where the notation is the same as given by Zu Putlitz. From (2) we obtain $Q(137)=0.20\times10^{-24}$ cm^2 which does not agree too well with Zu Putlitz's result of $Q(137)=0.28(3)\times10^{-24}$ cm^2. The disagreement is outside experimental error, and may be due to the $^1P_1$ and $^3P_1$ states having different values of $\langle 1/r^3\rangle_{av}$. From experience with other members of the group II elements, however, we would expect the result obtained from the $^3P_1$ state to be more reliable.

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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
Georgia Institute of Technology, Atlanta, Georgia

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This paper reports the measurement of apparent cross sections for production of slow positive ions and free electrons by He^+ ions incident on He, Ne, Ar, H_2, N_2, O_2, and CO in the energy range 0.133 to 1.0 MeV, and similar cross sections for He^{++} ions incident on He and H_2 in the energy range 0.5 to 1.0 MeV. Direct comparisons are made with experimental results obtained by other investigators for He^+ ions at energies up to 0.40 MeV. In the companion paper comparisons are also made with available theoretical calculations and with results predicted from the Bethe-Born approximation with the evaluation of certain parameters from earlier measurements with proton projectiles.

I. INTRODUCTION

We have measured the apparent cross sections for production of slow positive ions and free electrons by He^+ ions incident on helium, neon, argon, hydrogen, nitrogen, oxygen, and carbon monoxide for projectile energies over the range 0.133 to 1.00 MeV. We have also measured these cross sections for He^{++} ions on hydrogen and helium over the energy range 0.50 to 1.00 MeV. Measurements of these quantities by other investigators have been confined to lower energies.

The experiments described here constitute a segment of a continuing program of absolute determinations of the cross sections for ion and electron production at high energies by various light ions and atoms on the same targets. The results for protons incident on the target gases listed above have already been reported.[1,2] A detailed comparison of the proton results with the available theoretical calculations and with data for incident electrons has also been published.[3] Similar comparisons of the present results with theory and with the proton data are presented in the following paper (II).

We selected H_2 and He as target gases because of their importance in controlled fusion research and because their structural simplicity has permitted theoretical calculations of their cross sections. Calculations have not yet been made on the other noble gases, but Ne and Ar were studied because of the general interest in these gases and because of the desirability of obtaining data on heavier atomic systems. Also included are N_2 and O_2 since they are atmospheric constituents of considerable practical interest. Finally CO was included because it is a common contaminant in vacuum systems and because the comparison of data on CO and N_2 is of interest. These two molecules have the same number of electrons and somewhat similar structures.

The present results were presented at the Third International Conference on the Physics of Electronic and Atomic Collisions in London (July 1963) and a summary will be published in the Proceedings (North-Holland Publishing Company, Amsterdam, 1964). However, limitations on the permitted text length necessitated the omission of important details which are given here. Also, comparison is made here with results recently published by other workers.

II. EXPERIMENTAL METHODS

In all our high-energy collision studies, the projectile source has been a 1-MeV Van de Graaff positive-ion

* This work was partially supported by the Controlled Thermonuclear Research Program of the U. S. Atomic Energy Commision.

† Present address: CRUZ, Air Force Cambridge Research Laboratory, Bedford, Massachusetts. Portions of the results presented here were included in a thesis submitted by RAL to the faculty of the Georgia Institute of Technology in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

[1] J. W. Hooper, E. W. McDaniel, D. W. Martin, and D. S. Harmer, Phys. Rev. 121, 1123 (1961).

[2] E. W. McDaniel, J. W. Hooper, D. W. Martin, and D. S. Harmer, *Proceedings of the Fifth International Conference on Ionization Phenomena in Gases* (*Munich, 1961*) (North-Holland Publishing Company, Amsterdam, 1962), Vol. I, p. 60.

[3] J. W. Hooper, D. S. Harmer, D. W. Martin, and E. W. McDaniel, Phys. Rev. 125, 2000 (1962).

accelerator equipped for beam analysis and stabilization. Our method of measurement requires "thin target" conditions, in which less than a few percent of the projectiles undergo a single collision, so that only a negligible fraction experience multiple collisions. The slow positive ions and electrons produced in a well-defined volume of target gas are collected by two oppositely charged parallel-plate assemblies mounted parallel to and on opposite sides of the beam axis. The total current to each assembly is measured by sensitive vacuum tube electrometers. The intensity of the incident beam is determined by collecting the beam of fast projectiles emerging from the collision region in a Faraday cup. Absolute measurements are made on all the currents, so that absolute cross sections are obtained.

Slow positive ions are produced in the gas both by ionization of the target molecules (ejection of bound target electrons into the continuum) and by charge transfer involving the capture of bound target electrons by the projectiles. Since the residual ions are not subjected to e/m analysis, our experiments yield the *apparent cross section for positive ion production* σ_+, which is defined by the equation

$$\sigma_+ = \sigma^+ + 2\sigma^{2+} + 3\sigma^{3+} + \cdots,$$

where σ^{n+} is the cross section for production of a target ion with charge $+ne$. Free electrons are produced both by ionization of the target and by stripping (ejection of electrons from the projectiles into the continuum). Since with our apparatus we cannot distinguish between electrons produced by the two mechanisms, we report the *apparent cross section for free-electron production*, which is the effective area presented by a target molecule for production of free electrons by either mechanism. Of course, any ions created in the gas by dissociative ion-pair formation[4] or by transfer of electrons from the projectiles to the targets[5] will contribute to the slow-particle currents, but the cross sections for such reactions are small in our energy range. (Ion-pair formation is obviously impossible in He, Ne, and Ar and has never been reported in N_2. Electron transfer to Ne and Ar is also impossible, since these atoms have negative electron affinities.[6]) Creation of positive or negative ions by free electrons produced in the gas is completely negligible because of the low target-gas pressures and small dimensions which are used.

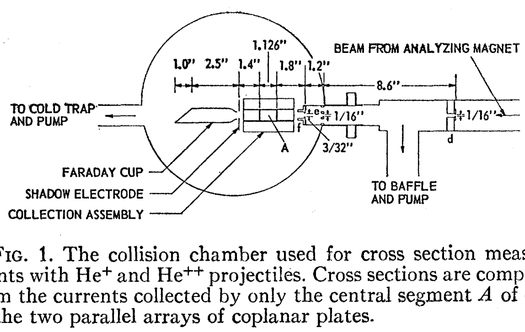

FIG. 1. The collision chamber used for cross section measurements with He^+ and He^{++} projectiles. Cross sections are computed from the currents collected by only the central segment A of each of the two parallel arrays of coplanar plates.

The detailed account of the experimental methods employed in the proton measurements described previously[1,2] is generally applicable to the present measurements and will not be repeated here. However, certain changes in apparatus and techniques necessary for the helium ion experiments will be discussed. Further details may be found in a report by Langley *et al.*[7]

The experimental differences between the present measurements and our measurements for incident protons are due chiefly to the following two considerations. First of all, the probability of charge-changing collisions (gain or loss of electrons by the fast incident ions) is much greater, relative to the probability of simple ionization, for helium ions than for protons.[5,8] This circumstance necessitated a reduction in the flight path of the ions between the evacuated beam-entrance pipe and the region in the target gas defined by the collector assemblies. Otherwise the beam would become contaminated with a significant fraction of projectiles in other than the intended charge state. Second, the parallel-plate collector assemblies had to be reduced in length by about a factor of three in order to maintain thin target conditions in the collector region with a reasonable target gas pressure.

The collision chamber used in the helium-ion measurements is shown in Fig. 1. The "condenser method" is employed, with only a transverse electrostatic field used for charged particle collection. The single collector assembly which is visible is offset from the plane of the figure; an identical assembly is located on the other side of the beam axis. The positive-ion collector is screened by a biased grid located $\frac{1}{4}$ in. in front of it to suppress secondary electrons ejected from the collector plates. The grid consists of 0.004-in.-diam stainless-steel wires strung 0.100 in. apart and perpendicular to the beam axis. A bias voltage of about 50 V with respect to the ion collector array is normally used for electron suppression. The particle transmission of the grid is assumed to be essentially equal to its geometric transmission, which is 96%. The separation between the grid and the electron collector on the other side of the beam axis is $\frac{1}{2}$ in. Equal and opposite voltages are applied to the grid and the electron assembly, the total potential difference being set between 100 and 1000 V. In each collector assembly all of the electrodes are held at the same potential, but currents only to the central electrode (A) are measured. The remaining electrodes

[4] E. W. McDaniel, *Collision Phenomena in Ionized Gases* (John Wiley & Sons, Inc., New York, 1964), Sec. 8-2.
[5] Reference 4, Sec. 6-6.
[6] Reference 4, Sec. 8-1.
[7] R. A. Langley, D. W. Martin, D. S. Harmer, J. W. Hooper, and E. W. McDaniel, Technical Status Report No. 15, U. S. Atomic Energy Commission Contract No. AT-(40-1)-2591, Georgia Institute of Technology, Atlanta, Georgia, 1 June 1963 (unpublished). (Available from authors on request.)
[8] S. K. Allison, Rev. Mod. Phys. 30, 1137 (1958).

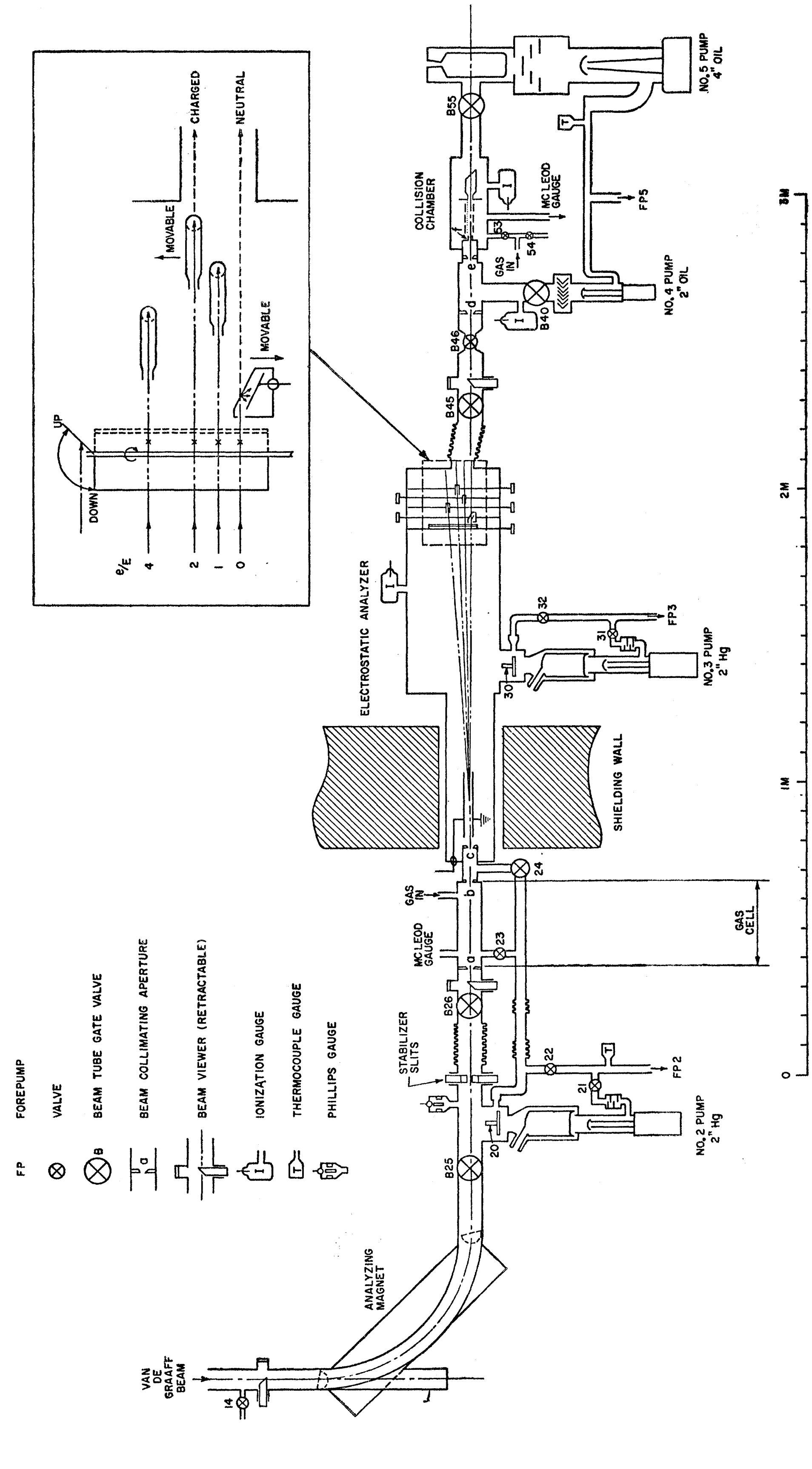

FIG. 2. Over-all view of apparatus used for measurements with He^{++} ions.

serve only to make the transverse electric field uniform in the vicinity of the active electrodes and to prevent secondary and photoelectrons ejected from slits and the chamber walls from reaching the A electrodes.

Considerable attention must be paid to the design of the beam collimator system and to the application of proper voltages to the collectors to minimize the collection on the active electrodes of fast electrons traveling in the beam direction. Such electrons can be produced with up to their full knock-on energy by fast beam projectiles grazing slits between the analyzing magnet and collision chamber.[9] The ion beam entering the collision chamber was found to be contaminated with such fast electrons. By means of careful collimator design and optimum adjustments of the guard electrode potentials, the contributions from this effect to the total currents collected were reduced to less than 4%. These contributions were subtracted from the observed currents as part of the background.[10]

The aperture designs and pumping arrangements are such that the greatest part of the pressure drop from the target region into the beam pipe at the right side of Fig. 1 occurs at aperture "f." Thus the effective beginning of the flight path in the target gas begins at "f." Collimation of the beam is provided by the smaller apertures "d" and "e," and only a few scattered particles impinge on the edge of "f." The opening in "f" presents a small solid angle to the secondary electrons produced at "e," and very few should be able to pass through. The thin plate containing "e" is perforated by three large off-center holes to present a small pumping impedance.

Since the Van de Graaff ion source does not yield enough He^{++} ions for our purposes, additional apparatus was required to produce He^{++} ions from the accelerated He^+ beam. A general schematic view of the apparatus used in the He^{++} ion measurements is shown in Fig. 2. This apparatus is similar to that used in the He^+ measurements with the addition of a gas cell for charge changing of the incident He^+ beam and an electrostatic analyzer for separation of the resultant He^{++}, He^+, He^0 components of the beam. Figure 2 is essentially a side view of the apparatus, except that for clarity the electrostatic analyzer section and the collision chamber are shown rotated 90° about the beam axis into plan view. The beam deflections produced by the analyzer are actually in the horizontal plane, rather than vertical as they appear in the figure. The gas cell is filled with argon at pressures between 1.0 to 7.0×10^{-3} Torr. A He^{++} beam of sufficient intensity and purity for the cross-section measurements can be obtained at the analyzer exit slit only for energies in the restricted range from 0.5 to 1.0 MeV.

Fast H^+, He^+, or He^{++} ions can be directed in turn into the collision chamber simply by suitably adjusting the electrostatic analyzer deflection potential and the gas supplied to the ion source of the Van de Graaff, thus permitting direct comparison and cross correlation of the slow-ion production cross sections for the several ions under identical conditions with the same apparatus.

III. EXPERIMENTAL RESULTS

Our results for He^+ ions incident on He, Ne, Ar, H_2, N_2, O_2, and CO are presented in Figs. 3–9, and the cross sections for He^{++} ions incident on He and H_2 appear in Fig. 10. In these figures the total apparent cross sections for production of positive ions, σ_+, and of electrons, σ_-, are given as functions of the incident helium-ion energy. The curves shown were fitted to experimental points at intervals of 0.05 MeV, each point being an average of at least fifteen separate observations.

Our data were obtained with target gas pressures in the range 0.5 to 1.0×10^{-4} Torr. Over this range the measured cross sections were shown to be independent of pressure.[7] The measured slow-particle currents were always less than 1% of the beam current, indicating that thin target conditions prevailed.

The absolute error brackets for the cross sections involving He^+ ions plotted in Figs. 3–9 are $\pm8\%$ for σ_+ and $\pm11\%$ for σ_-, while the relative accuracies of the cross sections with respect to each other are about $\pm5\%$. The absolute error brackets for the cross sections involving He^{++} plotted in Fig. 10 are $\pm7\%$ for σ_+ and $\pm10\%$ for σ_-, while the relative accuracies are about $\pm5\%$. These brackets represent our estimate of the maximum probable random and systematic errors due to all instrumental inaccuracies and reading errors.

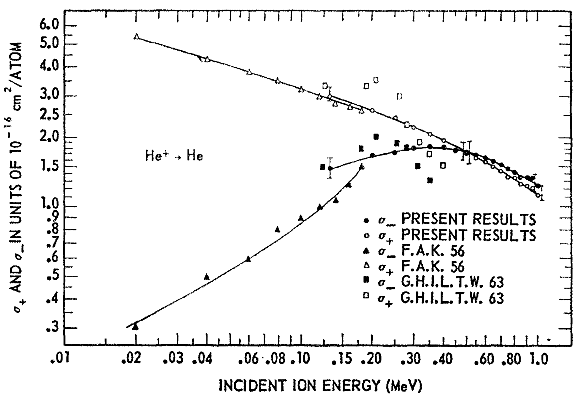

FIG. 3. Apparent cross sections for production of positive ions, σ_+, and free electrons, σ_-, by He^+ ions on helium. The present results are compared with data obtained by Fedorenko *et al.* (Ref. 12) and by Gilbody *et al.* (Ref. 14).

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[9] S. Kronenberg, K. Nilson, and M. Basso, Phys. Rev. 124, 1709 (1961).

[10] A small number of similar fast electrons are of course also produced by the collisions of the projectiles with the target gas itself. However, extensive saturation curve studies, which have not been presented in this paper, indicate that the fraction of these fast electrons which are not collected with the electrode arrangement and the field values used here can produce only a negligible error in the value of σ_-.

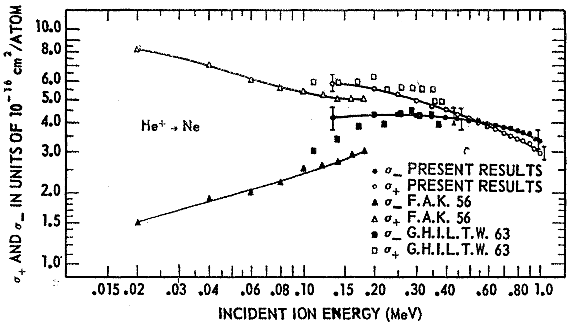

FIG. 4. Apparent cross sections for production of positive ions, σ_+, and free electrons, σ_-, by He^+ ions on neon. The present results are compared with data obtained by Fedorenko *et al.* (Ref. 12) and by Gilbody *et al.* (Ref. 14).

However, they do not include a possible systematic error in the determination of the target gas pressure, which was measured with a liquid-nitrogen-trapped McLeod gauge, that is caused by the pumping action of the cold trap.[11] Correction for this effect has not been made upon the data displayed in Figs. 3–10 because the magnitude of the effect has not yet been established beyond question. Furthermore, this correction does not appear to have been made to any of the published data with which our data are compared in this paper. If the pumping action effect is appreciable, the error in the data of the other investigators is probably of similar magnitude to the error in ours. For the present at least, it appears that the most meaningful comparison is to be made with the uncorrected data.

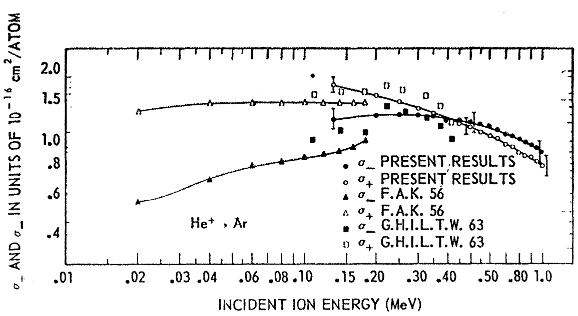

FIG. 5. Apparent cross sections for production of positive ions, σ_+, and free electrons, σ_-, by He^+ ions on argon. The present results are compared with data obtained by Fedorenko *et al.* (Ref. 12) and Gilbody *et al.* (Ref. 14).

[11] For a number of years, various investigators have been concerned over the possible effect of cold-trap pumping action on McLeod gauge pressure measurements. The streaming of mercury vapor from the gauge to the trap acts as a diffusion pump to make the partial pressure of the working gas lower in the gauge than in the vessel where the working gas pressure is to be determined. Recent quantitative investigations by H. Ishii and K. Nakayama [*1961 Transactions of the Eighth Vacuum Symposium and Second International Congress* (Pergamon Press, New York, 1962), pp. 519–524] and Ch. Meinke and G. Reich [Vacuum 13, 579–581 (1963)] indicate that the effect may be significant in certain cases. Specifically, these treatments indicate that there would be a substantial multiplicative error, different for each of our target gases but independent of pressure over the pressure range of our measurements. If their formulas were to be applied to our McLeod gauge, our cross sections would be revised downward as follows: He-2.8%; Ne-3.7%; Ar-12%; H_2-2.3%; N_2-11%; O_2-11%; CO-11%. As stated above, there is no doubt that the effect exists, but there appears to be some divergence of opinion about its magnitude. For this reason and the reason given above in the text, our data are plotted without the correction.

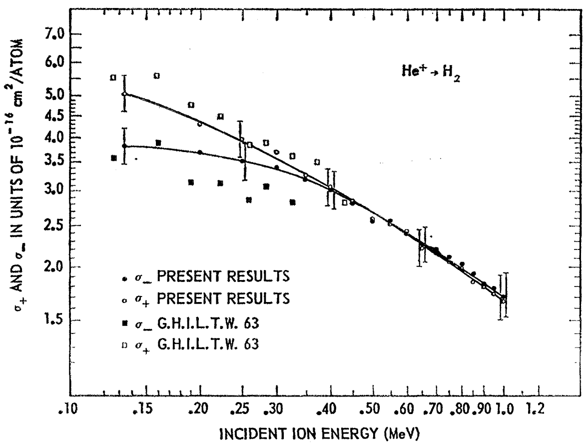

FIG. 6. Apparent cross sections for production of positive ions, σ_+, and free electrons, σ_-, by He^+ ions on hydrogen. The present results are compared with data obtained by Gilbody *et al.* (Ref. 14).

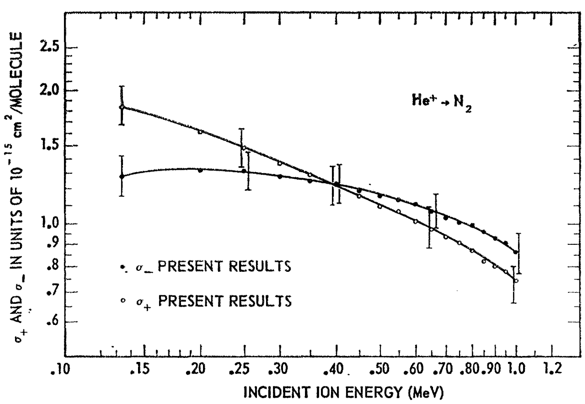

FIG. 7. Apparent cross sections for production of positive ions, σ_+, and free electrons, σ_-, by He^+ ions on nitrogen.

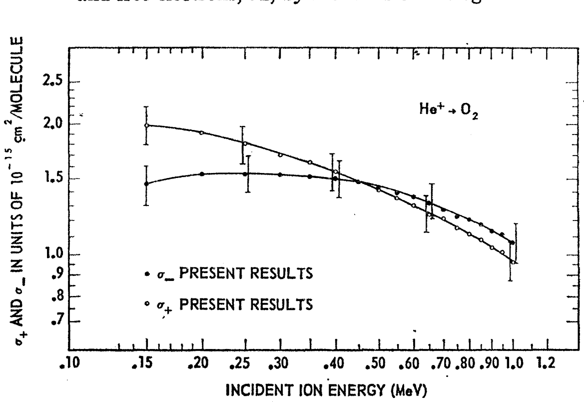

FIG. 8. Apparent cross sections for production of positive ions, σ_+, and free electrons, σ_-, by He^+ ions on oxygen.

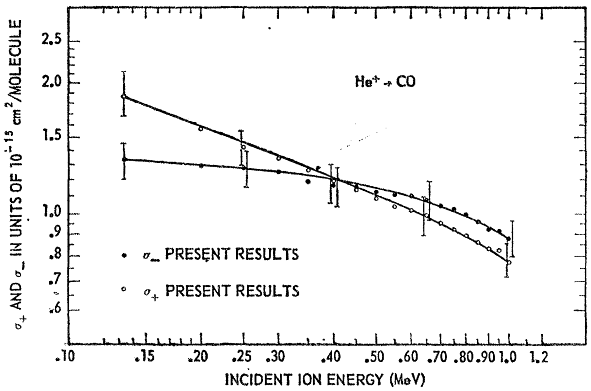

FIG. 9. Apparent cross sections for production of positive ions, σ_+, and free electrons, σ_-, by He^+ ions on carbon monoxide.

Also shown in Figs. 3–9 are all of the known results of other workers in the same energy range. The results of Fedorenko, Afrosimov, and Kaminker[12] for He^+ with energies up to 0.18 MeV were derived from direct measurements of σ_+ and σ_- by a condenser method quite similar to ours. The results presented by Fedorenko's group in a more recent report[13] did not differ significantly from those shown. The results of Gilbody *et al.*,[14] for He^+ with energies up to 0.40 MeV were obtained by a somewhat different method. Gilbody and his colleagues used condenser plates with a transverse electrostatic field and a longitudinal magnetic field to collect their slow positive ions and thus determine σ_+. The magnetic field confined the slow electrons formed in the gas to tight cycloidal-helical paths in the beam direction so that only positive ions were collected by the condenser plates in the measurement of σ_+. Grids were not required on the electrodes because secondary electrons were suppressed by the axial magnetic field. Gilbody *et al.*, did not measure the slow-electron current directly. They determined σ_- by subtracting from σ_+ their measured values of σ_c, the apparent total-charge-transfer cross section. To measure σ_c, they removed the longitudinal magnetic field and measured the *net* current to the pair of condenser plates. This approach was utilized because of concern over possible errors which they believed might arise from secondary effects in the measurement of electron currents.

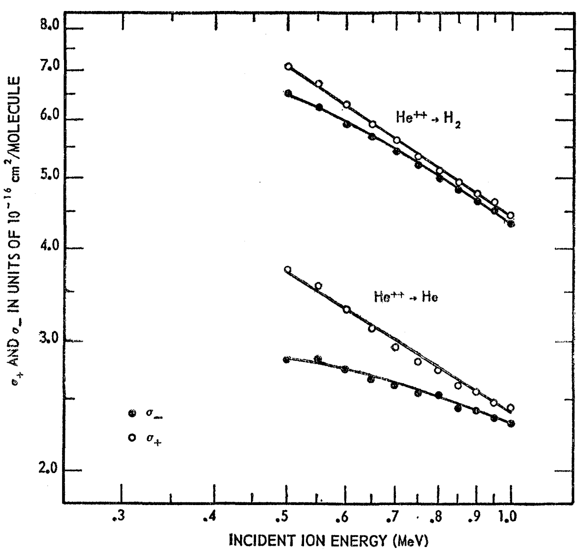

FIG. 10. Apparent cross sections for production of positive ions, σ_+, and free electrons, σ_-, by He^{++} ions on helium and hydrogen.

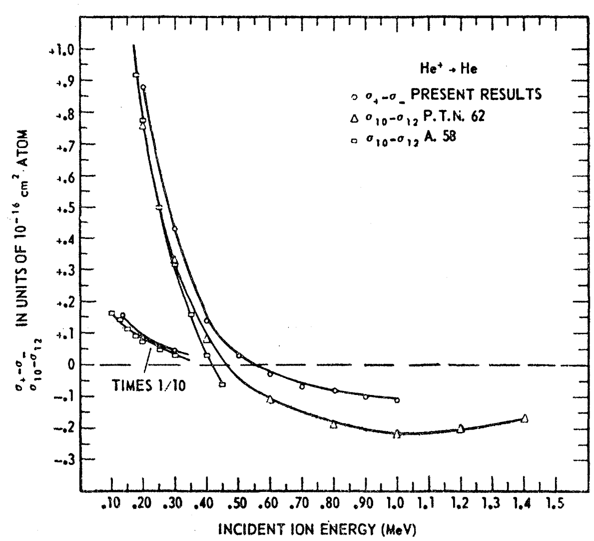

FIG. 11. Cross correlation between total ion and electron production cross sections and charge-changing cross sections for He^+ ions incident on He. The charge-changing cross sections are taken from Pivovar *et al.* (Ref. 15) and Allison (Ref. 8).

No data are known to be available for direct comparison with our He^{++} results.

A cross correlation can also be made between our data and direct measurements by quite different methods of the total "charge-changing" cross sections. Measurements of the stripping cross section σ_{12}, i.e., the total probability that the fast incident ion loses an electron, and the "pickup" cross section σ_{10}, have been made at other laboratories in our energy range for He^+ on targets of He, Ar, H_2, and N_2.[8,15] Similar measurements of the

[12] N. V. Fedorenko, V. V. Afrosimov, and D. M. Kaminker, Zh. Techn. Fiz. 26, 1929 (1956) [English transl.: Soviet Phys.—Tech. Phys. 1, 1861 (1956)].

[13] E. S. Solov'ev, R. N. Il'in, V. A. Oparin, and N. V. Fedorenko, *Third International Conference on the Physics of Electronic and Atomic Collisions* (*London, 1963*) (North-Holland Publishing Company, Amsterdam, 1964). See also E. S. Solov'ev, R. N. Il'in, V. A. Oparin, and N. V. Fedorenko, Zh. Eksperim. i Teor. Fiz. 45, 496 (1963) [English transl.: Soviet Phys.—JETP 18, 342 (1964)].

[14] H. B. Gilbody, J. B. Hasted, J. V. Ireland, A. R. Lee, E. W. Thomas, and A. S. Whiteman, Proc. Roy. Soc. (London) A274, 40 (1963).

[15] L. I. Pivovar, V. M. Tubaev, and M. T. Novikov, Zh. Eksperim. i Teor. Fiz. 41, 26 (1961) [English transl.: Soviet Phys.—JETP 14, 20 (1962)].

single and double pickup cross sections σ_{21} and σ_{20} were also made for He^{++} on the targets He and H_2. Like σ_+ and σ_-, these total charge-changing cross sections may contain contributions from several types of elementary collision events, in which the unobserved target molecule may be left in various charge states, with the release of various numbers of free electrons. However, provided only that double-electron pick up by fast He^+ ions may be neglected, it is nevertheless true for the case of He^+ that the difference $(\sigma_+-\sigma_-)$ from our measurements should be equal to the difference $(\sigma_{10}-\sigma_{12})$; similarly for the case of He^{++}, our $(\sigma_+-\sigma_-)$ should be strictly equal to the sum $(\sigma_{21}+\sigma_{20})$ of the pick-up cross sections. Figure 11 shows this comparison for one of the six cases for which both sets of cross sections are available, that of He^+ in He. There is excellent agreement at low energies, but about a factor of two difference at the high-energy end. However, it may be noted from Fig. 3 that our σ_+ and σ_- differ by only about 10% in this region, so that the discrepancy implies no errors worse than our quoted 5% relative error for σ_+ and σ_-. [By contrast, σ_{12} is an order of magnitude greater than σ_{10} in this region; therefore it is quite possible that the $(\sigma_{10}-\sigma_{12})$ difference is more accurate than our $(\sigma_+-\sigma_-)$ difference.]

Similar comparisons for the other five cases will not be shown here. Actually, the selected case is one of the least favorable. The comparison for He^+ in H_2 is quite similar, but the comparisons for He^+ in Ar and N_2, and for He^{++} in He and H_2 all give generally excellent agreement throughout the energy range of our measurements.

Because our ion production measurements and the total charge-changing measurements are conducted in entirely different ways that are subject to quite different kinds of possible systematic errors, the rather good cross correlations obtained are regarded as gratifying confirmation of both sets of measurements.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the assistance of J. W. Martin, who operated the Van de Graaff accelerator for the bulk of these measurements, and of L. J. Puckett, who assisted with the He^{++} measurements.

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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
Georgia Institute of Technology, Atlanta, Georgia

(Received 11 May 1964)

The theory of ionization of gases by fast, but nonrelativistic, ions is briefly reviewed, with emphasis on the correspondences expected at high energies among the cross sections for various projectile ions incident on a given target gas. The problem of deducing cross sections for simple ionization from experimental gross ion and electron production cross sections is discussed. The methods developed are applied to the experimental data presented in the preceding paper. Estimates are thus obtained of the simple ionization cross sections for He^+ ions incident on H_2, He, Ar, and N_2 in the energy range 0.133 to 1.0 MeV, and He^+ on Ne, O_2, and CO in the energy range 0.6 to 1.0 MeV. Similar results are obtained for He^{++} ions incident on H_2 and He in the energy range 0.5 to 1.0 MeV. These results are compared with semitheoretical predictions based upon empirical values of target-gas matrix elements determined from previous measurements of the ionization cross sections for protons incident on the same targets. It is shown that the ionization cross sections for He^{++} conform rather well to the predictions, and that the ionization cross sections for He^+ ions are in good agreement with those expected for a point-charge ion with the helium mass and an "effective charge" of $Z'e=+1.2e$. The ionization cross sections are also compared with explicit detailed calculations in the full Born approximation for the cases where such calculations are available. The agreement obtained is quite good in general.

I. INTRODUCTION

IN the paper immediately preceding (I. Experimental[1]) we reported apparent cross sections for production of positive ions, σ_+, and free electrons, σ_-, by He^+ ions incident on He, Ne, Ar, H_2, N_2, O_2, and CO and by He^{++} ions on He and H_2. The He^+ measurements covered the energy range 0.133 to 1.0 MeV; the energy of the He^{++} projectiles was varied over the range 0.5 to 1.0 MeV. These cross sections include contributions from any charge-changing events (in which the projectile gains or loses electrons) and from simple ionization events (in which one or more electrons are ejected from the target molecules without a change in the charge state of the incident particle). Information on the total cross sections for charge-changing collisions

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† Present address: CRUZ, Air Force Cambridge Research Laboratory, Bedford, Massachusetts. Portions of the results presented here were included in a thesis submitted by RAL to the faculty of the Georgia Institute of Technology in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

[1] R. A. Langley, D. W. Martin, D. S. Harmer, J. W. Hooper, and E. W. McDaniel, preceding paper, Phys. Rev. 136, A379 (1964).