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Formation of Excited States in a Helium Target by the Impact of 0.15- to 1.0-MeV Protons and Deuterons. I. Experimental*

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An optical technique has been used to determine the absolute cross sections for the excitation of various n^1S, n^1P, and n^1D states of neutral helium by the impact of 0.15- to 1-MeV protons on a low-pressure gaseous helium target. The emission resulting from the radiative decay of collisionally excited atoms is analyzed using an optical spectrometer, and detected by a low-noise photomultiplier. The absolute photon-detection efficiency of the system is determined with the aid of a tungsten-strip-filament lamp of known emissive power. It is shown how the rate of emission of photons may be related to the cross section for exciting the parent level in terms of known transition probabilities. Cross sections for the formation of various singlet excited states of helium by proton bombardment are presented as a function of projectile energy. Deuterons were used to extend the effective velocity range of the data in selected cases. The cross sections for the formation of the ^1S and ^1D states by excitation from the ground state show a rapid decrease with increasing projectile velocity. The ^1P-state excitation-cross sections peak at about 120 keV and fall off slowly with further increase of projectile energy. Data are also presented for the emission of the He II (4 → 3) transition induced by proton impact. Systematic discrepancies between previously published sets of data are identified as being caused by differences in the calibration of detector sensitivity. In a companion paper the present data are compared with theoretical predictions.

I. INTRODUCTION

THE study of processes leading to the formation of excited states as the result of ion-atom impact under single-collision conditions is of great fundamental interest with important applications in the physics of the upper atmosphere and many plasma devices. Previous measurements of this type have been primarily restricted to energies below 200 keV, and the present work on the excitation of helium by protons represents the first stage of a program to consider a variety of collisional excitation processes in the relatively unexplored high-energy region.

The cross sections for the formation of nine neutral helium levels have been measured, representing both dipole and quadrupole transitions from the ground state by a process of direct excitation;

$$H^+ + He = H^+ + He(nl). \qquad (1)$$

It is clear that there is no ambiguity in this mechanism as to the post or prior collision states of excitation or ionization of either of the colliding particles. A single measurement of an emission function of a He II spectral line has been made but cannot readily be expressed as a cross section for the formation of a specific excited state. The excited ion may be formed in a collision involving charge transfer

$$H^+ + He = H + He^+(nl), \qquad (2)$$

or by simultaneous ionization and excitation

$$H^+ + He = H^+ + He^+(nl) + e. \qquad (3)$$

In the case of the excited ion there is ambiguity as to the post-collision state of the projectile both as regards charge and excited state, although at the high energies used in this experiment it would be expected that the process of simultaneous ionization and excitation would predominate. Deuterons and protons at the same velocity of impact are expected to produce the same excitation cross section, and D^+ beams may be conveniently used to extend the lower limit of velocity range available to a particular experiment. In the present work, the deuterons were used only in a restricted number of cases where the extended velocity range materially assisted in the comparison of the present measurements with other published theoretical and experimental data.

The present study of the excitation of a helium target by the impact of protons was undertaken primarily for comparison with theoretical predictions, this being one of the few cases which is tractable by both existing experimental and computational techniques. Experience with the ionization of helium by protons[1] indicates agreement between experiment and the first-order Born approximation at impact energies above 500 keV. A similar situation is expected in the case of excitation phenomena, but since the majority of the existing data is confined to energies below 200 keV little significant comparison between theory and experiment has hitherto been possible. The present paper presents only experimental measurements of excitation cross sections; the comparisons with theoretical predictions are, for convenience, treated separately in the following paper.[2]

II. EXPERIMENTAL APPROACH

The passage of a beam of positively charged ions through a gas will result in the formation of excited states of a small number of target particles. In cases

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* This work was partially supported by the Controlled Thermonuclear research program of the U. S. Atomic Energy Commission.

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

[2] E. W. Thomas, following paper, Phys. Rev. **164**, 151 (1967).

where the excited products undergo spontaneous radiative decay, the analysis and quantitative detection of the emitted radiation allows us, in principle, to obtain a cross section for the formation of an excited state.

If an ion beam of particle density n (ions/cc) at a velocity v (cm/sec) is incident on a target of density N (molecules/cc), the rate of change of the population density of an excited state i of the target system may be expressed in the following manner:

$$\frac{dN_i}{dt}=nvN\sigma_i+\sum_{k>i}A_{ki}N_k-\sum_{j<i}A_{ij}N_i+C_i(n,N,v)\,. \tag{4}$$

The first term gives the rate of collisional population in terms of the cross section σ_i for exciting the level. The second term gives the rate of population by cascading from all states k higher than i, in terms of the radiative transition probability A_{ki} for the transition $k \rightarrow i$. The third term introduces the rate of depopulation of the state i by radiative decay to states j lower than i. Secondary collision processes affecting the density of excited states N_i such as collisional depopulation, collisional transfer, and population by absorption of resonance photons, are all included as a fourth term $C_i(n,N,v)$. Gabriel and Heddle[3] show specifically how such secondary processes may be included. For simplicity, we express them only as a single term which we recognize as requiring a linear dependence on ion beam flux and a nonlinear dependence on target density; the precise nature of the coefficient C_i will depend on the relevant secondary processes, and in some cases will be zero.

It is convenient to define a cross section for the emission of photons arising by the decay $i \rightarrow j$, in terms of the number of photons emitted per second from 1 cm of the beam path through the chamber J_{ij}, the number density of the target N, and the number of projectiles incident per second I; $\sigma_{ij}=J_{ij}(NI)^{-1}$. If $\mathcal{A}$ is the cross-sectional area of the ion beam, then $I=nv\mathcal{A}$, and $J_{ij}=A_{ij}N_i\mathcal{A}$. This cross-sectional area $\mathcal{A}$ cancels out of the final equations. Under conditions where equilibrium has been established between populating and depopulating mechanisms the excited state density N_i is invariant with time, and Eq. (4) may be written in terms of emission cross sections as follows:

$$\sigma_i=\sum_{j<i}\sigma_{ij}-\sum_{k>i}\sigma_{ki}+C_i'(n,N,v)\,, \tag{5}$$

where $C_i'(n,N,v)=C_i(n,N,v)/nNv$. If we take the state l to be one specific lower level, then the intensity of emission in the $i \rightarrow l$ transition may be related to the total photon emission by all decays;

$$\frac{J_{il}}{\sum_{j<i}J_{ij}}=\frac{A_{il}}{\sum_{j<i}A_{ij}}. \tag{6}$$

Equation (5) may be rewritten as follows:

$$\sigma_i=\frac{\sigma_{il}}{A_{il}}\sum_{j<i}A_{ij}-\sum_{k>i}\sigma_{km}\frac{A_{ki}}{A_{km}}+C_i'(n,N,v)\,. \tag{7}$$

The second term of Eq. (7) represents the cascade correction and has been written in terms of the level m to indicate that it is unnecessary to determine directly the emission cross section of the cascade transition; the measurement of any emission out of the level k may be related to the actual cascade transition using the ratios of transition probabilities.

Equation (7) shows that, under conditions where the emission cross section σ_{il} is found to be independent of target density, then the secondary processes leading to the population and depopulation of the level i are negligible and the term C_i' may be ignored.

If the emission functions for all transitions populating and depopulating level i can be measured directly, then Eq. (5) may be used to calculate an excitation cross section. In general, the limited spectral range of any one detection system renders this impossible. If the ratios of transition probabilities are known, then Eq. (7) may be employed utilizing a relatively small number of measured emission cross sections. It should be noted that only the ratios of transition probabilities are required for this procedure and, in the case of helium, these are known quite accurately from the self-consistent set quoted by Gabriel and Heddle.[3] In the present work appreciable cascade corrections were only required for measurements on the ^1P levels, and the second term of Eqs. (5) and (6) was otherwise neglected.

Significant population of excited states by secondary processes was generally excluded by the operation of the experiment under conditions where the emission cross sections were independent of target density and incident beam flux.

III. APPARATUS

The source of the incident protons was a 1-MeV Van de Graaff positive-ion accelerator, equipped with beam analyzing and stabilizing systems which provided a useful energy range from 0.15 to 1.0 MeV. The incident proton energy was determined by a 90° deflection in a regulated magnetic field to within ±2 keV. Beam currents of about 6 μA were typically employed.

A schematic diagram of the apparatus is shown in Fig. 1. The incident ion beam is collimated to $\frac{1}{16}$-in. diameter by two knife-edged orifices suitably biased to inhibit secondary electron emission. A third orifice in the form of a channel was used to provide the limiting aperture between the collision chamber and accelerator to inhibit gas loss from the cell. This orifice was chosen to have a diameter such that no particles which had traversed the first two apertures could be incident upon it, so reducing the possibility of secondary electrons and sputtered material entering the observation region.

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[3] A. H. Gabriel and D. W. O. Heddle, Proc. Phys. Soc. (London) **A258**, 124 (1960).

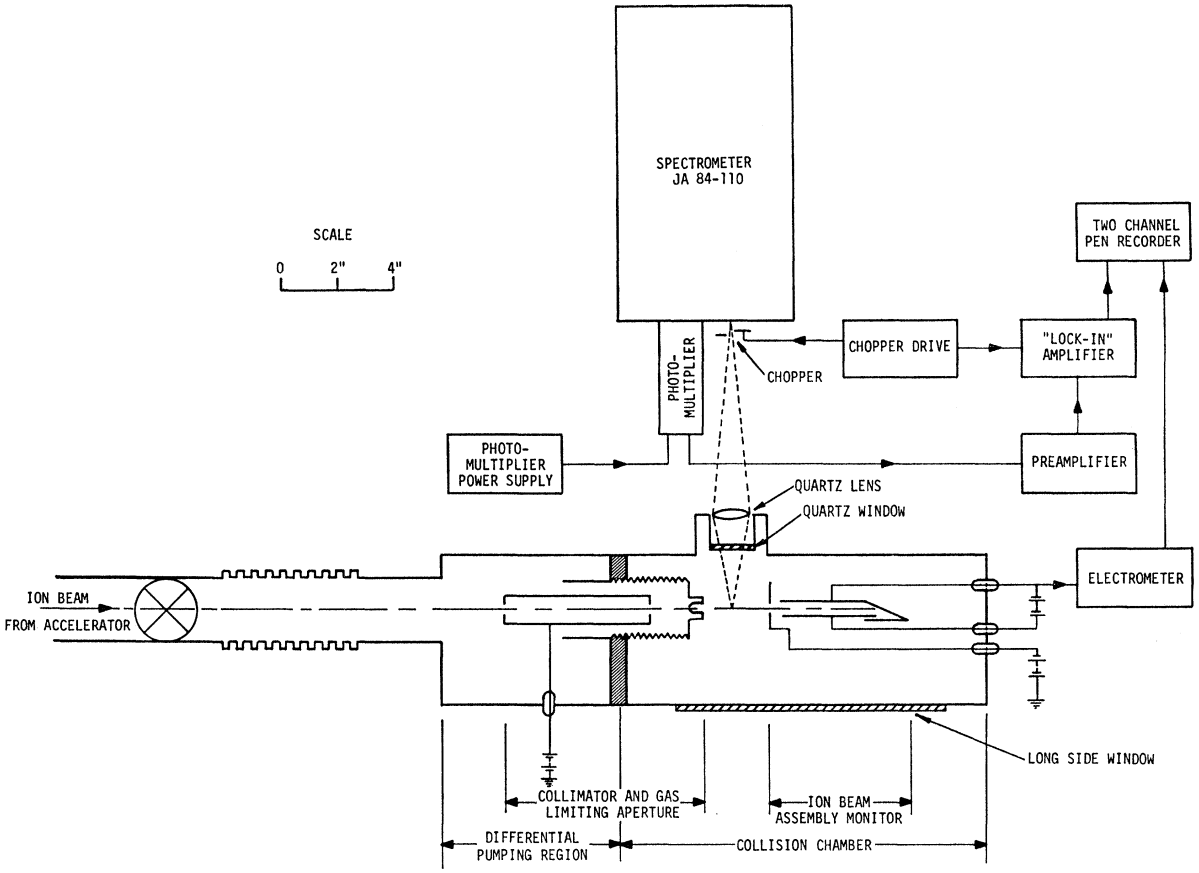

FIG. 1. Schematic diagram of the experimental apparatus.

The ion-beam current was monitored on a deep parallel-plate assembly with an inclined end. Tests indicated that the application of suitable biases to the beam-collection system resulted in complete suppression of secondary ions and electrons. Ion-beam currents were measured by an electrometer and displayed in one channel of a two-pen chart recorder.

Helium gas, stated to be 99.9% pure by the manufacturer, was passed through a cold trap to remove any condensable materials, and leaked into the collision chamber. The target gas pressure was measured using a McLeod gauge, suitable precautions being taken to reduce the influence of sticking and capillary depression errors.[4] Recently identified errors in McLeod gauge operation associated with the pumping of mercury from the reservoir to the cold trap[5] will influence the measurement of helium pressure by less than 4%. In view of the fact that the precise value of the correction is difficult to evaluate, it has been neglected, and an overall limit of accuracy in the pressure measurement of ±5% is adopted.

A quartz window is provided in the side of the chamber and an external quartz lens focuses light emitted from the collision region on the entrance slit of a Jarrel Ash 84-110 scanning spectrometer fitted with photomultiplier detection (EMI 6256S). To reduce the effects of photomultiplier noise an ac detection technique is used. A tuning-fork chopper modulates the light flux entering the spectrometer at 100 cps and the required signal in the output from the photomultiplier, identified by its specific frequency and phase, utilizing a "lock in" amplifier. The output from the light-detection system is displayed on the second channel of the pen recorder.

The optical system accepts radiation of a wavelength corresponding to the transition $i \rightarrow j$ emitted into a solid angle ω from a small section of the ion-beam path L to produce an output signal S_{ij}. Assuming that the radiation was isotropic (i.e., polarization was neglected) the photon emission rate is given by the following relation:

$$J_{ij}=\frac{4\pi}{\omega}\frac{S_{ij}}{LK(\lambda)}. \tag{8}$$

The dimensionless factor $K(\lambda)$ includes the detection sensitivity of the photomultiplier and losses at refractive and reflective surfaces. The most convenient technique for determining $K(\lambda)$ is to measure the signal from a known source of emission. A standard tungsten-strip-

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[4] P. H. Carr, Vacuum 14, 37 (1963).

[5] T. Takaishi, Trans. Faraday Soc. 61, 840 (1965).

filament lamp was used for this purpose. The optical system was withdrawn from the chamber with no change in the relative positions of the various optical components, and the lamp placed so that the strip filament was accurately positioned at the point previously occupied by the strip of emission from the ion beam. If the width of the filament is w, the area of the filament viewed by the optical system is wL. The emissive power of the lamp at the wavelength of interest E_λ is expressed in terms of the number of photons emitted per sec per Å bandwidth from unit area of the filament into 1 sr. The signal from the optical system when viewing the filament S_λ is determined by the inverse dispersion of the spectrometer D_λ(Å/mm) and the spectrometer exit slit width $d(mm)$:

$$S_\lambda = K(\lambda)E_\lambda D_\lambda dwL\omega. \tag{9}$$

By Eq. (8) and (9) we may express the rate of emission of photons from the collision experiment in terms of a ratio of two signals, the emissive power of the standard lamp, and certain readily determined geometrical factors. The solid angle ω and the length of beam path L seen by the spectrometer do not have to be determined:

$$J_{ij} = (S_{ij}/S_\lambda)E_\lambda D_\lambda dw4\pi. \tag{10}$$

The brightness temperature of the filament, typically 1050°C, was measured using an optical pyrometer and related to true temperature by the established procedures.[6] The emissive power of the filament was determined from tables provided by the manufacturer which are based on the work of De Vos.[7]

Care must be taken when using the incandescent standard lamp at wavelengths below 4300 Å to eliminate stray light from the very intense emission in the visible regions of the spectrum, which can completely obscure the low-intensity emissions observed in the ultraviolet. The scattering of a small amount of visible light to the exit slit of the spectrometer has been detected and eliminated by the use of suitable filters of known calibrated transmission. This problem is of no consequence when measuring emission from the collision region since the intensity of emission integrated over all wavelengths is very small.

IV. MEASUREMENT PROCEDURE

During preliminary tests the apparent emission cross section defined by Eq. (4) was plotted as a function of target gas pressure to establish a region of pressure independence, so-called single-collision conditions. In the case of n^1P and n^1D levels the effects of resonance absorption of radiation and collisional transfer caused some degree of variation down to the lowest pressure used ($\sim 0.5\times10^{-3}$ Torr). In such cases the apparent cross section was extrapolated to zero pressure and this value utilized. This procedure will be further discussed in later sections.

Experimental runs were normally taken by varying the energy of impact while keeping target pressure constant, preferably in the region where the apparent cross section was pressure-independent. The spectrometer was set manually at the wavelength of interest and the recorder chart run for a period of some minutes so that a good average value of optical and ion-beam signals could be obtained. Typical target pressures were in the region 1 to 4×10^{-3} Torr. In this manner a measurement was made of the emission cross section for a transition, repeated measurements at different pressures generally being consistent to within ±3%. The absolute detection efficiency of the system was determined at frequent intervals. In all cases except the excited helium ion, it was possible to use known transition probabilities in Eq. (7) to arrive at a measurement of a level excitation cross section.

The major source of possible error in the present work lies in the determination of the detection sensitivity of the optical system. The temperature of the standard-lamp filament could be determined to within ±5°K, leading to an uncertainty in the emissive power of ±10%. Difficulties in reproducing the precise position of the filament of the standard lamp lead to a further random uncertainty in the calibration of ±5%. The geometrical factors in Eq. (10) could be determined with high accuracy and it is estimated that the possible error in the calibration does not exceed ±15%, most of which represents random errors in alignment and temperature measurement.

It is estimated that the absolute magnitudes of most of the present measurements are accurate to within ±25%. In the case of the ^1P levels which are affected by resonance absorption of photons, the error limits are somewhat broader at ±35% because of certain required extrapolations. It should be noted that relative measurements are generally accurate to within ±10% since certain possible errors in the calibration of detection sensitivity and pressure measurement cancel out when determining ratios of cross sections.

V. POLARIZATION

The measurement of the polarization of the emitted radiation was not an objective in the present work. However, since the polarization gives rise to an anisotropy in the emission,[8] it was decided to make an estimate of the effects of polarization on the present measurements. A sheet of Polaroid was used as an analyzer and suitable corrections made for the different transmission of light through the spectrometer when polarized parallel and perpendicular to the entrance slit. In no case did the polarization fraction exceed 8%. Using the treatment of Smit,[8] this implies that the cross

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[6] G. A. W. Rutgers and J. C. de Vos, Physica **20**, 715 (1954).

[7] J. C. de Vos, Physica **20**, 690 (1954).

[8] J. A. Smit, Physica **2**, 104 (1935).

sections presented here, which are measured at 90° to the ion-beam path and assume isotropy in the emission, will be in error by less than 4%, because of the effect of polarization on the angular distribution.

VI. EXCITATION OF THE $1^1S \rightarrow n^1S$ TRANSITION

The emission functions of the $4^1S \rightarrow 2^1P$ (5047 Å), $5^1S \rightarrow 2^1P$ (4920 Å), $6^1S \rightarrow 2^1P$ (4169 Å), and $7^1S \rightarrow 2^1P$ (4024 Å) lines of neutral helium were measured. The emission was found to be linear with pressure up to the highest pressures used (10×10^{-3} Torr) and a normal operating value of 3×10^{-3} Torr was adopted.

Cascade into the ^1S levels can occur from higher ^1P levels through transitions which do not lie within the spectral range of the detection system. However, the measurement of an emission function of some other transition from the higher state k to a lower level, and the knowledge of the relative transition probabilities, will allow the evaluation of the cascade from the state k into the level of interest i. This feature is essentially allowed for by the second term in Eq. (7), and use was made of the emission functions of $k^1P \rightarrow 2^1S$ transitions to provide the emission functions σ_{km}. Cascade contributions from levels above $n=6$ could not be assessed in this manner, but an estimate was made assuming that the cross section for the formation of a level n decreases as n^{-3}. In all cases the cascade contribution to the n^1S population was found to be negligible.

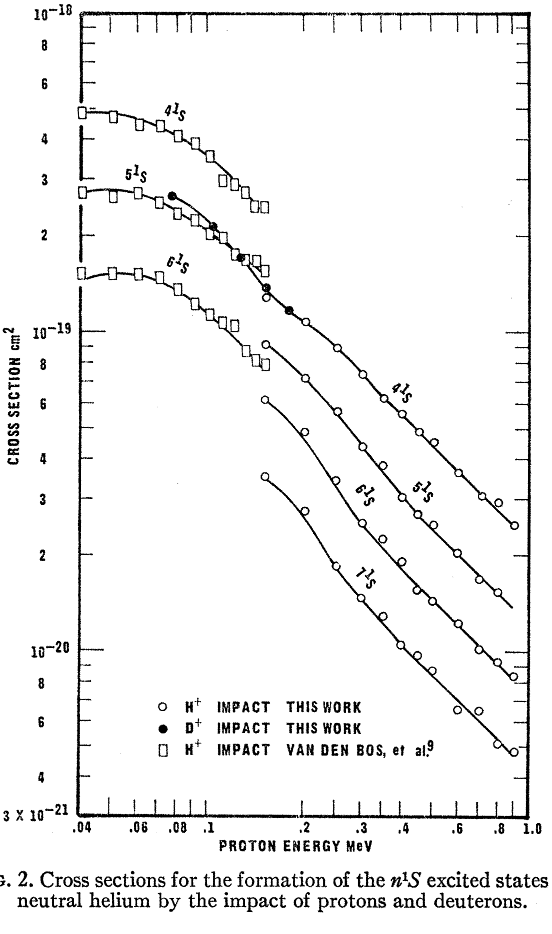

FIG. 2. Cross sections for the formation of the n^1S excited states of neutral helium by the impact of protons and deuterons.

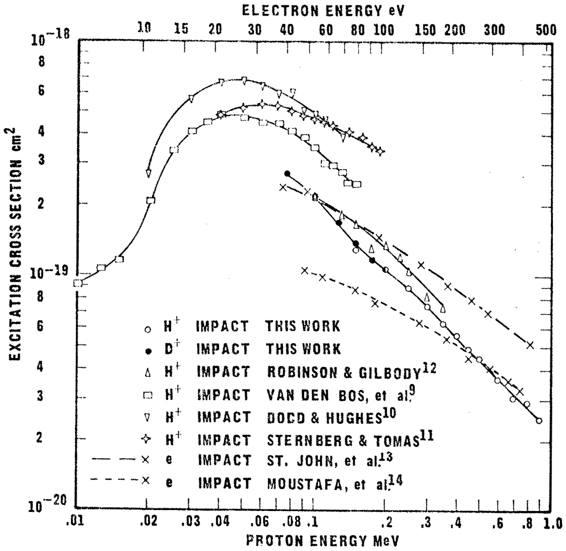

FIG. 3. Comparison of the cross sections for the formation of the 4^1S excited state of neutral helium by the impact of protons, deuterons and electrons.

The cross sections obtained for the formation of n^1S states, using Eq. (6) and ignoring the negligible cascade terms, are shown in Fig. 2. Incident deuterons were shown to produce the same cross sections as incident protons at the same velocity of impact, and were utilized to extend the lower velocity limit of our data for the case of the 4^1S level. The estimated limits of accuracy of the absolute cross-section data are ±25%.

Comparisons may be made with the data of Van den Bos *et al.*,[9] Dodd and Hughes,[10] Sternberg and Tomas,[11] and Robinson and Gilbody[12]; also with the electron impact data of St. John *et al.*,[13] and Moustafa *et al.*,[14] which according to the Born approximation should tend to be the same as for protons with equal impact velocities at sufficiently high velocities. For clarity, Fig. 2 shows only the comparison with Van den Bos *et al.* for the whole set of ^1S levels, while Fig. 3 shows all the various available data for the excitation of the 4^1S level alone.

The present work lies consistently below that of Van den Bos by factors which are outside the range of possible experimental error. However, the energy depen-

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[9] J. Van den Bos, G. Winter, F. J. de Heer, Physica (to be published); J. Van den Bos, thesis, University of Amsterdam, 1967 (unpublished). These results supersede the less extensive series by J. Van Eck, F. J. de Heer, and J. Kistemaker, Physica **30**, 1171 (1964).

[10] J. G. Dodd and R. H. Hughes, Phys. Rev. **135**, A618 (1964).

[11] Z. Sternberg and P. Tomas, Phys. Rev. **124**, 810 (1961).

[12] M. Robinson and H. B. Gilbody (private communication).

[13] R. M. St. John, F. L. Miller, and C. C. Lin, Phys. Rev. **134**, A888 (1964).

[14] N. R. Moustafa, F. J. de Heer, and J. Schutten, in *Proceedings of the Fifth International Conference on the Physics of Electronic and Atomic Collisions* (Nauka Publishing House, Leningrad, 1967), p. 489.

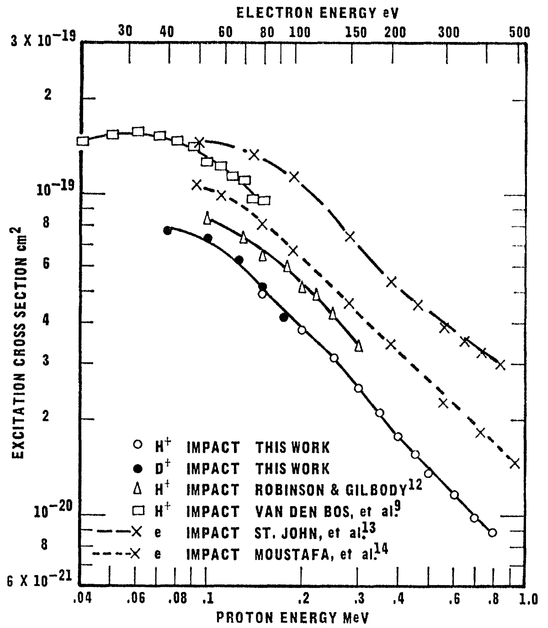

FIG. 4. Comparison of the cross sections for the formation of the 4^1D excited state of neutral helium by the impact of protons, deuterons, and electrons.

dencies and relative magnitudes of the cross sections at the region of overlap are very similar, suggesting that the difference lies in the absolute calibration. The work of Dodd and Hughes has a quoted uncertainty of ±40%, which represents agreement with Van den Bos but lies considerably above the present work. There is good agreement between the present data and the work of Robinson and Gilbody. Recent work by Denis *et al.*[15] on the excitation of the 4^1S, 5^1S, and 6^1S states, by proton impact at energies up to 500 keV, although not shown on these figures, is also in complete agreement with the present data. The work of Sternberg and Tomas[11] provides only an absolute determination of emission cross sections for D^+ impact, but a value is quoted for the relative magnitudes of H^+ and D^+ impact excitation cross sections, and we have utilized known transition probabilities to express the proton impact data as a cross section for the excitation of a level. There would appear to be little correspondence between the energy dependence of the work by Sternberg and the other available data. Neither of the electron impact experiments shows the same velocity dependence as the proton impact work, indicating that equality between the two types of measurements is not to be expected in the velocity range of the present experiment.

VII. EXCITATION OF THE 1^1S-4^1D TRANSITION

The emission function of the 4^1D-2^1P (4922 Å) transition was measured and converted to a cross section for the excitation of the 4^1D level using Eq. (7). The emission cross section exhibited a slight dependence on target pressure which could be ascribed to collisional transfer from the 4^1P state. Measurements were made at a target pressure of 1×10^{-3} Torr and extrapolated to zero pressure, the correction being of the order of 10%. Cascade from the n^1P levels was estimated by the procedures described in Sec. VI and found to be negligible. It is more difficult to assess the contribution from the ^1F states since no n^1F-n^1D transitions occur in the available spectral range of the present experiment. However, there is a theoretical prediction of the 4^1F cross section by Gaillard,[16] and if cross sections for higher ^1F states are assumed to decrease as n^{-3}, an estimate may be made of contributions from higher levels. On this basis, cascade into the 4^1D state might necessitate a correction of as much as 20%. In view of the impossibility of making an accurate correction for the population of the 4^1D state by cascade from the n^1F levels this was neglected completely, as indeed it was for the other experimental determinations with which comparisons are made. The present data are shown in Fig. 4 compared with the proton impact data of Van den Bos *et al.*[9] and Robinson and Gilbody.[12] The electron impact excitation data[13,14] at the same velocities of impact are also shown. It is observed that there is agreement within experimental error with the

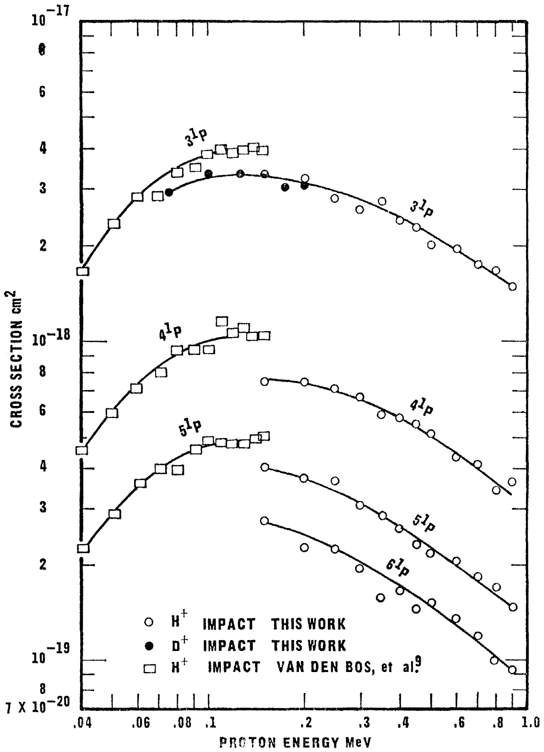

FIG. 5. Cross sections for the formation of the n^1P excited states of neutral helium by the impact of protons and deuterons.

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[15] A. Denis, M. Dufay, and M. Gaillard, Compt. Rend. **264**, 440 (1967).

[16] M. Gaillard, Compt. Rend. **263**, 549 (1966).

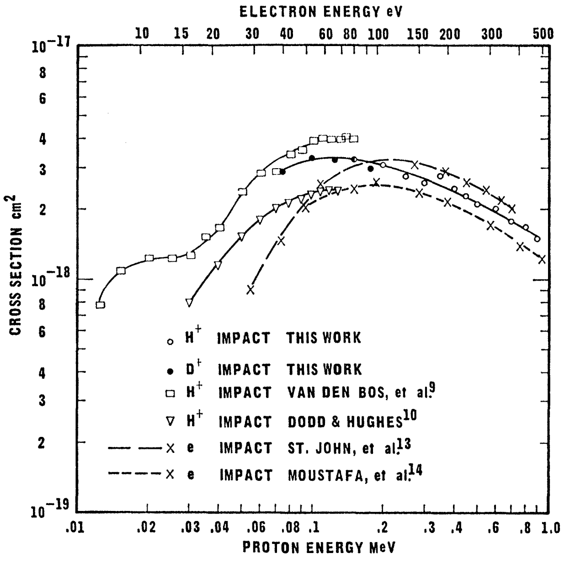

FIG. 6. Comparison of the cross sections for the formation of the 3^1P excited state of neutral helium by the impact of protons, deuterons and electrons.

measurements by Robinson and Gilbody[12] although, there is again, a systematic difference with the data of Van den Bos *et al.* Both the electron impact excitation experiments show approximately the same dependence of cross section on velocity as in the proton impact excitation data. It is to be noted that the similarity in the velocity dependence of electron and proton impact excitation cross sections is observed over most of the available velocity range of the present experiment for the 4^1D excitation, but in the case of the n^1S excitations does not occur until maximum impact velocities are reached.

VIII. EXCITATION OF THE $1^1S \rightarrow n^1P$ TRANSITION

The various n^1P levels are coupled optically with the ground state and their population is appreciably influenced by the absorption of resonance photons. The apparent emission cross section of the $n^1P \rightarrow 2^1S$ lines defined by Eq. (4) varies considerably with gas pressure, indicating that the term $C_i'(n,N,v)$ in Eq. (7) is nonzero. Phelps[17] has predicted the pressure dependence of the emission in such a situation for the case of an infinite cylinder, and also a target gas cell contained between infinite parallel plates. The treatment may be generalized to the consideration of practical collision-chamber geometries in which the final formulation is expressed in terms of an effective radius for the collision chamber and the true excitation cross section. In principle the fitting of the general curve to the experimental data, over a wide pressure range, should allow the determination of the two unknown factors. This technique has been used with success by Gabriel and Heddle,[3] who also included a necessary consideration of the somewhat lesser problem of collisional transfer. However, in the present work it proved impossible to represent the whole pressure dependence of the apparent emission cross section using a single value of the effective radius of the chamber. It was therefore decided to abandon this approach and use the pressure plots to extrapolate the apparent emission cross section to zero target pressure.

The n^1P levels are appreciably populated by cascade, and these contributions were assessed by the techniques established in Sec. VI using measured values of $n^1S \rightarrow 2^1P$ and $n^1D \rightarrow 2^1P$ emission functions and ratios of the relevant theoretical transition probabilities. Cascade corrections ranged from 4% for the 3^1P level to 1% for the 6^1P.

The difficulties of assessing cascade and resonance absorption effects will increase the uncertainty limits on this part of the experiment to ±35%. Excitation functions of the 3^1P, 4^1P, 5^1P, and 6^1P levels were determined and are shown on Fig. 5 with the data of Van den Bos *et al.*,[9] for comparison. A more detailed comparison of the 3^1P level with proton[9,10] and electron impact data[13,14] is shown in Fig. 6. In view of the considerable difficulty inherent in this measurement, the degree of agreement is surprisingly good, all three measurements by proton impact agreeing within experimental error. The electron impact data also correspond very well to the present data at high impact velocities.

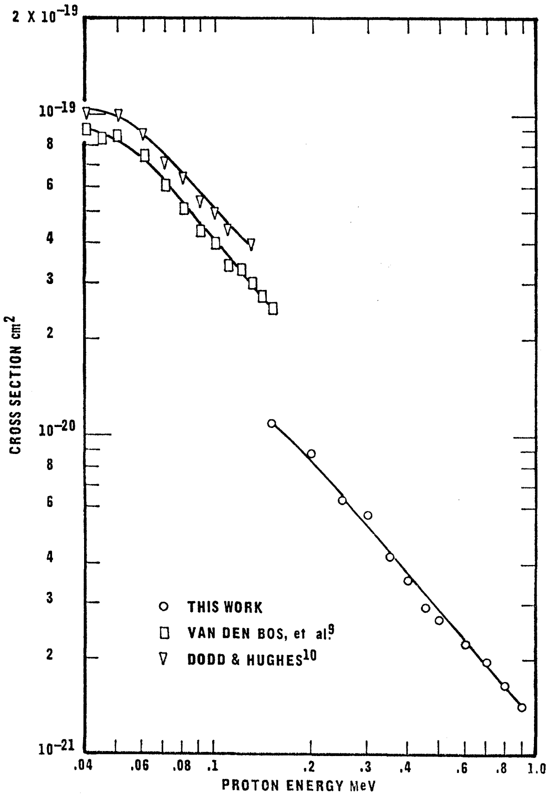

FIG. 7. Cross section for the emission of the He II 4686 Å ($n=4 \rightarrow n=3$) spectral line, induced by the impact of protons on a neutral helium target.

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[17] A. V. Phelps, Phys. Rev. **110**, 1362 (1958).

IX. THE EXCITATION OF THE HELIUM ION

The formation of the helium ion in an excited state may occur either as a result of charge transfer or ionization, and the present measurements are unable to separate these contributions. Also, the levels of a given principal quantum number all lie so close together that a group of transitions involving the same principal quantum number n but different angular quantum numbers l cannot be separated. Consequently, it is not readily possible to derive excitation cross sections from the measured emission functions. The present data on the formation of the excited helium ion are restricted to the measurement of the emission function of the $n=4 \rightarrow n=3$ (4686 Å) transition. The data are left in the form of a cross section for the emission of the spectral line and are shown compared with data from other sources on Fig. 7.

X. SUMMARY

The present work has provided a series of measurements of emission functions which have been used to calculate cross sections for the formation of various singlet excited states in a neutral helium target by proton impact. A single measurement of an emission function of a helium-ion line is also presented. The present work shows reasonable agreement with other published data for the relative magnitudes of cross sections for populating any one series of levels, and also of the energy dependence for such cross sections. However, there are some considerable discrepancies between absolute magnitudes. The calibration of the detection efficiency of the optical system is the most likely source of error in an experiment of this type. Such an error would be expected to cause a systematic difference between all measurements emanating from two separate determinations since the relative magnitudes of cross sections will not be greatly effected by errors in emissive power or geometrical factors. Surprisingly, the best agreement between all the available data is found in the measurement of the ^1P excitation cross sections where considerable care is necessary to assess the effects of resonance absorption and cascade. Apart from the case of n^1P levels, where the agreement may have been fortuitous, the present data agree well with the limited series of measurements by Robinson and Gilbody,[12] and differ from those by Dodd and Hughes[10] by a consistent factor of 150%. We have also observed that our unpublished measurements on certain other collisional excitation processes disagree with those obtained by co-workers of Dodd by a similar amount. The work of Van den Bos *et al.*[9] on the excitation of ^1S and ^1D states differs consistently from the present work by approximately 100%.

General theoretical considerations suggest that at sufficiently high impact velocities, electron and proton impact excitation cross sections should be the same. Although there are considerable differences between the magnitudes of the available data, a comparison of the velocity dependencies is instructive. We note that although electron and proton impact experiments give the same velocity dependence for the excitation of the n^1P and n^1D levels over most of the velocity range available to the present experiment, agreement in the case of the n^1S levels is not established.

In a following paper[2] comparisons are made with available theoretical predictions. Good agreement is found between the present experiment and distortion approximation calculations of the cross section for forming the ^1P excited state. Born-approximation calculations of cross sections for the formation of the ^1S and ^1D excited states are expected to be of poor accuracy due to the difficulty of choosing a suitable wave function, but agreement with experiment is found within the quoted limits of possible error.

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