Production of Lyman Alpha Radiation in Ion-Atom Collisions*

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The absolute cross section as a function of incident ion energy has been measured for the production of Lyman alpha radiation (using an O_2-filtered, iodine-filled Geiger counter as a detector) when ions impact on gases. The principal reactant pairs studied were: (He^+,H_2), (H_2^+,He), (H^+,He), (H^+,H_2), and (H_2^+,H_2) in the energy range from about 100 to 6500 eV. Reaction mechanisms are discussed for each case. The data are found in most cases to agree qualitatively with the adiabatic hypothesis of Massey. Cross sections also were measured for the production of countable ultraviolet radiation with the following reactant pairs: (H_3^+,H_2), (H_3^+,He), (H^+,N_2), (H_2^+,N_2), (H_3^+,N_2), and (He^+,N_2). No mechanisms are proposed for these cases. In an auxiliary experiment, the probability for producing ultraviolet radiation when H^+ and H_2^+ impinge on a metal surface was measured to be about 0.005 photon/ion.

INTRODUCTION

THIS paper reports measurements of absolute cross sections for the production of Lyman alpha radiation for a number of ion-gas collision partners. Ion energies ranged from about 100 to 6500 eV. The ion-gas combinations studied were (He^+-H_2), (H_2^+-He), (H^+-He), (H^+-H_2), ($H_2^+-H_2$), ($H_3^+-H_2$), (H_3^+-He), and (H^+, H_2^+, H_3^+, He^+-N_2). For each combination, (X^+-Y); the process studied was $X^++Y\rightarrow(\quad)$ +photon, where the photon has a wavelength of 1215.7 Å or other ultraviolet wavelengths as discussed in the section under Detector.

EXPERIMENTAL METHOD

A schematic diagram of the apparatus is shown in Fig. 1.[1] A ribbon beam of variable energy, mass-analyzed ions is focused into a collision region above which is an iodine-filled, oxygen-filtered Geiger counter similar to that described by Brackmann, Fite, and Hagen.[2] Ultraviolet photons of selected wavelength are counted by the counter-scalar combination. An electron gun is placed such that a beam of electrons can be introduced at right angles to but in the plane of the ion beam and such that the electron beam presents the same geometry to the counter as the ion beam. Counts of the uv radiation from the interaction of electrons and H_2 were referred to the absolute cross sections for the process as published by Fite and Brackmann,[3] and a comparison made with counts resulting from the interaction of ions with a gas. For equal ion and electron currents the cross section for the production of countable ultraviolet light was computed from the relation[1]

$$\sigma=\frac{N_+}{N_e}\sigma_{\text{cuv}}\frac{i_h}{\xi i_g}\left(\frac{N_1N_{20}}{N_2N_{10}}\right)\exp[-k_{L\alpha}(x_2-x_1)], \qquad (1)$$

where N_+ is the number of counts from ion-gas collisions, N_e is the number of counts from electron-H_2 collisions, σ_{cuv} is the cross section measured by Fite for countable uv production in electron-H_2 collisions, i_h is the ion gauge current reading when electrons are used to bombard H_2, i_g is the ion gauge current when ions are bombarding gas of type g, ξ is the ratio of the sensitivity of the ion gauge to g compared with that for H_2, N_1 and N_2 are the count rates when electrons are bombarding H_2 and when path lengths of 1 cm and 2 cm, respectively, of oxygen at atmospheric pressure are used for a filter, N_{10} and N_{20} are the count rates when electrons are bombarding H_2 and when the filter path lengths of 1 cm and 2 cm are evacuated, $k_{L\alpha}$ is the absorption coefficient per cm at Lyman alpha of oxygen at atmospheric pressure and, for these conditions, $x_2-x_1=1$ cm. The quantity in parentheses is a correction required because the ion-gas data and the initial electron-H_2 data were taken with a 1-cm path length of oxygen at atmospheric pressure in the filter; whereas Fite and Brackmann used a 2-cm path of oxygen at atmospheric pressure. If the spectral distributions of radiation from

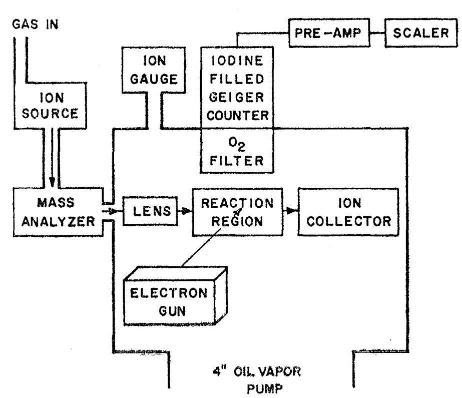

FIG. 1. Experimental arrangement.

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[1] Details of the apparatus may be found in Chap. 3 of a thesis by G. H. Dunn (unpublished).

[2] R. T. Brackmann, W. L. Fite, and K. E. Hagen, Rev. Sci. Instr. **29**, 125 (1958).

[3] W. L. Fite and R. T. Brackmann, Phys. Rev. **112**, 1151 (1958).

ion impact and electron impact were identical this correction would be unnecessary. The correction amounts to about 10%.

Figure 2 shows a comparison of the cross sections for the process, $e+H_2 \rightarrow$ countable ultraviolet, measured in this experiment with results obtained by Fite and Brackmann. Data of the present experiment are normalized to theirs at 100 eV electron energy. Both detectors observed photons at 90° with respect to the electron beam. It is seen that agreement is sufficiently close to justify the calibration procedure outlined above.

Pressures in the experiment were between 10^{-6} and 10^{-5} mm Hg and ion and electron currents were between 10^{-7} and 10^{-6} A. Signals were shown to be linear with pressure and with current, thus indicating the relative unimportance of secondary processes.

THE DETECTOR

The discriminatory action of the counter-filter has been described by Brackmann, Fite, and Hagen.[2] The counter itself is sensitive to wavelengths between

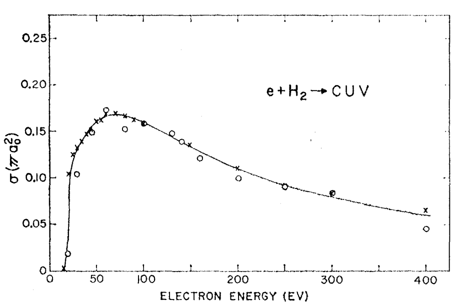


FIG. 2. Cross section for $e+H_2 \rightarrow$ countable uv. Circles represent the data of reference 3; crosses are the measurements of the present authors.

1080 Å, the transmission cutoff of the lithium fluoride windows, and about 1317 Å, the photoionization threshold for I_2. Between these limits oxygen is strongly absorbing except at seven narrow transmission windows[4] at 1108, 1127, 1143, 1157, 1167, 1187, and 1216 Å (Lyman alpha). The counter filter is thus sensitive only to wavelengths lying in these windows.

To discriminate among the seven windows to which the detector is sensitive, it is necessary to couple a knowledge of the counter-filter characteristics with reasoning based on properties of the emitting systems in a particular experiment. The major portion of the results reported here involve collisions between helium-hydrogen or hydrogen-hydrogen systems. The possible emitters thus are excited states of He, He^+, H_2, H_2^+, and H.

The helium atom has no detectable lines. He^+ has a line essentially at Lyman alpha corresponding to the Balmer beta line of its spectrum. Because no signal was

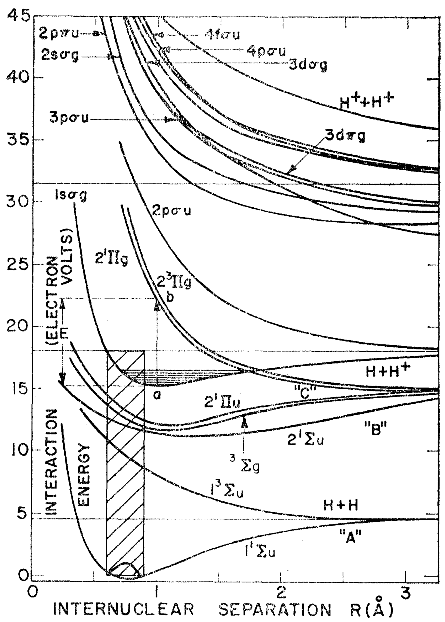


FIG. 3. Electronic states of H_2 and H_2^+ relevant to this paper.

observed in collisions of He^+ on He at energies up to 5 keV, we are led to consider He^+ radiation as an inconsequential contribution to the observations.

The hydrogen molecule has a number of repulsive excited states such as the $2\,^1\Pi_g$ and $2\,^3\Pi_g$ states shown in Fig. 3 as calculated by Kemble and Zener.[5] These two particular states separate into a normal and an excited H atom in the $2p$ state. Such repulsive states, thus, are possible sources of detectable radiation—the Lyman alpha from the excited H atoms. The molecule also has bound states ($2\,^1\Pi_u$ or C state and $2\,^1\Sigma_u$ or B state as shown in Fig. 3) which can radiate to the ground state of the molecule. Much of this radiation is detectable by the counter filter. Particular lines falling in the transmission windows of O_2 begin and end in definite vibrational states. Thus, a line at the 1108 Å window is the $B_0 \rightarrow A_0$ transition.[6] The $C_1 \rightarrow A_3$ transition gives a line at 1144 Å and O_2 has a window minimum at 1143 Å. Similarly, $C_1 \rightarrow A_5$ is at 1159 Å compared to the window at 1157 Å. Indeed, the rotational structure adds enough transitions that a line may be found at each of the seven oxygen windows. However, for the same reasons hundreds of lines fall between 1080 and 1317 Å, the wavelength response interval of the counter without the oxygen filter. One might thus expect that if there were significant excitation of all or most relevant molecular states, evacuation of the filter would yield a very marked increase in the count rate observed. A large effect has not been found, however.

The count rate with the filter evacuated is approxi-

[4] K. Watanabe, *Advances in Geophysics* (Academic Press Inc., New York, 1958), Vol. 5, p. 153.

[5] E. C. Kemble and C. Zener, Phys. Rev. **33**, 512 (1929).

[6] O. W. Richardson, *Molecular Hydrogen and Its Spectrum* (Yale University Press, New Haven, 1934).

mately twice as great as with O_2 in the filter at atmospheric pressure. If one extrapolates Watanabe's[4] curve for the absorption coefficient of O_2 at Lyman alpha to atmospheric pressure, he finds that the expected attenuation of Lyman alpha by our filter is 1.95. This is taken as evidence that transitions from the B and C states of H_2 do not contribute appreciably to the observations.

Figure 3 shows a number of the excited states of H_2^+ as calculated by Bates, Ledsham, and Stewart.[7] Of these only two are bound; the remaining states separate into a hydrogen atom and a proton. Thus, the $3d\sigma_g$ and $2p\pi_u$ states are bound with 1.36 and 0.26 eV, respectively. Because of the selection rule forbidding $\Sigma_g \rightarrow \Sigma_g$ transitions by dipole radiation, the $3d\sigma_g$ state can make transitions only to the $2p\sigma_u$ state. Such transitions will result in wavelengths too long to be observed by the counter filter. The transition $2p\pi_u \rightarrow 2p\sigma_u$ is forbidden, but $2p\pi_u \rightarrow 1s\sigma_g$ is allowed. The Franck-Condon principle requires that, because of the large internuclear separations for which the $2p\pi_u$ state is bound, only vibrational levels of $1s\sigma_g$ with $v \geq 10$ will be involved in the radiative transitions. A Morse potential was fitted to the $2p\pi_u$ potential curve and the vibrational levels were determined. Coupling this with a knowledge of the vibrational levels of the $1s\sigma_g$ state determined by Cohen, Hiskes, and Riddell[8] and specifying the width of the oxygen filter windows as 5 Å, one finds that there are five observable transitions in the 1167 Å window, nine in the 1187 Å window, and twenty-three in the 1216 Å window. No transitions fall within any of the other windows. However, about 160 transitions lie within the detectability limits of the counter with an evacuated filter. Thus from H_2^+ one might expect to detect a large intensity increase when the filter is evacuated. As noted above, this effect was experimentally found to be about 2:1, so bound H_2^+ seems to be an unlikely contributor to the observations.

Excited hydrogen atoms result from excited repulsive states of H_2 and of H_2^+. Radiation from the $2p$ state of H falls directly in the O_2 filter window at 1216 Å and is detectable. Atoms formed in the $2s$ state will pass from the observation region before being deactivated by collisions with gas, walls, or by stray fields and thus will escape detection.

In summary, there is reasonable evidence that the main contribution to the radiation observed in these experiments comes from the decay of hydrogen atoms from the $2p$ to the $1s$ state, in short, Lyman alpha.

One further limitation of the detector should be pointed out. In a number of cases (see proposed reactions under Results) the emitting system may be moving. Since the counter subtends a finite solid angle at the reaction region, some radiation will enter the counter filter at angles less than 90° and will be Doppler shifted to an extent dependent upon the particle energy and the angle. The discriminatory action of the filter may allow this effect to introduce a spurious energy dependence into the measured cross sections. An estimate[1] of magnitude of the effect indicates, however, that at the energies used in these experiments it is negligible, although at higher energies (30 keV) a 20% attenuation of Lyman alpha may be expected. The unimportance of the effect in the present experiments was demonstrated by baffling the counter so that only radiation arriving at angles successively closer to 90° could enter the counter. No detectable effect was found.

SURFACE EFFECTS

It was observed during the experiment that hydrogenic ions from the beam which struck a metal surface in the field of view of the counter gave off profuse amounts of countable ultraviolet light. If charge exchange followed by migration of the slow product ions to the wall produced such radiation in large enough proportions, it would be possible to completely misinterpret the results of the experiment. To assure ourselves that this effect was not important, we applied electric and magnetic fields in the collision region. No alteration of count rate was observed.

An estimate of the magnitude of countable ultraviolet production by ion impact on metal surfaces was obtained experimentally as follows. A 100-mesh gauze of 0.0008-in. W wire was mounted perpendicular to the ion beam directly beneath the counter. From knowledge of the geometric opacity of the gauze and the predetermined over-all sensitivity of the detector, it was found that within a factor of two, 0.005 photon is produced per ion hitting the surface for ions of energy between 200 and 2500 eV. This is about 10^4 times the predictions of Shekhter[9] who showed that the probability of neutralization of an ion near a metal surface accompanied by radiation is about 5×10^{-7}. Since the calculations refer to a clean surface, while the surface in our experiment was covered with a layer of gas, the discrepancy might possibly be accounted for.

To avoid contributions from extraneous light emanating from other parts of the apparatus, the surfaces of the collision chamber were coated with "gold black."[10] This coating, made up of minute gold particles, has a nominal reflectivity less than 0.5%.

RESULTS

All cross sections are presented in units of πa_0^2, where a_0 is the radius of the first Bohr orbit of hydrogen, i.e., $\pi a_0^2 \simeq 0.88\times 10^{-16}$ cm^2. Ion energies are laboratory energies and are given in keV.

[7] D. R Bates, K. Ledsham, and A. L. Stewart, Phil. Trans. Roy. Soc. London **A246**, 215 (1954).

[8] S. Cohen, J. R. Hiskes, R. J. Riddell, Jr., Phys. Rev. **119**, 1025 (1960).

[9] S. S. Shekhter, J. Exptl. Theoret. Phys. (U.S.S.R.) **7**, 750 (1937).

[10] L. Harris and J. K. Beasley, J. Opt. Soc. Am. **42**, 134 (1952).

A. He^+ on H_2

The mechanisms which could give rise to countable photons and their respective energy defects[11] are:

(1) $He^+ + H_2 \rightarrow He + H^+ + H^*$, $\Delta E_\infty = 3.5$ eV

(2) $He^+ + H_2 \rightarrow HeH^+ + H^*$, $\Delta E_\infty = 1.5$ eV

(3) $He^+ + H_2 \rightarrow He^+ + H + H^*$, $\Delta E_\infty = 14.5$ eV

(4) $He^+ + H_2 \rightarrow He^+ + H_2^*(B \text{ or } C)$, $\Delta E_\infty = 11.5$ eV

(5) $He^+ + H_2 \rightarrow (He^+)^*(4l) + H_2$, $\Delta E_\infty = 51$ eV.

Mechanisms 4 and 5 are excluded on the basis of the discussion in the section under Detector. That an appreciable contribution from mechanism 3 is unlikely follows from a simple application of the adiabatic hypothesis,[12] which for the large energy transfer necessary and for values of the interaction distance as low as 1 Å predicts a maximum cross section at an energy at least an order of magnitude higher than the observed peak in Fig. 4. Cross sections for reactions similar to mechanism 2 have been measured by other workers.[13,14] Momentum transfer reactions of this kind have been shown to decrease with increasing energy in contrast to the structure of the curve in Fig. 4. Moreover, the similarity in shape between the observed cross section for Lyman alpha and the total charge-exchange cross section found by Hasted,[15] reproduced in Fig. 4, is too striking to be coincidental. We conclude that mechanism 1 is the principal source of Lyman alpha in the present experiment. Hasted interpreted his cross section tentatively as due to charge exchange to the $2p\sigma_u$ state of H_2^+ (Fig. 3) which dissociates without radiation. The production of Lyman alpha in the present experiment strongly suggests that the radiating atoms come from antibonding excited states of the molecular ion. The H^* produced through mechanism 1 could only be observed when $H^* \equiv H(2p)$. When $H^* \equiv H(2s)$ the metastable atom would travel on in the beam without being detected. If the cross section for producing $H(2s)$ is comparable with that shown for obtaining $H(2p)$, then the two cross sections added together might account for the total charge-exchange cross section.

As a consistency check on our above interpretation, Ar^{++} ions were used to bombard H_2. The reaction analogous to mechanism 1 is $Ar^{++} + H_2 \rightarrow Ar^+ + H^+ + H^*$, with an energy decrement of only 0.2 eV. The adiabatic hypothesis predicts that the cross section should peak at about 11 eV (based on an interaction distance of 1.5 Å, as the later discussion suggests for the $He^+ - H_2$ data). Figure 5 shows the results of this measurement which apparently are consistent with the interpretation put forward. The Ar^{++} measurements were afflicted with a poor signal-to-noise ratio, and the calibration of the absolute cross section was referred to detector efficiencies derived from the other cross-section measurements. The results are presented only to corroborate our interpretation that mechanism 1 is the principal source of Lyman alpha when He^+ bombards H_2.

In addition to Hasted's measurement of total charge exchange between He^+ and H_2, the measurements of Gustafsson and Lindholm[16] should be discussed. These authors bombarded H_2 with He^+ and Ar^{++} and examined the charged fragments. In both cases they found a cross section for producing H^+ which was of the order of $0.023\pi a_0^2$. They point out, however, that their apparatus discriminates strongly against fragments with kinetic energy and suggest that the cross section could be considerably larger. The mechanism suggested

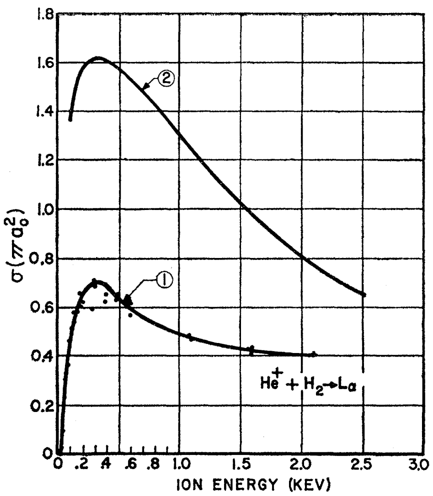


FIG. 4. Curve 1: Data from the present experiment for the production of Lyman alpha by He^+ ions bombarding H_2. Curve 2: Data from Hasted (reference 15) for the total charge transfer cross section of He^+ ions bombarding H_2.

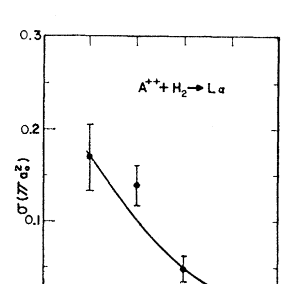


FIG. 5. Cross section for the production of Lyman alpha by Ar^{++} ions bombarding H_2 as measured in the present work.

[11] The energy defect used here is the difference between the internal energies of the initial and final states of the system at infinite separation. However, the probability of a charge exchange process will depend on details of the potential energy function of the ion-neutral system. Use of the energy defect so defined is an oversimplification justified principally because it can be ascertained and it has proved helpful in classifying charge-exchange reactions.

[12] H. S. W. Massey, Repts. Progr. Phys. **12**, 248 (1949).

[13] D. O. Schissler and D. P. Stevenson, J. Chem. Phys. **23**, 1353 (1955); **24**, 926 (1956).

[14] H. H. Gutbier, Z. Naturforsch. **12a**, 499 (1956).

[15] J. B. H. Stedeford and J. B. Hasted, Proc. Roy. Soc. (London) **A227**, 474 (1954), Fig. 6.

[16] E. Gustafsson and E. Lindholm, Arkiv Fysik **18**, 219 (1960).

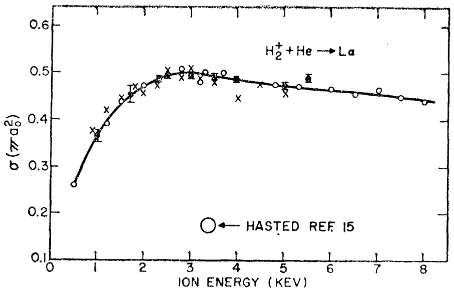


FIG. 6. Cross section for the production of Lyman alpha by H_2^+ ions on He. The lowest circle is the sole datum in this energy range given by reference 15 for H_2^+ on He.

by the present experiments does yield protons with kinetic energy and the cross section measured here (and in Hasted's experiment) is more than ten times that measured by Lindholm.

B. H_2^+ on He

The mechanisms to consider for this pair of reactants are:

(1) $H_2^+ + He \rightarrow H^+ + H^* + He$, $\Delta E_\infty = 11.25$ eV

(2) $H_2^+ + He \rightarrow HeH^+ + H^*$, $\Delta E_\infty = 9.25$ eV

(3) $H_2^+ + He \rightarrow H + H^* + He^+$, $\Delta E_\infty = 22.5$ eV

(4) $H_2^+ + He \rightarrow H_2^*(C \text{ or } D) + He^+$, $\Delta E_\infty = 20$ eV.

Figure 6 shows the measured cross section. The results of four runs are given by the open circles. The solid circles represent averages taken when ion energies were duplicated and error bars indicate the spread. Points plotted as crosses represent data taken with the chamber and counter baffled to eliminate any influence from Doppler shift.

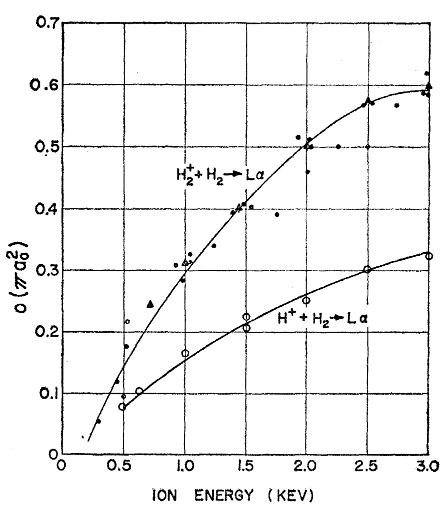


FIG. 7. Cross sections for production of Lyman alpha when H_2 is bombarded by H^+ and by H_2^+.

The open circle of Fig. 6 is taken from the cross section for total charge exchange as measured by Stedeford and Hasted.[15] The fact that the total charge-exchange cross section is smaller by a factor of 5 or 6 than the cross section measured here suggests that mechanisms 3 and 4 are relatively unimportant. This conclusion is consistent with the adiabatic hypothesis and with the conclusions reached in the discussion under Detector.

Mechanism 2 can be ruled out here by the same reasoning used in the case of mechanism A2, leaving mechanism 1 to account for the observations. It is to be noted that the end products for B1 are the same as for A1.

C. H^+ on He

The only mechanism giving observable radiation in this case is $H^+ + He \rightarrow H^* + He^+$ with $\Delta E_\infty = 21.1$ eV. Because of experimental difficulties, this cross section was measured at only one energy, 2800 eV, where its value was found to be $0.016\pi a_0^2$. Apparatus modifications are in progress which should allow measurement over the energy range 1 to 30 keV.

D. H^+, H_2^+, on H_2

Figure 7 shows the measured cross sections for these processes. The mechanisms most likely to contribute to the observations are thought to be the following. With H^+:

(1) $H^+ + H_2 \rightarrow H^* + H_2^+$, $\Delta E_\infty = 11.9$ eV,

(2) $H^+ + H_2 \rightarrow H^* + H^+ + H$, $\Delta E_\infty = 14.6$ eV,

(3) $H^+ + H_2 \rightarrow H^+ + H + H^*$, $\Delta E_\infty = 14.6$ eV,

(4) $H^+ + H_2 \rightarrow H + H^+ + H^*$, $\Delta E_\infty = 14.6$ eV.

With H_2^+:

(1) $H_2^+ + H_2 \rightarrow H + H^* + H_2^+$, $\Delta E_\infty = 13.3$ eV,

(2) $H_2^+ + H_2 \rightarrow H^+ + H^* + H_2$, $\Delta E_\infty = 11.3$ eV,

(3) $H_2^+ + H_2 \rightarrow H_2 + H^+ + H^*$, $\Delta E_\infty = 11.3$ eV,

(4) $H_2^+ + H_2 \rightarrow H_2^+ + H + H^*$, $\Delta E_\infty = 13.3$ eV.

With the present apparatus there is no way of resolving the relative contributions of these mechanisms. However, if one notes the small cross section for radiation when helium is bombarded by protons and the result of Carleton and Lawrence[17] for the process $H^+ + N_2 \rightarrow H^* + N_2^+$, where H^* radiates Balmer beta, it is reasonable to suppose that mechanisms 1 and 2 are relatively unimportant when protons are the bombarding particles. In contrast, however, when the bombarding particle is H_2^+ mechanism 1 is a dissociative charge exchange and mechanism 2 is a dissociation of the

[17] N. P. Carleton and T. R. Lawrence, Phys. Rev. **109**, 1159 (1958).

primary ion. There is independent evidence suggesting that mechanism 2 has a large cross section.[18] If more mechanisms contribute in the latter case than in the former, one may conjecture that the measured cross section for H_2^+ on H_2 should be larger than that for H^+ on H_2.

E. H_3^+ on H_2 and on He

Figures 8 and 9 show the results when H_3^+ is incident on H_2 and He, respectively. No attempt has been made to write down all the possible mechanisms for these cases. The arguments pertaining to the relative unimportance of bound excited states of H_2 and H_2^+ are not applicable here, since relative measurements with evacuated and O_2 filters were not made.

F. Ions on N_2

Figure 10 shows the cross section for the production of countable ultraviolet radiation when H^+, H_2^+, He^+,

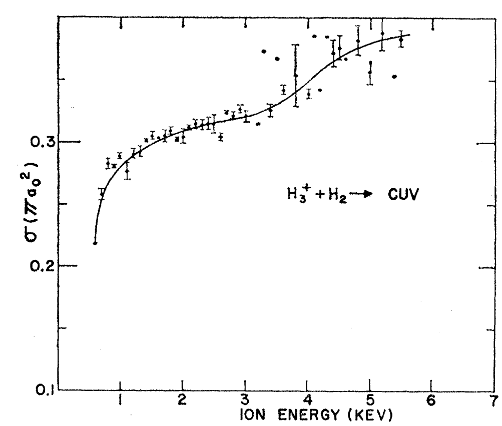


FIG. 8. Cross section for production of countable ultraviolet when H_3^+ bombards H_2.

and H_3^+ are incident on N_2. In all cases the radiation may fall within any of the seven O_2 windows, since both N and N_2 have lines in all of them. No relative intensity measurements between an evacuated and an O_2 filled filter were made for these cases. No tentative mechanisms are proposed.

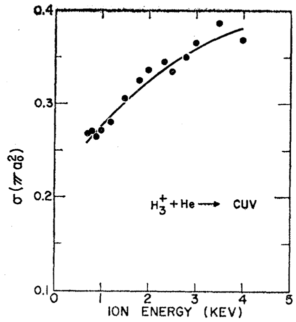
DISCUSSION

Of the processes examined here the only one for which quantum mechanical calculations of the cross section exist is for the case of protons on helium. Mapleton's[19] calculations, however, do not extend to the energy at which our single measurement was made.

One can examine the results from the standpoint of the adiabatic hypothesis put forth by Massey.[12] He suggests that when in an atomic collision the bombard-

[18] N. V. Fedorenko, V. V. Afromisov, R. N. Il'in, and D. M. Kaninker, J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 385 (1958).
[19] R. A. Mapleton, Phys. Rev. **122**, 528 (1961).

FIG. 9. Cross section for production of countable ultraviolet when H_3^+ bombards He.



ing particle approaches slowly enough for the electronic motion to adjust itself to the perturbation, a transition will be unlikely; and when the collision and transition times become comparable, the probability for a transition will be highest. Thus, one writes the familiar statement of the adiabatic condition, namely, that the cross section is small when

$$hv/a\Delta E_\infty \ll 1, \tag{2}$$

and the adiabatic maximum rule that the cross section is a maximum when

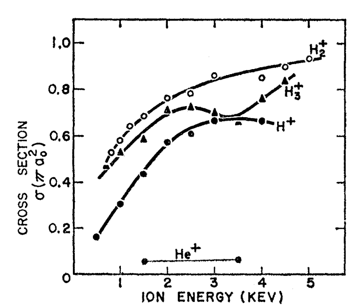
$$hv/a\Delta E_\infty \approx 1. \tag{3}$$

Here v is the relative velocity, a is the interaction distance, on the order of atomic dimensions, and ΔE_∞ is the difference in internal energies of the initial and final states of the system. Although these intuitive ideas do not have the sanction of a firm theoretical foundation, they are the only guides presently available and they have been shown to correlate a surprising amount of diverse data.

Thus, for example, Hasted,[20] and Hasted and Lee[21] have classified a large number of charge-exchange processes by using the above maximum rule to calculate the interaction distance, a. They find that, for most cases, this distance is about 8 Å. Hasted[20] notes that most cross sections for charge exchange rise in the adiabatic region according to an exponential of the form,

$$\sigma = \sigma_0 \exp[-K/E^{1/2}], \tag{4}$$

FIG. 10. Cross section for production of countable ultraviolet when various ions bombard N_2.



[20] J. B. Hasted, *Advances in Electronics and Electron Physics* (Academic Press Inc., New York, 1960), Vol. XIII, p. 1.
[21] J. B. Hasted and A. R. Lee, Proc. Phys. Soc. (London) **79**, 702 (1962).

TABLE I. Application of the adiabatic hypothesis to the experimental results.

Process	Constants for Eq. (4) σ_0 (πa_0^2)	K $(\mathrm{eV})^{1/2}$	ΔE_∞ (eV)	E_{max} (eV)	a from Eq. (3) (Å)	a from Eq. (4) (Å)
$He^+ + H_2 \rightarrow He + H^+ + H^*$	1.2[a]	5.7[a]	3.5	300	1.4	3
$H_2^+ + He \rightarrow He + H^+ + H^*$	0.94	25	11.3	2800	1.9	3.6
$H_2^+ + H_2 \rightarrow H + H^* + H_2$			13.3			
$\rightarrow H^+ + H^* + H_2$	1.43	34	11.3			6
$\rightarrow H_2 + H^+ + H^*$			11.3			
$\rightarrow H_2^+ + H + H^*$			13.3			
$H^+ + H_2 \rightarrow H^* + H_2^+$			11.4			
$\rightarrow H^* + H^+ + H$	0.83	41	14.6			7.5
$\rightarrow H^+ + H + H^*$			14.6			
$\rightarrow H + H^+ + H^*$			14.6			

[a] In this adiabatic region the ion beam energy spread introduces considerable uncertainty about these constants.

where $K = ka(\Delta E_\infty m^{1/2})$. His plots of K against $(\Delta E_\infty m^{1/2})$ give straight lines, indicating that ka is constant. If one further assumes that k is constant, a second measure of a is obtained. Using this method he again finds interaction distances of about 8 Å.

Some of the present data are found to follow an exponential rate of rise in the adiabatic region. The solid curves in Fig. 7 and the solid curves to the left of the maxima in Fig. 4 and in Fig. 6 are drawn from an exponential of the form cited. The interaction distance a has been calculated from the adiabatic maximum rule and also from the exponential rate of rise. Numerical values are given in Table I. The values of a for the cases involving helium are considerably smaller than those found by Hasted for most charge-exchange processes. Interaction distances found from the adiabatic maximum rule are only about half as large as those derived from the exponential rate of rise. The values of a when both reactants are hydrogenic in nature are near 8 Å as found by Hasted. If the suggested mechanisms for He^+ on H_2 and H_2^+ on He are, indeed, correct, and if there is some physical significance to the magnitude of a one is tempted to wonder whether the two reactions, generating identical products from an encounter which seems closer than ordinary, proceed through a "compound" intermediate state.

TABLE II. Comparison of cross sections at 2 keV for Lyman alpha and Balmer alpha production. All values are relative.

Incident ion \ Target gas	He	H_2
H^+	1[a]	30[a]
	1.5	30
H_2^+	60[a]	60[a]
	52	54

[a] Values taken from reference 22.

It is possible to compare relative cross sections at 2000 eV for some of the processes measured here with the relative cross sections at 2000 eV for production of Balmer alpha as measured by Dieterich.[22] This comparison is shown in Table II. One sees that the relative effectiveness of a given ion on a given gas is about the same for Balmer alpha as for Lyman alpha.

Fite[3] has estimated that the uncertainty in the data for $e + H_2 \rightarrow$ countable ultraviolet, the reaction used for calibration, is about $\pm 30\%$. Magnitudes in the present experiment were reproducible to within 20%, so an estimate for the uncertainty in the absolute values of the cross sections given here is about $\pm 40\%$. Polarization of the radiation emitted in these experiments is assumed to be negligible.

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[22] E. J. Dieterich, Phys. Rev. **103**, 632 (1956).