detecting events of this type could be enhanced if the fast-beam analyzer were also given a high-resolution angular capability, so that instead of receiving the entire fast beam, it could be set to receive only a narrow slice of the scattered beam, over a range in the scattering angle appropriate to the recoil angle.

A second reason for building a differential apparatus is that, if the scattering angle and the recoil angle are both measured for a single collision, with sufficient precision, it is possible to compute simply, from the conservation laws, the total inelastic energy loss, i.e., the total heavy-particle kinetic energy that was converted to excitation and electron kinetic energy. Such excitation normally represents only a very small fraction of the initial kinetic energy of the fast particle, particularly in the energy range of the present investigation, so it is not easily obtainable simply by measuring the final energies of the collision partners. The determination of the energy-loss spectrum for a given type of rearrangement collision would provide important information as to the nature of the basic excitation mechanisms involved in the particular rearrangement. Information of this type is of as much fundamental and practical interest as are the cross sections themselves.

D. Existing Coincidence Work Elsewhere

The very first known coincidence experiments in atomic collisions are rather recent, those of Afrosimov and coworkers at the Ioffe Institute in Leningrad, and of Everhart and Kessel at the University of Connecticut. Although, in the period since the earliest publications of these groups have appeared, workers in at least a half dozen other locations are known to have begun building coincidence apparatus of one kind or another, these two groups remain, to the present time, the only ones to have published any results.[1-16]

The first experiments of both groups were designed entirely for the second of the objectives mentioned above, i.e., the study of inelastic energy losses, rather than for total cross section measurements for a given charge rearrangement. In particular, both groups were initially interested in a particular anomaly that had been observed earlier in "hard" Ar-Ar collisions by Morgan and Everhart.[17] The early coincidence results[1-7] of both groups quite clearly refuted the original explanation that had been advanced by Morgan and Everhart, and indicated some sort of a massive discrete excitation of large parts of the entire electronic structure of the collision partners. Certain differences in the details of their results led the two groups to somewhat different assumptions about the basic nature of this excitation, and there has been a continuing controversy between them over this question, which has been only partially resolved by more recent work, and which was the subject of considerable discussion at a recent International Conference.[13,14]

More recently, both groups have made similar studies, with the same apparatus, of the inelastic energy-loss spectrum for other pairs of noble gas collision partners.[8-10,15] One case which both have studied, which is of particular interest, is that of Ne^+ into argon. Comparison of the results with the Ar-Ar case would have been expected to clarify the interpretation of the latter case. However, the Connecticut and Leningrad results again differ sufficiently that each party claims confirmation of his own earlier interpretation, and the matter remains unsettled. Neither laboratory has yet published any results for He^+ into argon. A clearcut finding of similar structure in the bombardment of argon by this truly simple projectile would perhaps provide a definitive answer to the questions of the basic mechanism. However, it may be that such structure, even if it exists in principle, will be of very low intensity, and will correspondingly be very difficult to detect, because of the low atomic number of the projectile.

While the original Leningrad apparatus has been used only for inelastic energy loss studies, a second type of apparatus has more recently been assembled at the Ioffe Institute, that is designed specifically for the measurement of total cross sections for given charge rearrangement processes. It has no angular scan capability, but utilizes a parallel-plate extraction field and large-aperture ion optics to effect total collection of all slow ions, without regard for their initial energies or directions of motion. Results published thus far[11,12,16] include the cases of H^+, H^0, and H^- ions on noble gases, and are restricted to energies well below the range of the present experiment.

E. Detailed Plan of the Coincidence Experiment

The apparatus being constructed in the present program has a combination of features that provide considerable flexibility in its use. When equipped with the smallest apertures in the collimators, it has high enough angular resolution for inelastic energy loss determinations. The recoil-ion analyzer is designed to be uniformly sensitive to slow ions of all energies down to the order of 1 eV, to permit differential cross section measurements for all but very "soft" collisions. The magnetic-deflection recoil-ion analyzer has sufficient momentum resolution to provide an independent measurement, with modest resolution, of the energies of the fastest recoil ions. A retarding potential arrangement is included which can be used to "bias out" the extreme low end of the recoil-ion energy distribution (which has a nearly isotropic angular distribution in the laboratory reference frame due to the thermal motions of the target molecules), to facilitate differential cross section measurements, and to provide direct observation of the low end of the energy distribution. The small apertures can at will be replaced by larger ones, and an extraction field arrangement provided, to convert the recoil-ion analyzer to a total-collection geometry. It should thus be possible, with this apparatus, to obtain total cross sections even for rearrangement processes in which a significant fraction of the recoil ions have appreciable energies, to determine at least roughly the form of the energy distribution of the recoil ions, and further to examine the inelastic energy-loss spectrum itself.

Portions of the construction of the apparatus took place prior to the period covered by this report, and have been discussed in detail in the last previous Progress Report. This included the construction of the recoil-ion analyzer, and of the rotary mount assembly for both of the analyzers. Preliminary non-coincidence studies performed with this much of the system demonstrated that the recoil-ion analyzer was indeed sensitive to recoil ions of very low initial energies, and they established that the great majority of all the recoil ions, even of the doubly-, triply-, and higher-charged recoil ions, have very low energies of less than the order of 1 eV, for proton bombardment of helium or argon. Even for the case of Ne^+ into argon, it was shown that most of the doubly- and triply-charged recoil ions had energies of less than a few eV. With these points established, the total collection geometry with an extraction field was installed, and measurements were made of the relative total production of variously-charged recoils by protons into helium and argon. These results have all been discussed in the last previous Progress Report, and are presented in detail in the current Technical Report that has been mentioned above (See Sec. IV). In addition, a paper on the results for protons into helium was presented at an international conference in Leningrad in August, 1967 (See Sec. IV).

II. PROGRESS DURING THE CURRENT PERIOD

Essentially all of the effort during the period covered by this report has gone into the further construction of the differential coincidence analyzer apparatus. Final assembly of the whole system was completed only recently, and alignment procedures are continuing at the time of this writing. It was anticipated, a year ago, that this stage would have been reached a few months ago, and that the first experimental investigation with the complete system would be well under way by the present time. The delay has been occasioned chiefly by extra effort that has been given to two matters, specifically the retarding potential assembly and the recoil-analyzer detector, which are discussed below in the context of the rest of the work performed in this period.

A. Retarding Potential Electrode Assembly

As has been discussed above, a retarding potential arrangement in the recoil-ion analyzer was needed to study the low-energy end of the recoil-ion energy distribution, and to "bias out" the isotropic low end of the distribution when performing differential measurements. The preliminary results found in the previous period, mentioned above and described in the last previous Progress Report, had been obtained using a very makeshift arrangement, in which the retarding potential was applied to an electrode in the analyzer accelerating gun that had been designed and intended for another purpose. The discovery that so many of the recoil ions actually have such very low energies indicated the importance of having a very well-engineered arrangement, if results of any quantitative significance were to be possible. Specifically, it would be desirable that the arrangement have very "sharp cutoff" characteristics, meaning ideally that ions on all trajectories allowed by the collimators, having energies even only slightly above the cutoff, will be transmitted, while ions on all trajectories with energies below the cutoff will be stopped. In addition, one needs to know accurately the ratio of the cutoff energy to the retarding potential applied to the electrode, which will not be unity because the potential field will have only a "saddle point" maximum within the aperture in the retarding potential electrode.

To our surprise, we were unable to find a detailed description of such a well-engineered arrangement in the literature, despite the rather lively interest that has existed in recent years in "retarding potential difference" methods, in connection with electron-bombardment studies. It appears that in most cases in the electron work, a grid has been used as the retarding potential electrode. The "saddle point" problem gets little mention, since it is overshadowed and absorbed by problems with contact potentials, which necessitate an empirical calibration of the relation of the cutoff potential to the applied potential anyway.

We have precluded the use of a grid in our case for two separate reasons. First, because of the very small dimensions of our collimated recoil-ion beam, no known type of high-transmission grid would have a "fine" mesh size compared to the beam size, and so there would be a large uncertainty in the transmission factor. Secondly, and perhaps more importantly, surface reactions of slowly-moving multiply-charged ions on the grid wire surfaces could be a source of great difficulty to us.

The arrangement we are using was designed and evaluated with the aid of a greatly enlarged scale mock-up in an electrolytic tank, which we built up for this purpose. The arrangement consists of a cylindrical hole of diameter more than twice the beam dimensions, through a plate whose thickness is 1.67 times the hole diameter, which is located between two thin, grounded plates with smaller circular apertures. The tank tests showed that the saddle-point area is quite flat over more than half the diameter of the hole, with a potential of about 94% of that applied to the thick plate.

This arrangement has been constructed and installed as an integral part of the collimator, immediately following the second collimator aperture. Its parts have been rhodium plated, as have all of the other surfaces that are "seen" by the ion beam, before it is accelerated for analysis. The addition of these parts required disassembly and some rearrangement of the whole accelerating electrode structure, which then had to be realligned optically when it was reassembled.

B. Detector for the Recoil-Ion Analyzer

It is required of this detector that it have a uniform and high counting efficiency, as close to 100% as possible, for ions of any charge or mass, with all values of initial energy (at the analyzer entrance collimator) down to essentially zero. It is further required that the detector be virtually "noise free", i.e., that it produce very few random pulses which cannot be discriminated electronically from the true ion pulses. The arrangement originally installed, and used to obtain the earlier non-coincidence results mentioned several times above, was an open, 14-stage multiplier, floated far below ground potential. The first dynode, on which the ions impinge, had to be at a sufficiently high negative potential that all incident ions were "post accelerated" to an energy sufficient to produce a count. This potential was normally much larger than the optimum voltage across the dynode string, so that it had to be arranged that the anode or collector end of the multiplier was also at a somewhat lower, but still "high" negative potential with respect to laboratory ground, and the signal pulses then had to be passed to ground through a high voltage blocking capacitor.

In tests described previously, it was determined that first-dynode potentials of at least 12 to 15 kV were in general required to produce "saturation" in the count rates, with fixed beams of helium or argon ions of various charges. On occasion, it was found possible to go as high as about 22 kV before the noise problem became excessive, although it was more commonly necessary to set a limit of about 18 kV. We reported last year that this arrangement seemed to be workable, and that we could say tentatively that this detector problem was solved.

However, further operating experience has shown this scheme to be a never-ending source of trouble. It could never be kept free, for very long at a time, from excessive noise caused by breakdown or corona from one point or another in the high-voltage circuitry. Progress on other matters was stalled repeatedly when the test schedules were interrupted by unexpected troubles with the detector, and it was at last concluded that some other scheme would have to be worked out.

The scheme which has been developed and installed is not at all original in its main, basic idea, namely, that there be an electrode carrying a high negative potential, to which the ions are accelerated, and from which they produce secondary electrons. These secondary electrons are then accelerated back through the same high voltage to a detector that is near ground potential, but is physically as well as electrically remote from the high potential electrode. The detector itself could be any of several types: A Cs-I crystal and photomultiplier scintillation counter seems to have been adopted as standard in the experiments at the Ioffe Institute, while several other groups have favored open multipliers, and still others have used solid-state detectors of the sort that are currently finding much use in nuclear physics.

Although this basic idea is not original, we venture to think that the particular geometrical arrangement we have devised offers some unique advantages. The high potential electrode is an aluminum sphere $1\frac{1}{2}$ inch in diameter. A large hole, 7/8 inch in diameter, is bored half-way through the sphere, ending with a flat bottom at the midplane of the sphere. A radial slot only large enough to pass the incident ion beam is cut into the side of the sphere, intersecting the large hole. The slot makes an angle of 75° with the axis of the large hole, and is aimed at the center of the flat surface at the bottom of the hole. The incident ions are directed at the sphere along the direction of the slot. They are accelerated toward the sphere, but enter the slot, and pass through it to impact at 15° grazing incidence at the center of the flat bottom of the large hole. The secondary electrons emitted find themselves in an axial field parallel to the axis of the hole, and are accelerated out of the hole in that direction toward the distant detector.

This arrangement was designed to avoid or minimize several problems which are relatively well known to be troublesome in detectors of this general type. The spatial regions in which the approaching ions and the departing electrons are accelerated by the high potential are separated physically, being nearly 1/4 of the way around the sphere from each other, so that the fields in each region can be shaped as required for optimum performance. The ion acceleration region is symmetric about the plane of the beam, so that the ions are accelerated "straight ahead", and the point of impact is virtually independent of the initial energy of the ion. The impact surface, from which the secondary electrons are emitted, is partially shielded from the high fields around the sphere, because of the fact that it is "buried" deep inside the sphere. The electric field is relatively weak near this surface, although it should be more than sufficient to pick up all of the secondary electrons and move them axially out of the hole. Because the field is weak near the surface, it will produce a negligible last-second deflection of the ion beam, to cause any systematic variation of the impact point with initial energy, and it should also produce negligible field emission of extraneous electrons from the impact area. Field-emission electrons coming from other regions of the sphere surface, in particular from around the rim of the large hole, are prevented from reaching the detector by a limiting aperture, that also serves as a focus electrode for the true secondary electrons coming from the impact area at the bottom of the hole.

The final detector presently in use is the same open multiplier that previously served as the entire detector, but it would be a quite simple matter to substitute either a scintillation counter or a solid state detector if desired. The only voltage applied to the multiplier is the roughly 5 kV required across the length of its dynode string, and voltages of only this magnitude are available from a highly stable, low noise supply that was designed specifically for use with counters. Tests have established that there are fewer spurious pulses which masquerade as signal pulses if the first-dynode end of the multiplier is grounded, and the collector end is 5 kV positive, than with the reverse arrangement, first tried, in which the collector end is grounded and the first dynode is 5 kV negative.

Tests with incident argon ions of low initial energy have demonstrated that this detector system shows excellent saturation characteristics, in that the count rates are very constant for sphere potentials from about 11 to more than 22 kV. There is white noise at the amplifier output of about 200 mV peak to peak, with the gain settings normally employed, which the discriminator may be set to exclude entirely. The number of spurious pulses exceeding this threshold is less than 5/second and is independent of the sphere potential up to values of 22 kV. It thus appears that this system will function as required, yielding an essentially 100% counting efficiency, with low noise, and excellent stability.

C. Fast-Beam Analyzer

The fast beam analyzer is a simple electrostatic-deflection instrument, which need have only sufficient resolution to distinguish the charge state of the scattered fast particles. It is mounted on a massive arm that is part of the same angular support assembly that supports the collision chamber, the incident-beam collimator, and the recoil-ion analyzer, so that both analyzers may be made to rotate accurately about the same vertical axis, and so that the collimators of both analyzers as well as that for the incident beam may all be aimed accurately at that axis. The collimator of the fast beam analyzer is identical in construction to the other two, and may be fitted with either a set of very small apertures, for high angular resolution, or with a set of larger apertures when high resolution is not required.

Because of the high energies of the fast beam particles, the analyzer is designed to work with only small-angle deflections of less than 6°, so that inconveniently large voltages will not be required. In view of the tight collimation of the entering beam, and the restriction to small angle deflections, there need be no concern about beam focusing or other such ion-optical effects, but it becomes necessary that the detector position be quite accurately determined and reproducible. The most elaborate component of the whole instrument is, in fact, the mechanical assembly that performs this positioning function.

The analyzer is housed in a 4-in. id stainless steel pipe about 25 in. long, where the fast beam enters at one end along the axis. The deflection voltage is applied to one of two parallel plates 5 in. long and 3/8 in. apart, located close beyond the last aperture of the collimator. Emerging from between the plates, the beam traverses a field-free region about 18 in. long to reach the detector plane. In this plane, the He^{+} and He^{++} components in a 1.0-MeV helium beam will have been deflected 0.6 and 1.2 inches from the axis, respectively, by a deflection potential of 5000 Volts.

The detector, a 1-in. diameter commercial silicon detector, is enclosed in a small metal box having a 1/4-in. diameter entrance aperture in its front face. The assembly is mounted by a rigid shaft to an external positioning assembly, which permits controlled 2-dimensional motion of the assembly in the detector plane. A vacuum seal around this movable assembly is provided by a flexible metal bellows. The support shaft, which extends into the vacuum to the detector location, is oriented vertically, and is hollow and open to the atmosphere at the upper end. A refrigerant may be poured into it to maintain the detector at reduced temperature, if this is required to reduce the noise level. In addition to serving as an electrostatic shield, the metal box surrounding the detector serves as a baffle to minimize condensation on the cold detector.

The signal lead from the movable detector is a bare, rigid lead to a feedthrough on the upper end of the movable assembly, which is spaced mechanically away from the surrounding grounded housing to keep its capacitance low. The preamplifier is mounted on the movable assembly outside the vacuum, close to the feedthrough, to which its input jack is connected by a piece of coaxial cable only 1 inch long.

One last feature is a small Faraday cup, mounted from the rear endplate on the cylinder axis, behind the detector plane, where it will receive the entire beam when there is no deflection potential applied to the plates. This cup will serve to monitor the total intensity of the scattered charged beam at each angle, before its components are deflected to the silicon detector. This indication will be important when working with the smallest possible scattering angles very close to the main beam, since the silicon detector can be very quickly damaged by an excessive flux of fast particles.

The construction and assembly of the fast beam analyzer have been completed, and it has been mounted and aligned, as described below.

D. Alignment

All of the fine collimating apertures in this apparatus have been cut in the centers of a number of identical metal "buttons" of 0.3430-in. outside diameter, which fit snugly into holes of like diameter in the main collimator pieces. If the buttons are removed, straight rigid rods or pins of the same diameter can be inserted into these holes, with their axes quite accurately parallel to the beam axes defined by the apertures in the buttons. If the bottom plate of the collision chamber is removed, a similar pin may also be inserted into an accurately centered hole bored into the top end of the massive axle about which the analyzers rotate.

The original line-up of the apparatus was accomplished mechanically, with the aid of such pins. A small rectangular block was milled containing three mutually perpendicular holes, whose axes were to intersect in a single point, as accurately as could be assured with the best available shop machinery. The block was supported with this point at the collision center by the axle pin, inserted into one of the holes. The positions of the three collimators were then adjusted so that pins inserted in the incident beam collimator and the fast beam analyzer collimator would slip into the two ends of a second hole in the block, and a pin inserted into the recoil analyzer collimator would slip into the third of the 3 mutually perpendicular holes. This procedure was intended to assure the accurate aim of all three collimators toward the rotation axis, and to define the 0° position of the fast beam analyzer and the 90° position of the recoil analyzer.

Unfortunately, the precision of this procedure left a good bit to be desired. The limited space in the collision chamber required the use of short pins, which extended only into the first of the "button holes" of each collimator, rather than through both the front and rear holes. The insertion of longer rods through both holes, from the rear end of each collimator, could not be accomplished without rather extensive dismantling of other parts of the apparatus, especially in the case of the recoil analyzer, and it was decided not to resort to this procedure for the present. In any case, the same space limitations required that the block be so small that the bore lengths of the 3 mutually perpendicular holes were too short. It was found that the described procedure provided reproducibility in the 90° position of only somewhat better than 1/2 degree, which is not accurate enough for inelastic energy loss determinations. This mechanical line-up was therefore regarded as only preliminary.

The light beam of a small gas laser was then passed through the incident beam collimator and the fast beam analyzer collimator. The small aperture buttons were then installed one by one, while small alignment adjustments were made. This procedure produced internal and mutual alignments of these two collimators, and definition of the 0° position, which are thought to be satisfactory. This alignment has since been verified by passing the accelerator ion beam straight through both collimators, and the results indicated that the expected angular resolution has in fact been achieved.

Unfortunately, the angular limitations imposed by the metal bellows connecting the three collimators to the collision chamber do not permit that the recoil analyzer may also be rotated to the 0° position, to perform a similar verification of its alignment and its indexing to the angle scale. An ingenious mirror arrangement has been suggested by our colleague E. W. Thomas, to produce an accurate 90° reflection of the light beam that is not dependent on exact location of the mirror assembly. We expect eventually to utilize this idea for an accurate verification of the 90° position, but for the present we will tentatively accept the existing alignment and proceed with some of the other tests of the system. As indicated below, we will attempt to reproduce certain of the published results from other laboratories, which will provide an indication of the existence of any serious errors.

At present, we are involved with other alignment problems involving the relative positions of the magnet, the detector, and the other components of the recoil analyzer. The new detector arrangement imposes much more strict collimation requirements on the exiting beam than did the former arrangement, and we are meeting with temporary difficulties. Work on these problems is continuing.

E. Auxiliary Ion Source

A small ion source has been constructed, which can be inserted into the beam entrance pipe of the apparatus. It will serve to provide a beam with an energy of a few keV, to be used for test purposes at times when the Van de Graaff accelerator is in use on the excitation experiments which constitute the other half of the research performed under this contract.

III. PLANS FOR THE BALANCE OF THE PRESENT PERIOD

When the alignment problems described above appear to be sufficiently well in hand, we plan to examine the case of Ne^+ into argon, to verify that the published results for this case of the Connecticut[9,10,14] and Leningrad[8,16] groups can be reproduced. If this can be done satisfactorily, it will be considered an excellent general check of the entire experimental system. Following a satisfactory conclusion of this test, we expect to begin at once a detailed study of the inelastic energy loss spectrum for the case of protons into argon, which is being proposed as a part of the program for the new period.

IV. TRAVEL AND PUBLICATIONS

Dr. D. W. Martin attended the Fifth International Conference on the Physics of Electronic and Atomic Collisions, which was held in Leningrad, USSR, in July, 1967. There, he visited the Ioffe Institute, saw both of the two "Leningrad experiments" mentioned at various places in this report, and met several of the Russian scientists involved in this work. Dr. Martin was privileged to observe a detailed discussion between Everhart and the Russian scientists regarding the differences between their results for the Ar-Ar case, and had several discussions with Everhart, Kessel, and Russek regarding these matters. After the Conference, he went on a tour to

Kharkov, which had been specially arranged for the Conference participants. There he visited the laboratory of L. I. Pivovar. He had several discussions with Professor Pivovar, much of whose work has a direct connection with some of the work performed under this contract. On the return trip, he made brief visits with F. de Heer in Amsterdam, with H. B. Gilbody and R. Browning in Belfast, and with J. Hasted in London. A detailed report of these travels, required by the AEC, has been prepared separately.

At the Conference, a paper was presented on some of the work performed under this contract, entitled "Analysis of the Recoil Ions Produced by Fast Protons". The 1500-word abstract which was printed in the Conference Proceedings has been released as AEC Document No. ORO-2591-26.

The Ph.D. thesis of L. J. Puckett, covering in detail all of the results from this program for a period of some two years ending in late 1966, has been prepared for release as a Technical Report. To be designated as AEC Document No. ORO-2591-35, this report will be available on about December 1, 1967.

No other publications have been made within the period covered by this report. However, a manuscript presenting the results of the gross ionization studies for He^{++}, He^{o}, and H^{o} beams (included also in the above Technical Report) is now in final stages of preparation for submission to The Physical Review.

V. INCIDENT REPORT

There have been no incidents for which a report would be required, within the period covered by this report.

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ORO-2591-38

IONIZATION AND CHARGE TRANSFER

CROSS SECTIONS

PROGRESS REPORT NO. 21

Covering the Period

December 1, 1967 to November 30, 1968

By D. W. Martin

G. O. Taylor

USAEC Document Number

ORO-2591-38

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

U. S. ATOMIC ENERGY COMMISSION

OAK RIDGE, TENNESSEE

30 November 1968

School of Physics
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

ORO-2591-38

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Ionization and Charge Transfer Cross Sections
Progress Report No. 21

The period covered by this report is December 1, 1967 through November 30, 1968. This period corresponds to the first 9 months of the 12-month extension provided for by Modification No. 10 of Contract No. AT-(40-1)-2591, plus the final 3 months of the preceding period.

This report will be concerned only with the ionization and charge transfer phases of the total program conducted at Georgia Tech under this contract. This portion of the program was the subject of Part A of our proposal of December 1, 1967, covering the present period. The excitation measurements phases of Part B of the proposal are covered in a separate Report, No. ORO-2591-37, of this same date. Our past practice of issuing separate reports is continued, because the two parts of the program are relatively distinct and independent.

I. INTRODUCTION

A. Objectives of this Program

All effort during the present period, as well as in the last preceding period, has been directed toward the perfection of a differential scattering apparatus for coincidence studies of ionization and charge transfer collisions. The motivation for such experiments, and the experimental capabilities for which the apparatus was designed, have been discussed at some length in previous reports. (In particular, see Progress Report No. 20, Dec. 1, 1967, Documnet No. ORO-2591-34, which also includes a discussion of similar studies conducted or in progress elsewhere.) These matters will be dealt with only very briefly here.

The coincidence experiment has been undertaken as a logical extension of earlier work in this program, in which cross sections for total slow ion and free electron production were measured for fast hydrogen and helium ions and atoms, in each of their possible charge states, incident on several representative target gases. The incident-particle energy ranged from 0.15 to 1.0 MeV. Particular emphasis was laid to accurate determination of the relative cross sections for the various projectiles and targets. From the results, we sought to evaluate the cross sections for the separate processes contributing to the total ion and electron production, that is, for ionization and charge exchange, to compare with theoretical calculations where available, and to establish empirically the systematics of these cross sections with respect to the nature of the target gas and/or the projectile particle.

The chief difficulty in interpreting these measurements lay in the uncertainty as to the contribution of "higher order" processes involving more than one electron, such as multiply-ionizing collisions, or collisions in which both charge transfer and ionization occur. While there exists considerable information from other sources on charge transfer, and to a lesser extent on multiple ionization, information of either an experimental or theoretical nature about the combination processes was essentially nonexistent. Direct measurement of cross sections for well defined processes, in which the final charge states of both projectile and target from a single collision are determined in coincidence, would remove much of the ambiguity in the earlier measurements. The results would provide a more meaningful comparison with the existing theory, and might be expected to stimulate the further development of theory for the higher order processes.

Even though the first objective of the experiment is the determination of total cross sections for given rearrangement processes, the apparatus has been designed to be capable of measurements that are differential in both the projectile scattering angle and the recoil angle. One reason for this is to be able to determine explicitly, for each elementary process, the contribution of "hard" collisions in which the projectile scattering angle is appreciable, and the target recoils at an angle forward from 90° with appreciable kinetic energy. In the most cases, the total cross sections cannot be obtained, however, simply by measuring differential cross sections and integrating over the angles, because the scattering is strongly peaked at 0° with, correspondingly, very small kinetic energies for many of the recoil ions. The recoil-ion analyzer has been designed to be, as far as possible, uniformly sensitive to recoil ions of all energies; as a practical matter, however, the sensitivity must fall off for energies less than some minimum value, due to interference from residual stray fields, scattering, etc. Data that has been described in the previous report indicates that our recoil-ion analyzer retains an appreciable sensitivity for ions that enter its collimator with initial energies down to of order 2 eV or less. The same data also shows clearly that a large fraction of the recoil ions have energies right down to, and probably beyond, whatever point represented our effective cutoff. The measurement of total cross sections thus requires the application to the collision region of a transverse electric field, sufficient to sweep into the analyzer all of the slow ions formed along a well-defined length of the fast projectile beam, or at least all slow ions formed with initial kinetic energies less than a certain maximum value. For those cases where an appreciable fraction of the ions are found to exceed this maximum, a total measurement for the slowest ions and a differential measurement for the faster ions can, in principle, be combined to obtain the total cross section.

Apart from the use of the differential capability to assure that any contributions from "hard" collisions are not missed in the total cross section determinations, the measurement of differential cross sections is of intrinsic interest. Any structure observed in the cross section for a given process could be expected to reveal information about the mechanisms involved in the process. The only existing differential coincidence experiments that have been published (see Progress Report No. 20 for an extensive reference list) were designed specifically to investigate certain structures observed in the inelastic energy loss, in heavy particle collisions such as Ar-Ar, for very "hard" collisions involving a large scattering angle. In these studies, the inelastic energy loss was not measured directly, but was determined from the conservation laws and from the measured scattering and recoil angles. To resolve the structure of interest it was necessary that the angle between the scattered and recoil trajectories be determined with an accuracy of the order of 5 minutes of arc. The present apparatus has been designed to be capable of similar angular resolution, to permit studies of the same kind. The observance of similar structure for a light projectile would be expected to clarify certain ambiguities of interpretation that have persisted in the studies conducted elsewhere with heavier projectiles. (See Progress Report No. 20 for further details.)

B. Earlier Work in this Program

The initial construction of all of the major components of the differential scattering apparatus was completed prior to the present period. The main assemblies included here are:

A 60-degree magnetic-deflection analyzer for the slow recoil ions, designed to determine the charge/mass ratio of the ions, and to provide a direct but only modest-resolution measurement of their energies;

An electrostatic-deflection analyzer for the scattered fast projectile particles, designed to distinguish only their charges;

A stainless steel, rhodium plated collision chamber, coupled to both analyzers and the beam entrance pipe by flexible metal bellows, which permit the analyzers to be rotated independently through suitable angular ranges;

A mechanical pivot assembly which supports both analyzers, the collision chamber, and the beam entrance pipe and collimator, having precision bearings on which the two analyzer assemblies can be rotated independently about a common axis.

A commercially available silicon detector had been installed in the fast-beam analyzer, and shown to be entirely satisfactory, having a very low noise-count rate and an apparent 100% counting efficiency throughout the energy range of the incident particles.

The detector arrangement which had originally been installed on the recoil-ion analyzer was a 14-stage nude multiplier floated with its first dynode at 12 to 18 kV negative high voltage, to provide the ions sufficient "post-acceleration" for efficient counting. This arrangement had been used successfully in previously reported non-coincidence measurements of the relative total production of He^{+} and He^{++} by protons incident on helium, performed as an overall check of the recoil-ion analyzer system operating in its total collection mode. This detector arrangement had, however, proved to have very troublesome noise problems arising from corona and arcing of the high voltage. In the last previous period, a new detector arrangement was devised and constructed. It is a variant of a familiar scheme in which there is a single large and smooth-surfaced electrode at negative high voltage, on which the ion beam impacts. The secondary electrons produced accelerate away from this electrode to a suitable detector, which can be at or near ground potential, and is both physically and electrically isolated from the high voltage. Having certain unique features that were described in some detail in the last previous report, this detector had been tested in part, and proclaimed to be entirely satisfactory; it will be seen in the next section that this judgement has proved to be premature.

At the time of the last report, we were engaged in what was believed to be the last stages of a final alignment of the overall system. It was believed that we would quite soon be able to begin a detailed coincidence study of the case Ne^+ on argon, for comparison with the published results of Afrosimov, et al.[1] for this case as a final check of the entire analyzer system.

II. PROGRESS DURING THE CURRENT PERIOD

Careful study of the characteristics of each of the component parts of the differential scattering apparatus have, in the present period, brought to light several problems that have required extended study. As will be detailed further below, a major problem involving the recoil-ion detector still remains at the present time. Although it is believed that the nature and source of the problem are now well understood, and there are definite plans which we believe will resolve it, these plans are yet to be carried out. It would thus be premature to claim with assurance that the problem has been definitely and finally solved. As a result of this situation, no coincidence measurements have as yet been carried out. In the meantime, however, work with the fast-projectile analyzer has produced certain non-coincidence measurements that are of intrinsic interest. These are being pursued further at the present time, and some of the preliminary results already obtained will be presented below.

It should perhaps be clarified that the expected count rates in the coincidence studies are rather low, and that the complete apparatus constitutes a fairly complex system with a good many adjustable parameters. It is really not very feasable to grope about empirically for preliminary coincidence results, until all segments of the system are shown to be functioning properly

[1]Afrosimov, Gordeev, Panov, and Fedorenko, Zh. Tekhn. Fiz. 36, 123 (1966); (English transl.: Foviet Phys.-Techn. Phys. 11, 89 (1966)).

in a manner that is fully understood. That is to say, useful coincidence data can be obtained only by making rather extended counts at carefully predetermined settings of essentially all of the experimental parameters; one cannot reasonable expect to learn very much by twisting the knobs in hopes of stumbling across a suitable combination of settings. Thus, even though it would be reassuring to be able to say we had already obtained some preliminary coincidence data, even though of dubious ultimate value due to uncertainties in some parts of the apparatus, little time has been spent in seeking such data.

Discussion of the problems that have taken up much of the effort in this period will be arranged here according to the segment of the apparatus involved, rather than in a chronological sequence.

A. Recoil-Ion Analyzer

The new detector arrangement mentioned above, which had just been installed at the time of the last report, had been shown to display satisfactory saturation in the count rate with increase of the high voltage, as previously reported. However, examination of its output with a pulse-height analyzer showed that many of the pulses were of very small amplitude. Thus the count rate was a sensitive function of the pulse-height threshold settings of the counting circuitry, and there was no ready way to determine its actual counting efficiency for any given choice of the settings. It was eventually realized that the nude multiplier first used to detect the secondary electrons was a rather poor choice. The same high voltage potential that post-accelerates the ions into the large electrode (see general description in Section I) also accelerates the resulting secondary electrons toward the electron detector. The 12 kV or more required to assure the production of at least one secondary electron by nearly every single incident ion gives the secondaries an energy, at the electron detector, considerable higher than that for optimum production of further secondaries on impact with the metal surface of the first dynode of a nude multiplier.

A scintillation detector for the secondary electrons, consisting of a small anthracene crystal mounted on a photomultiplier, was therefore installed in place of the nude multiplier. This produced some improvement in the form of the pulse-height spectra. Certain time-dependent effects that were at first observed in the sensitivity were traced to charge build-up on the insulating surface of the crystal and the glass envelope of the phototube, which affected the trajectories of the approaching electrons. This problem was solved by depositing a thin gold film on the front surface of the crystal, and by hiding the exposed glass surfaces behind a grounded metal mask. In all, the scintillation detector was definitely superior to the nude multiplier, although it was still less than ideal, and some thought was given to the possibility of substituting a solid state detector of a type used in nuclear studies for low-energy beta rays.

However, attempts at making further improvements in this detector arrangement were discontinued at this point, because it had become apparent that there were some rather more serious and fundamental problems with the overall arrangement, for our particular application. A basic feature of the novel geometrical arrangement we had designed (see Progress Report No. 20 for further details) was a rather narrow entrance slot for the incident ion beam, at the surface of the sphere which is the high-voltage electrode. The sheer physical size of the various components made it impossible to locate this slot in the normal exit focal plane of the magnetic analyzer, a 60-degree deflection instrument having a deflection radius of only 5 cm. As mounted, the slot was located more than 2 inches behind this plane. By removing completely the exit slit in the normal focal plane of the analyzer, and adjusting the focus of the electrostatic lens system that initially accelerates the ions into the analyzer, it should of course be possible to focus the emerging ion beam on the slot in the sphere. In designing this detector arrangement, it had been assumed that such a mode of operation would be satisfactory.

A basic requirement, if this analyzer system is to produce meaningful cross section measurements, is that the properties of the ion optics be very well defined and known. In the original design, all initial ion trajectories within the cone defined by the entrance collimator of the whole analyzer assembly were to pass unobstructed to the detector. The early studies of the analyzer with the original detector, which had a large aperture located just behind the normal focal plane, had given no indication that this objective was not, in fact, achieved.

In the arrangement with the new detector, however, the ion optics have been substantially altered. Attempts to optimize all of the beam controls have been found to produce ambiguous and confusing results; it does not seem to be possible to identify any unique array of optimum settings. One very distressing finding was that under some conditions, the application of a small voltage to the retarding potential electrode actually produces an increase rather than a decrease in the count rate. This electrode was specifically designed for biasing out, or excluding, the lowest-energy ions in the entering beam, by means of such a voltage, and it had previously been found to function just as intended. It eventually became clear that, even though the new detector arrangement is sound in its own concept and functions rather well, its incompatability with the rest of the analyzer had made an unacceptable jumble of the overall optics of the system.

In seeking for alternatives, our attention has been drawn to a relatively new type of detector, commercially available, that is popularly known as a "funneltron". This is a variant of the "Channel electron multiplier" that opens in a funnel at the input end, to provide a reasonable-sized aperture. We have received information to the effect that, if equipped with a grid across the mouth of the funnel, which alters the shape of the electric field within the funnel, these devices have a uniform and apparently high sensitivity to incident heavy ions across most of the funnel aperture.

If all of the information we have heard about the funneltron does prove to be true, it looks as if it will be the final answer to all problems related to the recoil-ion detector. These devices are small in physical size, so there is no problem in locating one close behind the normal focal plane of the analyzer. The exit slit can be restored to its proper place in the focal plane, and all of the ion optics will be restored to the arrangement of the original design. A Model B-419-BL Channel Multiplier having a 10-mm diameter aperture cone (funnel) has been procured from Mullard, Inc., and was received recently. We plan to conduct extensive tests of this device to try to determine its detection efficiency, using an auxiliary vacuum system and ion source, before installing it in the main apparatus.

B. Fast Beam Analyzer

The fast beam analyzer, only recently assembled at the time of the last report, has given us no serious difficulties; however, some time was involved in studying its characteristics and learning how to use it properly. It was found that an upper limit must be imposed on the deflection voltage applied to the parallel plates of the analyzer, such that the ions of the highest charge present in appreciable abundance are not deflected enough to strike one of the plates; without this precaution, ions first grazing the edge of the plate can be scattered to the detector and lead to quite confusing results. In practice, the detector is first stationed at a maximum-deflection position and the deflection voltage is increased to bring the successive charge states to the detector in turn, beginning with the highest, until the maximum voltage for the particular beam and energy is approached. Then the voltage is left fixed, while the detector is moved toward the axis to pick up the lowest-charge states.

As it is presently set up, the analyzer fully resolves from one another ions of charges 1 through 5, while having flat topped peaks for all 5 which assure that the entire beam of the selected charge reaches the detector. With a slightly smaller aperture at the detector, charge state 6 can also be resolved. The line shape is trapezoidal as expected; fully resolved means that the flaring sides of one trapezoidal line do not encroach on the flat top of the next, and that each species can be counted at a single setting in the middle of its flat topped peak, entirely independent of the intensity ratios of the two. With a change in the parallel plate spacing, to delay the onset of the scattering problem mentioned above, so that larger deflections can be used, the fully resolved range could probably be extended to charge state 9 or 10 with little difficulty.

C. Collision Chamber and Angle-Resolving Collimators

The collimator for the incident beam consists of 3 apertures spaced several inches from one another. The first 2 apertures (numbered in the direction of travel of the beam particles) are both 0.025 in. wide, horizontally. Since the beam from the Van de Graaff incident on these apertures comes, in effect, from a small diameter source that is about 10 feet away (the focus spot of the accelerator analyzing magnet), the first two apertures should define a paraxial beam with very little angular divergence. The third and final slit is wider (originally 0.035 inch) and is intended mainly to separate the target gas volume from the evacuated beam pipe. It is mounted at the end of a long metal cone that extends deep into the collision chamber to a point quite near the scattering axis (originally about 1/2 inch), in order to minimize the path length of the beam particles in the target gas before they reach the collision region.

The horizontal profile of the beam entering the collision chamber has been studied by moving the fast beam analyzer through the beam, at 0°, with no scattering gas in the chamber. The earliest such studies showed that, although the width of the intense central part of the beam was just as expected, there were unsymmetrical "skirts" on either side of the beam that indicated poor alignment of the incident beam and its collimator. Optical alignment of the apertures with a laser beam was therefore repeated, more carefully this time. Further profile studies showed much improvement, but it was noted that as soon as the scattering angle setting is small enough that any part of the acceptance cone of the fast-beam analyzer could "see" the edge of the final slit of the beam entrance collimator, scattered particles were observed in sufficient intensity to be troublesome in comparison with the gas-scattered intensity during a measurement with gas in the chamber. That these scattered particles really came from the slit edge was verified by deflecting them to the silicon detector of the analyzer (a simple Faraday cup on the analyzer axis was being used for these profile studies, because the full beam intensity is much too high for the silicon detector). Examination of the pulse-height spectrum clearly showed the particles to be degraded in energy. The onset of this effect, for the original slit arrangement described above, was at about 3° scattering angle.

For the fast-particle differential scattering measurements described in the next section, the final slit of the beam-entrance collimator has been moved back further from the scattering center, since for these non-coincidence measurements it is not so essential to minimize the total path length in the gas. At the same time, a somewhat larger last slit was installed, and improved pumping was provided in the long beam pipe preceding the collimator, to reduce scattering in this region that would tend to increase the divergence of the collimated beam. With these improvements, the "skirts" on the beam profile do not extend beyond about 1 1/2 degrees, and are of sufficiently reduced intensity that it should be possible to obtain useful results down about 1 degree.

D. Differential Scattering Measurements

In the course of studying the characteristics of the fast-beam analyzer system, a number of qualitative non-coincidence observations were made of the differential scattering of fast particles by gas targets. Measurements of this kind serve as useful background information for the coincidence experiment, and are of intrinsic interest in themselves. Modifications of the collision chamber necessary to perform quantitative measurements of differential scattering cross sections have been completed recently. A new top for the chamber was constructed, which is penetrated by several pipes, set at angles such that they radiate from the collision center. In one of these, there has been installed a bellows-sealed linear motion actuator, arranged to move a small Faraday cup into a position in the beam path at the collision center, for direct quantitative measurement of the fast-ion beam intensity at this point. The actuator has a travel of some 2 inches, sufficient to move the cup well out of the way when it is not in use.

In a second one of the pipe stub arms, there has been installed a photomultiplier and lens, to view the light arising from excitation of the target gas by the fast beam. The lens is arranged to focus light originating from a segment of the beam path onto the photocathode of the multiplier. This arrangement serves to monitor the product of the target gas density and the instantaneous beam intensity without interrupting the beam; the total count of the multiplier during a scattering measurement is proportional to the integrated intensity of the beam during the measurement, and is used to normalize the scattered-particle counts. The multiplier arrangement is being carefully checked to assure that its count rate is not influenced by the angular position of the fast-beam analyzer in any manner, such as by the reflection of excitation light from the nose of the analyzer collimator cone. (A cruder photomultiplier arrangement temporarily installed earlier was found to be so influenced, because as it turned out, the optical arrangement was such that the multiplier could "see" the tips of the collimator cones of the fast-beam and recoil-ion analyzers.)

A program of quantitative measurements is presently underway, of the differential cross sections for scattering into each of the possible final charge states, i.e., He^0, He^+, and He^{++}, for He^+ ions incident on argon. Calibrations will be performed to provide absolute quantitative results which will be independently publishable. A few of the early results, which should be regarded as preliminary and only semi-quantitative, are presented here.

In Fig. 1 are shown the relative fractions P_0, P_1, and P_2, of He^+ ions scattered at 5° in helium, that are in the final charge states He^0, He^+, and He^{++}, respectively. The energies of the incident He^+ ions range from 0.150 to 0.900 MeV. Also shown for comparison are the similar results at lower energies of Everhart and coworkers[2], extending up to 0.250 MeV. The oscillatory behavior of P_0 observed at lower energies was interpreted by Everhart as indicative of the repeated exchange of an electron between the colliding atoms, because it was noted that the several maxima in P_0 are evenly spaced, if plotted against the reciprocal of the fast-particle velocity; this latter quantity is

[2]Ziemba, Lockwood, Morgan, and Everhart, Phys. Rev. 118, 1552 (1960).

proportional to the duration of the encounter, or collision time. Since the collision time associated with Everhart's highest-energy peak in P_0, near 0.200 MeV, appears to be itself the common divisor of the collision times of all of the other peaks observed, it was presumed to correspond to a single exchange. It was therefore predicted that this would be the last such peak observed, as the energy is increased. The present results bear out this prediction, in that P_0 is found to decrease monotonically for higher energies. It is rather interesting that P_2 is observed to be increasing to an appreciable fraction over just the same energy range in which P_0 is decreasing to a negligible fraction.

Not shown here are similar measurements of P_0, P_1, and P_2, again for the case of He^+ on helium, as functions of the scattering angle from 4° to 9°, for a single fixed energy of 0.450 MeV. The observed dependence on angle was essentially flat, just as Everhart found it to be at lower energies.

In Fig. 2 are presented preliminary measurements of the differential cross sections for scattering into each of the 3 final charge states, for He^+ incident on argon at 0.400 MeV.

III. PLANS FOR THE BALANCE OF THE PERIOD

The differential scattering measurements will be continued, to obtain complete and quantitative results for the case of He^+ on argon over the energy range 0.150 to 1.00 MeV, over as large a range of the scattering angle as is practicable. Concurrently, we will proceed with evaluation tests of the "funneltron" detector. Presuming that this device does prove to be a satisfactory ion detector of high efficiency, it will be installed in the recoil-ion analyzer, and tests will be commenced to determine if the ion optics of the analyzer are then sufficiently well defined to begin coincidence measurements for He^+ on argon.

IV. TRAVEL AND PUBLICATIONS

Dr. D. W. Martin attended the 21st Annual Gaseous Electronics Conference held in Boulder, Colorado, in October, 1968.

A manuscript entitled "Cross Sections for Ion and Electron Production in Gases by 0.15 - 1.00 MeV Hydrogen and Helium Ions and Atoms," which presents all of the results encompassed by the title that have not been published previously, has been submitted to The Physical Review. This manuscript has been assigned the USAEC Document Number ORO-2591-36.

V. INCIDENT REPORT

There have been no incidents for which a report would be required, in the period covered by this report.

VI. FIGURE CAPTIONS

Fig. 1. Relative fractions of He^+ ions scattered at 5° in helium that are scattered into the final charge states He^0, He^+, and He^{++}.

Fig. 2. Differential cross sections for scattering from argon of 0.400 MeV He^+ ions, into each of the final charge states He^0, He^+, and He^{++}.

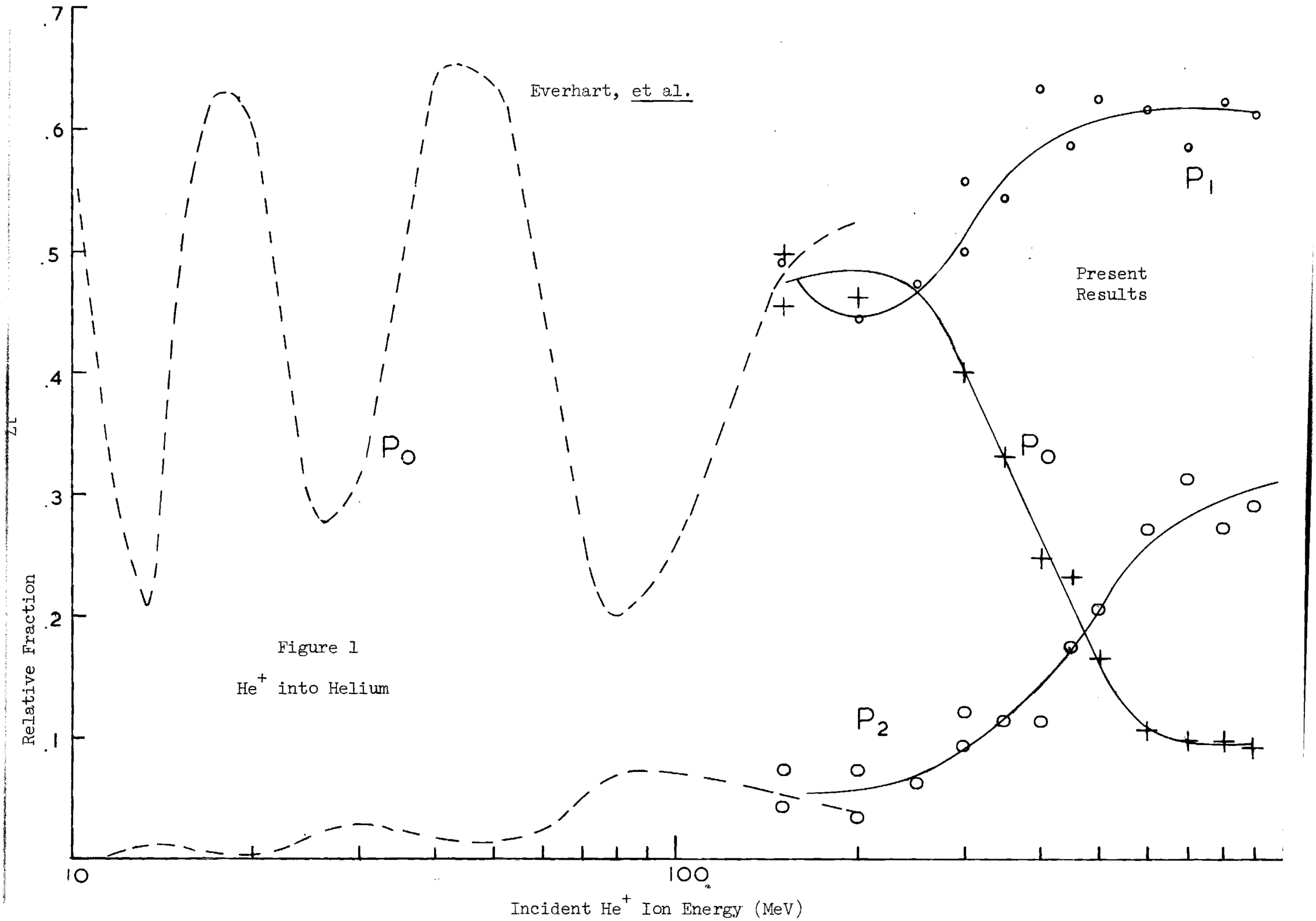

Figure 1

He^+ into Helium

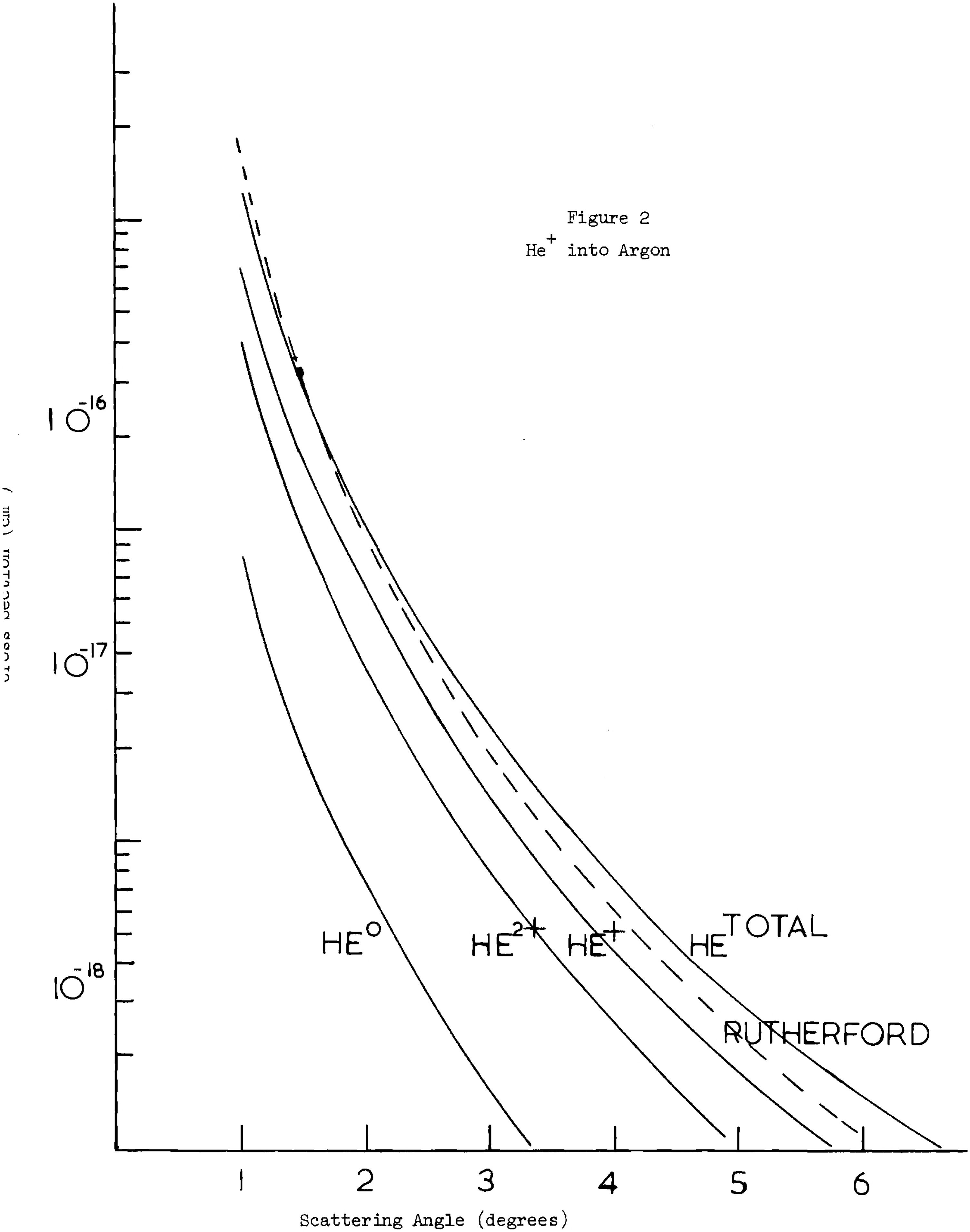

Figure 2
He^+ into Argon

ORO-2591-43

IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

PROGRESS REPORT NO. 22

Covering the Period

December 1, 1968 to November 30, 1969

By D. W. Martin

G. O. Taylor

D. E. Troyer

USAEC Document Number

ORO-2591-43

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

U. S. ATOMIC ENERGY COMMISSION

OAK RIDGE, TENNESSEE

30 November 1969

School of Physics
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

ORO-2591-43

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IONIZATION AND CHARGE TRANSFER CROSS SECTIONS

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IONIZATION AND CHARGE TRANSFER CROSS SECTIONS
Progress Report No. 22

The period covered by this report is December 1, 1968 through November 30, 1969. This period corresponds to the first 9 months of the 12-month extension provided for by Modification No. 11 of Contract No. AT-(40-1)-2591, plus the final 3 months of the preceding period.

This report will be concerned only with the ionization and charge transfer phases of the total program conducted at Georgia Tech under this contract. This portion of the program was the subject of Part A of our proposal of December 1, 1968, covering the present period. The excitation measurements phases of Part B of the proposal are covered in a separate Report, No. ORO-2591-44, of this same date.

I. INTRODUCTION

The program of Part A of this contract has for some time been centered about a differential scattering apparatus, designed for detailed cross section measurements of fundamental ionization and charge transfer processes involving incident hydrogen and helium ions in the high-energy range from 0.15 to 1.00 MeV. This apparatus incorporates two particle analyzers which are independently rotatable about a common axis in a collision chamber, having directional entrance collimators to define the angles, relative to the direction of the incident beam, of the trajectories of both scattered beam particles and recoiling target particles. The analyzers move on precision bearing assemblies which, with the use of sufficiently small collimating apertures, are capable of defining the recoil and scattering angles to within about 5 minutes of arc.

The analyzer for the fast scattered particles utilizes a small-angle electrostatic deflection, and has sufficient energy-over-charge resolution only to distinguish the various charge states of the scattered particles. The analyzer for the recoiling slow ions is a 60° magnetic-deflection instrument of moderate momentum resolution. In addition to distinguishing the various charge states of the recoiling particles, it is designed to provide a direct but limited-resolution energy determination for the more energetic particles. The analyzer also incorporates an electrode array for retarding potential difference or "RPD" measurements of the recoil particle energies at the lower end of the energy spectrum. Both analyzers are equipped with single-particle detectors, and with circuitry to permit the correlation, through time coincidence, of the scattered and recoil particles from single collision events. The system is designed to have the ultimate capability of measuring cross sections, differential in both the scattering and recoil angles, for well defined collision events in which the final charge states of both collision partners are specified.

The present apparatus differs from several somewhat similar coincidence-scattering systems that have been constructed elsewhere, chiefly in the provisions for low-energy sensitivity and for direct energy measurements in the recoil-ion analyzer. Several of these other systems have recoil-ion analyzers more nearly like the present scattered-particle analyzer. They were designed primarily for studies of "hard" collisions with large scattering angles, in heavy particle-heavy particle collisions, for the most part at somewhat lower energies. Such collisions involve relatively large recoil-particle energies, and the interest has been chiefly in the study of certain large inelastic effects rather than in the measurement of cross sections. The heavy-particle energy losses involved in these effects have been determined from accurate measurements of the scattering and recoil angles and the use of general conservation laws, rather than through direct measurements of particle energies. Extensive references to the early work along these lines has been given in previous reports.

The present apparatus has been designed specifically for light projectiles at higher energies, and for cross section measurements that are not restricted to very hard collisions with large scattering angles. It must therefore be capable of dealing with rather low-energy recoil particles, whose energies would be more accessible to direct measurement than to an indirect determination through angles and conservation laws.

The program involving this apparatus has followed naturally from an extensive series of earlier measurements, for such projectiles, of total slow-ion and electron production cross sections. A central interest in these measurements was always the detailed comparison of the results with available theoretical calculations. The projectile energies extended into a relatively little explored range where validity of the high-energy theoretical approximations is to be expected, and our comparisons sought to test the boundaries of this region of validity. One of the chief ambiguities in these comparisons arose from the fact that our gross production cross sections really represented only sums of the cross sections for a number of elementary types of events, including higher order or multi-electron processes such as multiple ionization, simultaneous ionization and charge transfer, etc. Rather little theoretical work has been done on such processes. Although upper bounds for their cross sections can often be set from simple measurements, actual measurements for such processes would in general require a coincidence arrangement with charge analysis of both of the partners from a single collision.

The angular discrimination features of the apparatus were included for several reasons, even though the total cross sections for many such types of events could probably be measured accurately, for these light projectiles, with a simpler total collection arrangement for the slow recoil ions. It is first of all necessary to determine for a given higher order process, by means of differential measurements that can be integrated over the angles, the possible contributions to the total cross section from hard collisions involving energetic recoils, before one can be certain of the accuracy of a total collection measurement. Secondly, a differential measurement is obviously of intrinsic interest in that it provides greater detail about the nature of the process. Finally, it was of considerable interest to see if one could detect, for the light projectiles incident on a heavy target atom, any evidence of large inelastic effects similar to those found for heavy incident particles. With the simpler projectiles, such effects would be easier to interpret, and would help to resolve some of the disagreement that has existed as to the basic nature of the processes observed with heavy projectiles. These matters have been treated only rather briefly here since they have already been discussed in much detail in some of our earlier reports.

The design and construction of this coincidence scattering apparatus was begun some time ago. Most of the major components had been completed prior to the beginning of the period covered by this report. Further details which appear in our earlier reports will not be repeated here.

II. PROGRESS DURING THE CURRENT PERIOD

A. Scattering Measurements for He^+ Ions.

A series of non-coincidence measurements of the scattering of He^+ ions has been completed in the present period, utilizing only the analyzer for fast scattered particles. Extensive measurements were made for an argon target, as well as less extensive measurements for targets of helium and neon. The scattered particles were sorted into the three charge states He^{o}, He^{+}, and He^{++} (the yield of scattered He^{-} ions is negligible at the high energies involved). For the argon and helium targets, absolute differential cross sections, at three energies in the range 0.2 to 0.6 MeV, for scattering into each of the above charge states, were measured absolutely as functions of the scattering angle from 1^{o} to about 8^{o}; similar measurements at only one angle were obtained for a neon target. For all three targets, the fractions P_n of incident He^{+} ions scattered at fixed angles into charge state n (n = 0,1,2) were measured as functions of energy from 0.15 to about 0.8 MeV.

Detailed results of this investigation have been presented in a recent Technical Report (AEC Document No. ORO-2591-41) and will not be repeated here, but a few of the general characteristics of the results will be described briefly. Plots vs incident energy of the charge fractions P_n were found to join smoothly to Everhart's well known results[1] in the adjacent lower energy range. Of particular interest was the behavior of the neutral fraction P_o, in the helium target. At lower energies an oscillatory behavior had been seen, having the property that the successive maxima are evenly spaced when plotted against the reciprocal of the incident particle velocity. One such maximum was found to occur right at the extreme upper limit of Everhart's energy range; he estimated its position to be at 0.25 MeV. From the position of this maximum on the 1/v plot, it appeared

[1]Ziemba, Lockwood, Morgan, and Everhart, Phys. Rev. 118, 1552 (1960).

that it must be the last such maximum to be expected with increasing energy (decreasing 1/v). The present results have borne out this expectation; from a maximum which we find to be more nearly at about 0.19 MeV, P_o decreases monotonically with increasing energy thereafter. Interestingly, the fraction P_2 of scattered He^{++} ions increases rapidly with energy over just the range where P_o is decreasing most rapidly.

The fractions P_n were found to be entirely independent of the scattering angle over the range covered, at these energies; plots vs scattering angle, at fixed energy, of the absolute differential cross sections for scattering into charge states 0, 1, or 2, respectively, were found to be parallel curves of virtually identical shape to one another, and to the plot of their sum, which we have called the total scattering cross section. This total cross section was found to agree very well as to shape, and within the estimated experimental errors as to absolute magnitude, with a total scattering cross section calculated classically for a screened Coulomb interaction potential.

At least general agreement with the classical calculation had been expected, on the basis of various previous findings at lower energies; the quite satisfactory agreement in absolute magnitude is in fact an encouraging indication that there are no serious systematic errors in the measurements and calculations relating to the geometrical solid angle and detection efficiency of the fast particle analyzer. However, one of the objectives of the investigation had been to determine whether, at these energies, there would be detectable anomalies in the smooth cross section curves at those angles where the distance of closest approach in the collision reaches a value where the onset of large inelastic effects might be expected. Such anomalies had been seen in measurements of comparable angular resolution at lower energies, with incident heavy particles, in cases where large inelastic effects had previously been seen in coincidence-scattering studies. No such anomalies could be detected with certainty in the present measurements for He^+ ions.

Further details and a full presentation of the data are given in the Technical Report mentioned above. A manuscript presenting the complete results is in preparation for submission to The Physical Review.

B. Progress on the Slow-Ion Analyzer

In our last Progress Report (No. 21, November 30, 1968, AEC Document No. ORO-2591-38) we discussed the difficulties that had arisen in the calibration of the ion optics of the slow recoil-ion analyzer, due to an earlier change to a detector that could not be located at the proper focal plane of the analyzer because of its sheer physical size. We indicated our intention of investigating the possibility of substituting another type of detector that would be small enough to be located at the optimum position, so that the ion optics could be restored to the original design configuration.

"Channel electron multipliers" of two different types, both fitted with roughly 10-mm diameter cones on their input ends to increase their effective apertures (often called "funneltrons") were procured from Mullard, Ltd., and the Bendix Corp., respectively. A carefully designed series of tests was set up, utilizing low-energy ion beams from a small accelerator in another laboratory, to evaluate the suitability of these devices as absolute counting detectors. The arrangement used provided for variation of the ion impact energy on the device from essentially zero upward, with constant beam intensity, along with independent variation of the operating voltage applied across the device, and of the potential of a field-shaping planar grid located at the mouth of the funnel. The ion beam was of small diameter compared to the funnel, and could be directed at will to any part of the aperture. The tests verified all that we had heard about these devices. Operated as discrete counters in the saturation mode, which requires operating voltages of around 3 kV, they produce large output pulses of quite uniform pulse height that are very readily discriminated from the low level noise. With the entrance grid at the same potential as the inlet end of the funneltron, the sensitivity is essentially constant over almost the entire area of the funnel. Excellent saturation behavior in the plot of count rate vs ion impact energy indicated that the detection efficiency reaches essentially 100% for light ions of about 1.5 kV or more, and for heavy ions (Ar^+) of about 2 kV or more. Thus for positive ions, the funneltrons require only a single negative supply of around 3 kV, connected to both the inlet end and its grid, to serve as highly efficient and virtually noisefree detectors for ions of any mass and even zero initial kinetic energy. The devices are small in size, and insensitive to exposure to the air. Thus they are almost ideal detectors for low-energy positive ions, admirably suited to all of the requirements for our slow-ion analyzer.

The funneltrons do show an appreciable loss of gain and pulse height with increasing count rate, but this produces no significant loss of counting efficiency at the rates that are anticipated in the present application. One other source of potential difficulty should perhaps be mentioned. In our test arrangement, with the particular type of input grid we were using, it was noted that significant background counts occurred whenever the inlet end and its grid were more than about 2 kV negative relative to the facing electrode of the ion-beam system. These counts were attributed to the field emission of electrons from the front surface of the grid. The electrons would produce ions in the residual gas in the system, which were then accelerated into the detector and counted.

A simple mounting configuration has been devised which avoids this problem altogether. A roughly hemi-spherical cup of aluminum of about 2-inch diameter, with a polished outer surface, has a round-edged hole at its center, which is just slightly smaller than the mouth of the funnel. The funneltron, with a grid stretched directly over the mouth of the funnel, is mounted with a conducting cement directly against the inside surface of the cup, so that the funnel "looks out" through the round-edged hole. The negative high voltage connected to the inlet end of the device is also connected directly to the cup. The rigid cup is mounted to the apparatus frame on insulating supports and provides, through the cement joint, the entire mechanical support of the funneltron.

This arrangement partially shields the front surface of the grid from large fields, and eliminates having any sharp edges at negative high voltage facing the region viewed by the funneltron. The cup also serves to protect the rather fragile funneltron mechanically, and shields it electrically. Mounted to the apparatus in this fashion, with ordinary residual-gas pressures of order 10^{-6} Torr in the system, the funneltrons have proved to be essentially free of background counts and noise at their normal operating voltages of around 3 kV.

Two funneltrons have been mounted to the slow-ion analyzer in this fashion, one at the 60° analyzed-beam position, and one at the "straight through" position. Both are functioning entirely satisfactorily.

To facilitate the required study and evaluation of the slow-ion analyzer, a simple electron-bombardment ion source has recently been installed, temporarily, in the collision chamber, so that it faces toward the entrance collimator of the analyzer. This source provides a ready source of slow ions for test purposes, and avoids the need for tying up the Van de Graaff accelerator for long periods. Although not yet completed at the time of this report, the evaluation and calibration program is well underway. It has been demonstrated again that the analyzer is indeed sensitive to ions of energies down to no more than 1 or 2 eV. It remains to be established exactly what the low-energy cutoff energy is, and just how the sensitivity varies for energies near the cutoff.

III. PLANS FOR THE REMAINDER OF THE PRESENT CONTRACT PERIOD

All effort is presently being directed toward the calibration of the slow-ion analyzer. It is expected that this effort can be brought to clearcut conclusions in the near future. At that time we will begin immediately the coincidence studies of He^+ ions incident on Argon that were described in our last proposal.

IV. TRAVEL AND PUBLICATIONS

D. W. Martin and G. O. Taylor attended the VI-th International Conference on the Physics of Electronic and Atomic Collisions, held in Cambridge, Mass., in July. A paper on this research entitled "Investigations of the Scattering of He^+ by Noble Gases at High Energies" was presented there. Dr. Martin also attended the 22nd Annual Gaseous Electronics Conference, held in Gatlinburg, Tenn., in October, where he served as Chairman of a session on heavy-particle collisions.

The manuscript entitled "Cross Sections for Ion and Electron Production in Gases by 0.15-1.00 MeV Hydrogen and Helium Ions and Atoms" (AEC Document No. ORO-2591-36), mentioned in the last previous report, has been published. The reference is L. J. Puckett, G. O. Taylor, and D. W. Martin, Phys. Rev. 178, No. 1, 271 (1969).

G. O. Taylor completed the requirement for the Ph.D. in Physics in September 1969, with the submission of a thesis based on this research entitled "Scattering of He^+ Ions by Noble Gases at High Energies". The text of this thesis has been adapted as a Technical Report of the same title (AEC Document No. ORO-2591-42), which was released in September.

V. INCIDENT REPORT

There have been no incidents for which a report would be required in the period covered by this report.

VI. ACKNOWLEDGMENTS

The ion-beam tests of the funneltron detectors described in Section II-B were conducted by Mr. R. L. Fitzwilson and Dr. J. N. Fox. This assistance is most gratefully acknowledged.