Formation of Fast Excited H Atoms Induced by Impact of H^+, H_2^+, and H_3^+ Atoms on Molecular and Noble-Gas Targets*

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An experimental investigation has been made of the formation of excited hydrogen atoms by charge-transfer neutralization of H^+ and collisional dissociation of H_2^+ and H_3^+. Data are presented for the formation of $H(3s)$ induced by H^+, H_2^+, and H_3^+ impact on the noble gases; for H_2^+ impact on H_2, D_2, N_2, and Ar, the measurements include formation of $H(3s)$ and $H(3d)$ states. Projectile energies range from 100 to 600 keV. The cross sections for producing hydrogen in the $n = 3$ states have been determined by quantitative measurement of collisionally induced Balmer-α emission. The contributions from the $3s$, $3p$, and $3d$ states were separated by a method employing the different lifetimes of each state. Data are consistent with previous measurements made at lower energies. In dissociation the cross sections are generally the same for the formation of the $3s$ and $3d$ states; they show a slow decrease as a function of projectile energy. Cross sections for formation of $H(3s)$ by charge transfer show the expected rapid decrease with increasing energy. Differences between cross sections for various target gases suggest that the internal structure of the target atom will be an important factor in any prediction of these cross sections.

I. INTRODUCTION

The processes studied in this work may be summarized by the following four reaction equations:

$$H^+ + X \rightarrow H^*(3s) + [X^+] \ , \tag{1}$$

for X = He, Ne, Ar, Kr, and Xe;

$$H_2^+ + X \rightarrow H^*(3s,\ 3p,\ 3d) + [H^+ + X] \ , \tag{2}$$

for $X = H_2$, D_2, N_2, and Ar;

$$H_2^+ + X \rightarrow H^*(3s) + [H^+ + X] \ , \tag{3}$$

for X = Ne, Ar, Kr, and Xe; and

$$H_3^+ + X \rightarrow H^*(3s) + [H_2^+ + X] \ , \tag{4}$$

for X = Ne, Ar, Kr, and Xe. The experiment yields no information on the state of excitation, ionization, or molecular association of the postcollision reaction products shown in brackets. The energies of the incident ions range from 100 to 700 keV.

The experimental technique involves quantitative measurement of the Balmer-α line emitted from the projectile beam after it has traversed a gaseous target. The Balmer-α emission results from the decay of the $3s$, $3p$, and $3d$ levels; the contributions from these three levels are separated by a time-of-flight technique based on the different lifetimes of the three contributing states.

This work is an expansion of our previous studies of these same processes.[1-3] In the previous work we studied the formation of $H(3s)$, $H(3p)$, and $H(3d)$ resulting from H^+ impact on He,[1] Ar,[1] and various molecular targets[2] (H_2, N_2, NO, O_2, CO, CO_2, CH_4, C_2H_4, C_2H_6, and C_3H_8), as well as H_2^+ and H_3^+ impact on helium.[3] The present paper extends the earlier measurements to a wider variety of cases and for H^+ on He and Ar provides a moderate extension of the projectile energy range covered in the previous work.[1]

Measurements of $H(3s)$, $H(3p)$, and $H(3d)$ formation have also been carried out by Hughes and coworkers both for the case of charge transfer[4,5] and for dissociation.[6] The work of Hughes and co-workers pioneered the time-of-flight technique that we employ here. Their work extends up to impact energies of 120 keV and may therefore be compared with the studies described here. There are also other studies of these processes at even lower energies carried out by Andreev *et al.*[7,8]; these are too low in energy to be compared with the work here but they are consistent with the studies of Hughes *et al.*[5] at intermediate energies. A detailed listing of the previous data and also measurements on the formation of other excited states of hydrogen have recently been published.[9]

II. EXPERIMENTAL METHOD

The experimental technique and apparatus used in this present investigation are identical to those reported previously. Only a brief description will be given here; the reader is referred to a preceding paper[1] for a more detailed discussion.

Projectile ions are produced and accelerated by a vertically mounted 1-MeV Van de Graaff accelerator equipped with a standard rf discharge source. The ion beam is rotated into the horizontal plane, and thus momentum analyzed, by a large electromagnet. The beam is well collimated and allowed to traverse a differentially pumped cell containing a target gas at a pressure on the order of 5×10^{-4} Torr. In this cell excited hydrogen atoms are formed by the mechanisms described by Eqs. (1)–(4).

Because of the high velocity of these atoms they suffer only negligible angular deflection. The beam, now containing an excited neutral component, enters a 1-m-long flight tube containing only background gas at a pressure of about 10^{-6} Torr. The flight tube is fitted with a long glass window which permits the observation of a small segment of the beam (0.60 cm) by a photomultiplier detector and interference filter system. A discussion of the absolute calibration of detection sensitivity for this system may be found in a previous paper.[1] The entire photon detection system is mounted outside the flight tube on a movable table. The detector can be translated automatically in order to observe the Balmer-α radiation intensity as a function of distance from the exit of the target cell. The beam ultimately enters a standard Faraday-cup arrangement located at the end of the flight tube. The current from this cup is monitored by a precision-integrating electrometer system and hence allows the determination of the incident projectile beam entering the target cell.

By monitoring the target-gas pressure and temperature it is possible to obtain, by a series of observations, the Balmer-α radiation intensity per unit length of beam, normalized to projectile flux and target density, as a function of distance from the exit of the target cell. Thus one can obtain the normalized empirical intensity function. It is then assumed that this intensity function is the sum of three exponentially decaying components characteristic of each excited hydrogenic state, $3s$, $3p$, and $3d$. Using a least-squares technique, one can mathematically decompose the empirical intensity function into the three exponentially decaying components. Knowing the geometry of the target cell one can then determine the cross section for producing each of the three states, $3s$, $3p$, and $3d$. In the present experiment the collection of data is automated; the mathematical analysis described above is carried out by a computer.

III. EXPERIMENTAL ERROR

The experiment is arranged so that the Balmer-α emission due to the interaction of the beam with the background gas in the flight tube can be measured independently at all points along the beam. This measurement takes into account a slight increase in background due to gas flowing out of the target cell. This background is carefully subtracted from the total observed Balmer-α emission at each point along the beam. For the present series of experiments discussed here, this background generally constituted less than 10% of the total Balmer-α signal. Careful consideration was also given to the removal of the intrinsic thermal noise background of the photomultiplier and any possible background arising from the production of x rays by the accelerator system.

All target gases were obtained commercially and had impurity levels less than 0.1%. The target was passed through a cold trap prior to entering the target cell. The target-gas pressure was measured to within 1% accuracy by means of a capacitance manometer. Account was taken of thermal transpiration effects. In order to determine the target density, account was also taken of a small (3–5 °C) temperature rise of target gas during a given experiment.

Errors in the measurement of beam current were always less than 1%. Errors arising from the effects of beam neutralization were assessed and generally found to be negligible.

At the energies used in this experiment the Balmer-α emission from the projectiles exhibited considerable Doppler broadening. This has the result that the detection efficiency of the system varies with the energy of the projectile beam that is being observed. This variation was taken into account by the techniques developed previously.[1,10] Possible inaccuracy in the projectile energy due to errors in the calibration of the accelerator system was always less than 2%. The effect of errors in beam energy on the accuracy of the mathematical deconvolution procedure is quite small; a detailed discussion of the analysis of this problem is given in a preceding paper.[1]

The total systematic error in any particular cross-section measurement should not exceed 16.5%. Systematic errors in the energy dependence of cross sections are probably no larger than 3–5%. Random errors in a given observation of the Balmer-α intensity were usually much less than 7%, leading to random errors in the $3s$ and $3d$ cross sections of less than 10 and 15%, respectively. A more detailed discussion of the contributing errors is to be found in our previous report.[1]

IV. FURTHER CONSIDERATIONS

A number of effects can alter the ideal form of the Balmer-α intensity function assumed in the mathematical analysis of the data. These effects can introduce errors in the cross-section measurement. A brief listing of these effects is given below and the reader is referred to our earlier reports[1–3] for a full discussion.

In the present experiment, the pressure in the target cell was always maintained sufficiently low to avoid multiple-collision events between the beam projectile and targets. If this is not done, a number of processes come into play which severely complicate the equations governing the buildup of excited atoms in the target cell. For example, a newly formed excited neutral hydrogen atom may undergo collisional destruction upon secondary impacts with the target atoms or molecules. On the other hand, a ground-state neutral may be promoted to the $n=3$ level by a subsequent collision. Although efforts have been made to make quantitative mea-

surements of such secondary effects, the problem is generally too complicated—particularly for the case of H_2^+ and H_3^+ projectiles. For the purposes of the present experiment it was only necessary to show that multiple-collision effects are negligibly small. This was accomplished by operating the experiment in a region where the observed Balmer-α signal varies very linearly with pressure. This generally requires that measurements be made with target-cell pressures between 1×10^{-4} and 5×10^{-4} Torr. Reduction of target-cell pressure much below 1×10^{-4} Torr does not provide sufficient signal strengths for accurate measurements.

Errors in determining the population of excited atoms emerging from the target cell can arise from failing to consider the inevitable pressure gradients at the entrance and exit channels of the target cell. The largest correction required is for the $3p$-state population produced by low-velocity projectiles such as 100-keV H_3^+ ions. The need for this correction is due mainly to the short decay length of slow $3p$ atoms and their resulting loss in traversing the exit channel of the target cell, where there is a target density depression.

Spurious electric and magnetic fields can alter the decay of excited states through Stark mixing. A number of tests were made to assess the effect of small electric and magnetic fields in the region where the decay of the excited hydrogen atoms is observed. It was concluded that no measurable effects could be observed for the small fields which might accidentally be present in the target cell and flight tube (e.g., Earth's magnetic field, electric fields due to charge buildup on insulating films, etc.). A more complete discussion of this problem has been given previously.[1]

Emission from the $3p$ and $3d$ states may be anisotropic due to polarization. An exact correction for this effect would require a knowledge of the populations of the m_l magnetic substates. This information could not be obtained in the present experiment. It has been shown,[10] however, that neglect of polarization will cause a maximum error of +9 to −14% in the $3p$ cross section and +11 to −16% in the $3d$ cross section.

The population of states above the $n=3$ level will surely give rise to some cascade into the $3s$, $3p$, and $3d$ states. This cascade can alter the population of states emerging from the target cell as well as introducing exponential decay terms (characteristic of the lifetimes of the higher states), giving rise to additional Balmer-α radiation. This, of course, could invalidate the simple mathematical analysis of the data. The problem of cascade has been investigated in the case of the formation of $n=3$ hydrogen atoms by the charge-transfer neutralization of H^+[1] and extended to the case of dissociation of molecular ions. In the present work, decay curves have been examined for the presence of components not characteristic of a $3s$-, $3p$-, or $3d$-state lifetime. No substantial components were found and the analysis of the data proceeded on the assumption that cascade could be neglected. Actually, cascade effects can increase the apparent size of the measured cross sections while altering the shape of the decay curve only slightly. A small variation in slope can be obscured by the random statistical fluctuations in the data. Our present analysis of cascade is not completely conclusive, but it is believed that cascade contributes an uncertainty in the cross section of no more than 5%.

It is possible that the prior collision vibrational states of the molecular projectiles play an important role in the dissociation process leading to neutral-atom formation. Variations in the ion-source operation conditions were made in an attempt to observe such effects. No dependence of apparent cross section on ion-source operating conditions was found. Recently McClure and Peek[11] have reviewed the available information on how ion-source conditions influence measured dissociation cross sections; there is little indication that the vibrational states appreciably influence dissociation cross sections at the energies used in this experiment, although there are large effects observed for collisions at a few tens of kilovolts energy. McClure and Peek[12] also point out that the Born approximation predicts that the dissociation cross section would not be greatly dependent on the initial vibrational state for the high energies used in this experiment. With all these various factors in mind we conclude that the vibrational state of excitation of the molecular projectile does not significantly influence the cross sections measured here.

V. H^+ + NOBLE GASES

A. Data

In Fig. 1 we display the cross sections for formation of $H(3s)$ by charge-transfer neutralization of H^+ in He, Ne, Ar, Kr, and Xe gases [Eq. (1)]. The data for He and Ar targets are reproduced from our previous publication[1] with additional new data points at 500 and 700 keV. For clarity the individual data points are given in Table I and they are omitted from the figure. Also shown in the figure are some previous measurements at lower energies by Hughes *et al.*[5]; these data are in good agreement with the present work.

As one would expect, the helium cross section is consistently smaller than that for the heavier atoms. If, however, the cross-section curves for the heavier atoms (Ne, Ar, Kr, and Xe) are compared, one immediately notices a number of crossings of the data curves. For example, neon gives a lower cross section than Ar, Kr, and Xe at an energy of 100 keV, but exceeds the cross sections for all

three of the heavier gases at 200 keV and drops below Kr and Xe by 700 keV. The reason for this behavior may be associated with the internal structure of the target atoms and the different excited states that may be formed in the targets.

It is interesting to compare the present data with previous measurement of cross sections for neutralization of H^+; such cross sections are essentially the sum of cross sections for formation of the hydrogen ground state plus all excited states. For example, consider the work of Toburen *et al.*[13] with targets of He, Ar, and Kr; at any given energy the relative values of total neutralization cross sections for the different gases are very similar to those exhibited by our present measurements of H(3*s*) formation. One may deduce the fraction of neutral atoms formed in the 3*s* state in a particular target simply by taking the ratio of the present cross-section data to the previous measurements of total neutralization cross sections by Toburen *et al.*[13] Doing this we find that about 4% of the H atoms are formed in the 3*s* state for energies between 100 and 300 keV while that ratio drops to 2% at 700 keV; this behavior is essentially independent of the target.

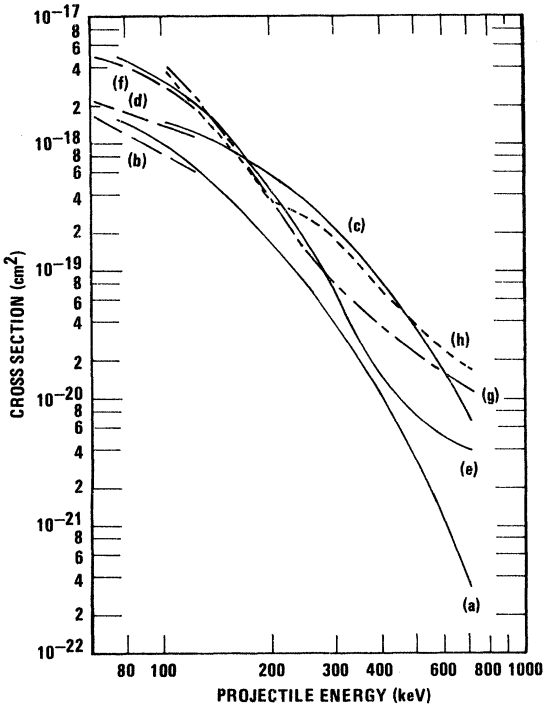

FIG. 1. Cross section for the formation of H(3*s*) by charge-transfer neutralization of H^+ in various gases. Individual data points are omitted for clarity (data points are given in Table I). (a) Present data, helium target; (b) Hughes *et al.* (Ref. 5), helium target; (c) present data, neon target; (d) Hughes *et al.* (Ref. 5), neon target; (e) present data, argon target; (f) Hughes *et al.* (Ref. 5), argon target; (g) present data, krypton target; (h) present data, xenon target.

TABLE I. Cross sections for the formation of H(3*s*) by charge-transfer neutralization of H^+ in various gases.

Energy (keV)	Cross section (10^{-20} cm^2) He	Ne	Ar	Kr	Xe
75	159[a]		462[a]		
100	107[a]	147	309[a]	412	380
125	59.5[a]		181[a]		
150	39.0[a]		106[a]		
200	15.6[a]	52.4	35.9[a]	33.7	34.5
250	7.5[a]		14.1[a]		
300	3.42[a]	22.9	6.13[a]	7.55	17.5
400	1.03[a]				
450	0.63[a]				
500	0.24	2.72	0.69	2.2	3.9
550	0.26[a]				
700	0.034	0.61	0.42	1.2	1.6

[a]Data points from our previous publication (Ref. 1).

B. Discussion

There are few theoretical predictions of cross sections for the formation of excited states by charge transfer. A detailed Born approximation for a helium target has been given by Mapleton[14] and this is in good agreement with experiment.[1]

In the absence of quantum-mechanical treatments of the charge-transfer problem it is valuable to consider use of classical methods. Garcia *et al.*[15] have discussed the classical prescriptions of Gryzinski[16] that permit an estimate of charge-transfer cross sections. In particular, Garcia *et al.* show that Gryzinski's formulation reduces to the following rather simple relationship at high projectile energies:

$$\sigma \frac{E^3\lambda^3}{U_B} = \frac{2\pi e^4}{3}\left(\frac{\lambda E}{U_A}\right)^2\left(\frac{7+3(\lambda E/U_A)}{(\lambda E/U_A+1)^2}\right) . \qquad (5)$$

Here σ is the cross section for charge transfer when a singly ionized projectile of energy E captures an electron; the binding energy of the electron in the target atom before the collision is U_A and the binding energy of the electron in the projectile atom after the collision is U_B. The factor λ is the ratio of electron mass to projectile mass. The cross section is per electron in the outer shell of the target. This relationship suggests that $\sigma(E\lambda)^3/U_B$ is a function only of $E\lambda/U_A$. Thus cross sections σ measured as a function of impact energy E for a variety of different targets may be scaled together. It has been noted[15] that this scaling prescription is very similar to the one derived by Bates and Mapleton[17] which is applicable to total cross sections for neutralization of protons in various targets. Garcia *et al.*[15] test the effectiveness

of Eq. (5) and find that it does indeed provide a scaling of various cross sections for H^+ neutralization in rare gases and in potassium vapor. It was suggested[15] that this scaling procedure should permit the prediction of unknown cross sections.

We can attempt to apply this same scaling procedure to the measured cross sections for excited hydrogen formation by charge transfer. Mapleton[18] points out that the cross section σ to be used in Eq. (5) is that for a capture process with a specific change of the electron energy and therefore includes capture into all angular-momentum substates of a given principal quantum number. Thus we will use the sum of cross sections for the formation of the $3s$, $3p$, and $3d$ levels; let us call this $\sigma(n=3)$. Figure 2 shows cross sections scaled according to Eq. (5). One axis is the quantity $\sigma(n=3)\ (E\lambda)^3/U_B$; E is the projectile impact energy (in eV), U_B the binding energy of the captured electron in the $n=3$ state of hydrogen (1.511 eV), and λ is $\frac{1}{1836}$. The horizontal axis is $E\lambda/U_A$, where U_A is the binding energy of the electron before capture; that is to say, U_A is the ionization potential of the target. It is not clear that this scaling procedure should be applicable to molecular targets but nevertheless we do include data for H_2, O_2, and N_2. In the molecular cases the cross section for the atom is assumed to be half the measured cross section for the diatomic molecule. For the molecules (H_2, O_2, and N_2) we have taken U_A to be the ionization potentials of atomic H, O, and N; there is some justification for using instead the molecular ionization potentials but this does not in fact appreciably change the plotted position of the data points. There is one further factor that must be included. The cross sections predicted by Eq. (5) are per electron in the outer shell of the target. Thus the cross sections for Ne, Ar, Kr, and Xe are for six electrons in the outer shell. The measured cross sections for He and the estimated cross sections for H, O, and N have been multiplied by factors of 3, 6, 1.5, and 2, respectively, to give the cross sections for six equivalent electrons in each case. The data plotted according to this prescription in Fig. 2 have been obtained from three sources. There is the work of Hughes *et al.*[5] at energies up to 120 keV for targets of He, Ne, Ar, H_2, N_2, and O_2. There is our own previous work[1,2] at energies above 75 keV for targets of He, Ne, H_2, N_2, and O_2. Finally, there are the data from the present paper for Ne, Kr, and Xe; in this case we have only the cross sections for the $3s$ level and have plotted these as $\sigma(n=3)$. Our previous work[1,2] for He, Ar, H_2, and N_2 has shown that the sum of the $3p$ and $3d$ cross sections is never greater than 50% of the $3s$ cross section at impact energies above 75 keV; if this is assumed to hold also for Ne, Kr, and Xe then our plotted data may be too low by 50% or less.

In view of crudeness of the approximations made in the derivation of Eq. (5) it is gratifying that the data points shown in Fig. 2 agree as well as they do. The scatter is certainly less than that exhibited

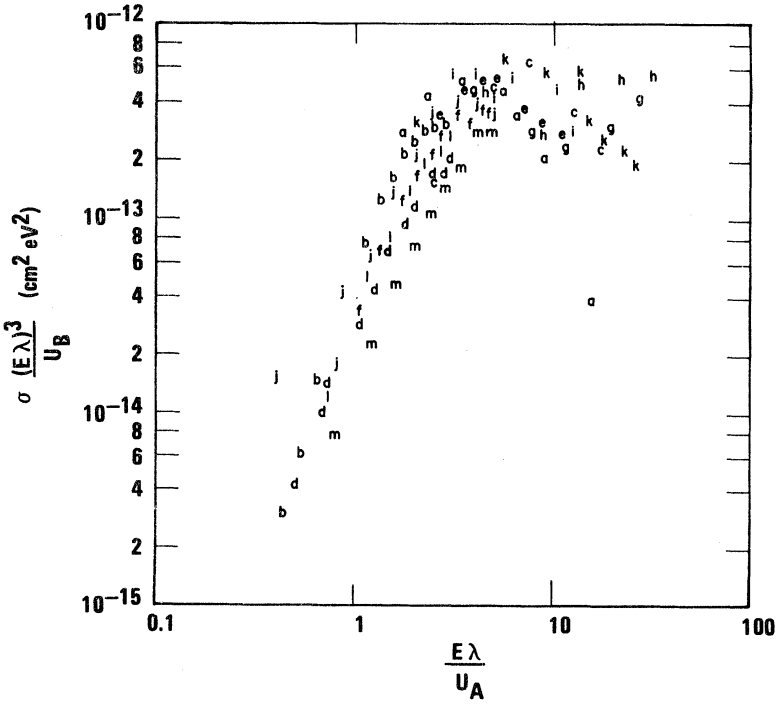

FIG. 2. Scaling of cross-section determinations using the prediction of Gryzinski; $\sigma(n=3)\ (E\lambda)^3/U_B$ shown as a function of $E\lambda/U_A$. Cross sections are for the reaction $H^+ + X \rightarrow H^+(n=3) + X^+$. The sources of data points are as follows: (a) and (e), Ford *et al.* (Ref. 1); (b) and (k), Ford *et al.* (Ref. 2); (c), (g), and (h), present data; (b), (d), (f), (j), (l), and (m), Hughes *et al.* (Ref. 5). Targets include He (a and b), Ne (c and d), Ar (e and f), Kr (g), Xe (h), H (i and j), N (h and l), and O (m).

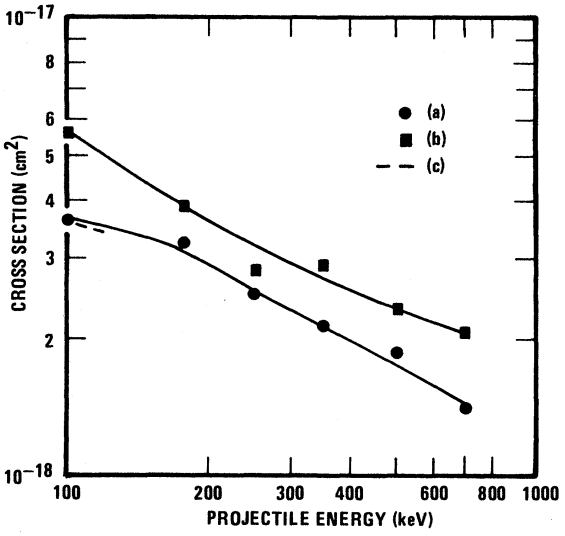

FIG. 3. Cross sections for the formation of fast H(3*s*) and H(3*d*) by collisional dissociation of H_2^+ in a H_2 target. (a) Present data for H(3*s*) formation; (b) present data for H(3*d*) formation; (c) data of Hughes *et al.* (Ref. 6), for H(3*s*) formation.

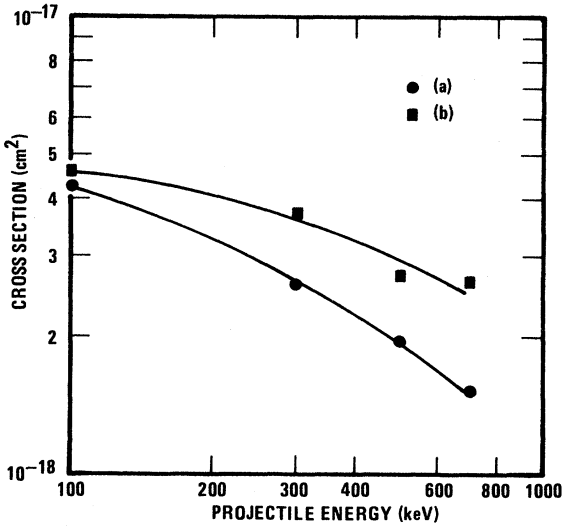

FIG. 4. Cross section for the formation of fast H(3*s*) and H(3*d*) by collisional dissociation of H_2^+ in a D_2 target. (a) H(3*s*) formation; (b) H(3*d*) formation.

when Garcia *et al.*[15] applied this scaling procedure to total cross sections. Following Garcia *et al.*[15] we would suggest that Eq. (5) may be used to scale measured cross sections in order to predict unknown cross sections for excited-state formation; the accuracy would appear to be within a factor of 3 or better.

VI. $H_2^+ + H_2, D_2, N_2$, AND Ar

For this set of reactions, described by Eq. (2), we have measured the cross sections for formation of the 3*s* and 3*d* states. Figures 3–6 show the results obtained. Lines have been drawn through the various data points; these lines are given only to show the general trend of the data and do not indicate detailed knowledge of the cross-section behavior between data points. Also shown in Figs. 3, 5, and 6 are some previous measurements by Hughes *et al.*[6] of the cross sections for formation of H(3*s*); these generally lie below the present data but the discrepancy is within the combined limits of accuracy of the two determinations.

Some data for the formation of H(3*p*) have been obtained but they are of very poor quality. The lifetime of the 3*p* level is very short and the decay takes place within a few millimeters of the gas-cell exit aperture. Thus in the decomposition of the intensity function, to get the three separate cross sections, the 3*p*-state value is based on only one or two intensity measurements very close to the gas-cell exit; moreover, the emission is only some 1% or so of the total emission intensity. As a result of these factors the statistical accuracy of the 3*p*-state data points is very poor. Our estimates of the accuracy limitations (see Sec. III) are valid for H(3*s*) and H(3*d*) but not for H(3*p*). We have chosen not to present the data points for H(3*p*)-state formation on the grounds that they are of very poor statistical reliability. Nevertheless, our measurements do indicate that the cross sections for formation of H(3*p*) in a given target are always similar to the corresponding cross sections for the formation of H(3*s*)

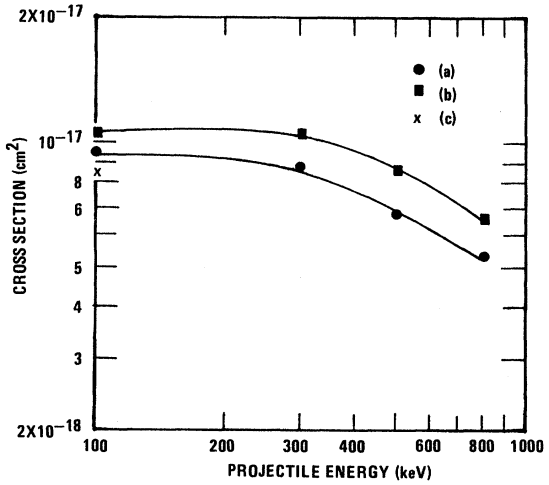

FIG. 5. Cross section for the formation of H(3*s*) and H(3*d*) by collisional dissociation of H_2^+ in a N_2 target. (a) Present data for H(3*s*) formation; (b) present data for H(3*d*) formation; (c) data of Hughes *et al.* (Ref. 6), for H(3*s*) formation.

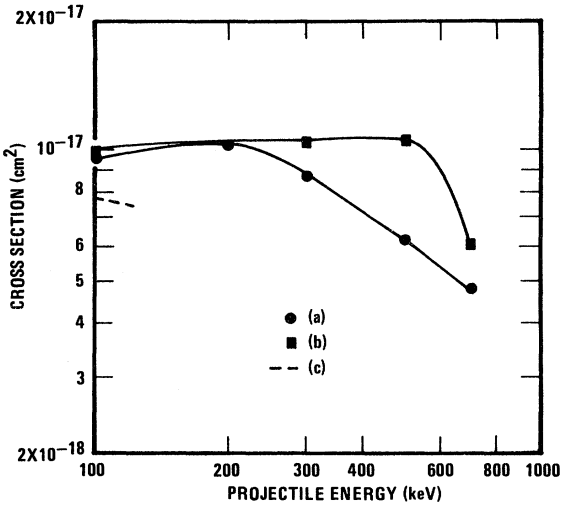

FIG. 6. Cross section for the formation of H(3s) and H(3d) by collisional dissociation of H_2^+ in an Ar target. (a) Present data for H(3s) formation; (b) present data for H(3d) formation; (c) data of Hughes *et al.* (Ref. 6) for H(3s) formation.

and H(3d) also exhibiting similar variation with impact energy.

Figures 3 and 4 show data for H_2^+ impact on targets of H_2 and D_2, respectively. Within the random error of the measurements (± 10% for the 3s state and ± 15% for the 3d state[1]) there is no significant difference between data for these two targets.

It is interesting to note that, for a given target, the behavior of the 3s-, 3p- (not shown), and 3d-state-formation cross sections is very similar. The 3d-state cross section exceeds by a small factor the 3s cross section. There are no detailed theoretical predictions with which these cross sections may be compared. The fact that the cross sections vary with the nature of the target indicates that the target structure plays an important role in the dissociation mechanism; this is probably linked to the excitation of the target during the collision.

VII. H_2^+ AND H_3^+ + NOBLE GASES

In this set of measurements, described by Eqs. (3) and (4), we present only the cross sections for the formation of H(3s). Figure 7 shows all the data for H_2^+ impact and Fig. 8 all the data for H_3^+ impact; in both cases we include data for a helium target from our previous publication.[3] The lines connecting data points are drawn to indicate the general trend of the cross sections and do not imply any detailed knowledge of cross-section behavior between data points.

There are some previous data by Hughes *et al.*[6] on these processes for impact energies up to 120 keV. These previous measurements for H_2^+ impact lie below our data but the discrepancy is just within the combined error estimates for the two sets of measurements. In the case of H_3^+ impact the data of Hughes *et al.*[6] lie as much as 50% below the present measurements. In contrast to this behavior in dissociation, the cross sections for charge transfer in noble gases measured by Hughes *et al.*[5] are in good agreement with our measurements shown in Fig. 1. It is puzzling that the data by Hughes *et al.* become progressively lower than our measurements as one goes from H^+ to H_2^+ to H_3^+ projectiles; the apparatus remains the same for all measurements and most sources of possible error should be the same in all cases.

The various cross sections generally decrease with increasing impact energy and have some indications of weak structure. A particular example is shown in Fig. 7 where cross sections for all targets drop more sharply at 300 keV than anywhere else in the energy range studied. Similar behavior at this energy was also observed by Sweetman[19] in studying the reaction

$$H_2^+ + Ar \rightarrow H^+ + H^0 + Ar \quad . \tag{6}$$

McClure and Peek[11] discuss, in general terms, the behavior of dissociation cross sections and cite other examples where such behavior occurs. It

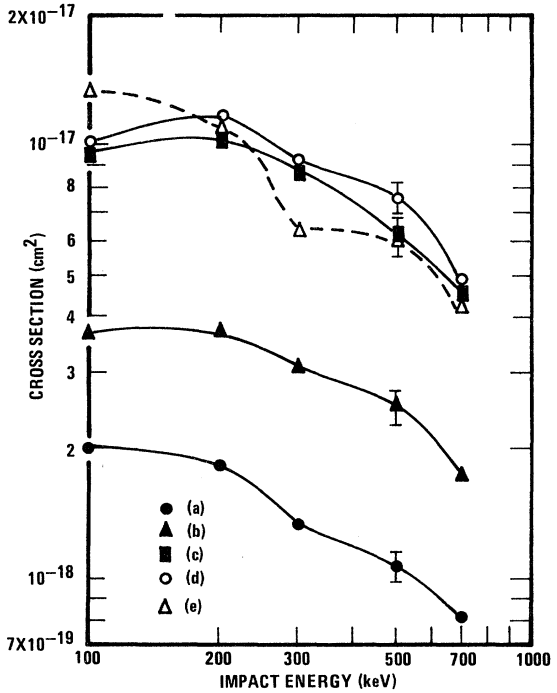

FIG. 7. Cross sections for the formation of H(3s) by collisional dissociation of H_2^+ in various noble-gas targets. Error bars on 500-keV data points indicate our estimates of maximum random error (±10%) for all data points. (a) He target (from Ref. 3); (b) Ne target; (c) Ar target; (d) Kr target; (e) Xe target.

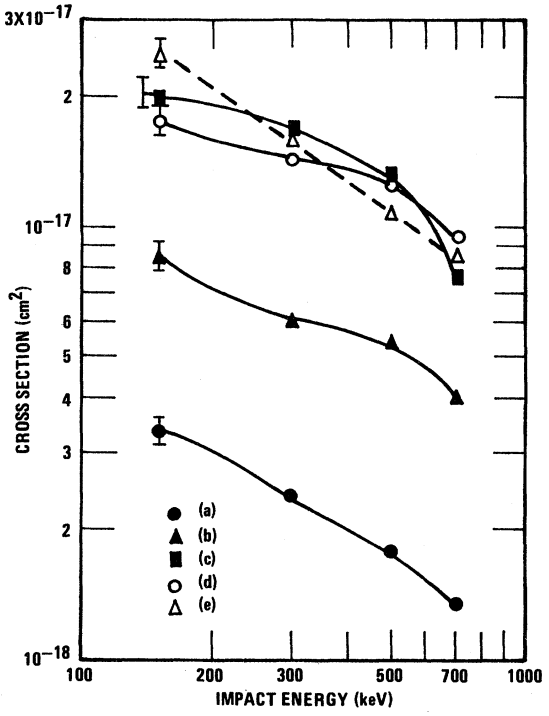

FIG. 8. Cross sections for the formation of H(3s) by collisional dissociation of H_3^+ in various noble-gas targets. Error bars on 150-keV data points indicate our estimates of maximum random error (±10%) for all data points. (a) He target (from Ref. 3); (b) Ne target; (c) Ar target; (d) Kr target; (e) Xe target.

seems likely[20] that a cross section for a single well-defined dissociation mechanism does not show such structure. In measurements like the present work, however, the detected fragment may be produced by a number of different reaction channels; the structure then will represent the sum of the cross sections for the various mechanisms that give rise to the detected fragment.

An interesting comparison may be made between the reactions described by Eq. (6) and the reaction described by Eq. (3) for an argon target. The cross section for H^0 production of 200 keV, as measured by Sweetman[19] and by Guidini,[21] is about 2×10^{-16} cm^2. The cross section for H(3s) production, as given in Fig. 7, is 10^{-17} cm^2; moreover, the cross sections for 3p and 3d production are about equal to that for 3s production (see Sec. VI). Thus the cross section for producing atoms in the $n=3$ level is about 3×10^{-17} cm^2 and represents 15% of the total neutral-hydrogen production. Similar results are available at other energies and for other targets. It appears, therefore, that the dissociation of H_2^+ produces a rather large fraction of atoms in excited states.

VIII. SUMMARY

Dissociation of H_2^+ in the various targets studied here gives similar cross sections for the 3s, 3p, and 3d levels. All the cross sections show the expected general behavior as a function of increasing impact energy: Charge-transfer cross sections decrease rapidly and dissociation cross sections decrease slowly. Weak structure is observed which is possibly due to the existence of various competing channels in the collision process; in particular, there is the possibility of exciting various target states and, for dissociation, there are various available channels by which the molecule may fragment. In the study of H_2^+ and H_3^+ dissociation on noble gases we find little difference between cross sections for the heavier targets Ar, Kr, and Xe; cross sections for He targets, however, lie almost an order of magnitude lower and cross sections for Ne have an intermediate value.

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[1]J. C. Ford and E. W. Thomas, Phys. Rev. A **5**, 1694 (1972).

[2]J. C. Ford and E. W. Thomas, Phys. Rev. A **5**, 1701 (1972).

[3]J. C. Ford, F. M. McCoy, R. Conrads, and E. W. Thomas, Phys. Rev. A **5**, 1705 (1972).

[4]R. H. Hughes, H. R. Dawson, B. M. Doughty, D. B. Kay, and C. A. Stigers, Phys. Rev. **146**, 53 (1966).

[5]R. M. Hughes, C. A. Stigers, B. M. Doughty, and E. D. Stokes, Phys. Rev. A **1**, 1424 (1970).

[6]R. H. Hughes, D. B. Kay, C. A. Stigers, and E. D. Stokes, Phys. Rev. **167**, 26 (1968).

[7]E. P. Andreev, V. A. Ankudinov, S. V. Bobashev, and V. B. Matveyev, Zh. Eksp. Teor. Fiz. **52**, 357 (1967) [Sov. Phys.-JETP **25**, 232 (1967)].

[8]E. P. Andreev, V. A. Ankudinov, and S. V. Bobashev, in *Fifth International Conference on the Physics of Electronic and Atomic Collisions: Abstracts of Papers, Leningrad* (Nauka Publishing House, Leningrad, 1967), p. 307.

[9]E. W. Thomas, *Excitation in Heavy Particle Collisions* (Wiley, New York, 1972), Chap. 9.

[10]J. L. Edwards and E. W. Thomas, Phys. Rev. A **2**, 2346 (1970).

[11]G. W. McClure and J. M. Peek, *Dissociation in Heavy Particle Collisions* (Wiley, New York, 1972), p. 122.

[12]Reference 11, p. 169.

[13]L. H. Toburen, M. Y. Nakai, and R. A. Langley, Phys. Rev. **171**, 114 (1968).

[14]R. A. Mapleton, Phys. Rev. **122**, 528 (1961).

[15]J. D. Garcia, E. Gerjuoy, and J. E. Welkner, Phys. Rev. **165**, 72 (1968).

[16]M. Gryzinski, Phys. Rev. **138**, A336 (1965).

[17]D. R. Bates and R. A. Mapleton, Proc. Phys. Soc. Lond. **87**, 657 (1966).

[18]R. A. Mapleton, *Theory of Charge Exchange* (Wiley, New York, 1972), p. 194.

[19]D. R. Sweetman, data reproduced in Oak Ridge National Laboratory Report No. ORNL-3113, revised 1964 (unpublished).

[20]Reference 11, p. 130.

[21]J. Guidini, C.R. Acad. Sci. (Paris) **253**, 829 (1961).