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Production of Lyman-α radiation in collisions of protons and hydrogen atoms*

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The cross sections for Lyman-α production by the processes H^+ (or D^+) + $H(1S) \rightarrow H^+$ (or D^+) + $H(2P)$ (direct excitation) and H^+ (or D^+) + $H(1S) \rightarrow H(2P)$ [or $D(2P)$] + H^+ (charge transfer) have been measured over the energy range 0.75–29 keV using a modulated cross-beam technique with liquid-helium cryopumping. Signals from the direct excitation and the charge transfer were separated by a Doppler-shift technique. The absolute cross sections were assigned by comparison with excitation of Lyman-α on electron impact. For direct excitation, general agreement in shape with the data of Stebbings *et al*. and of Morgan, Geddes, and Gilbody was found except for structure at 1.3 keV. The pseudostate calculations of Cheshire, Gallaher, and Taylor predicted the present experimental points well. For charge transfer, our results agree with those of Morgan, Geddes, and Gilbody at energies higher than 11 keV and have similarity in shape to the work of Stebbings *et al*. A peak appeared in our cross-section curve at the energies around 1.7 keV. Acceptable agreement with the pseudostate calculations was found up to the maximum energy except for the appearance of the peak at 1.7 keV.

I. INTRODUCTION

The cross sections for the production of Lyman-α radiation in collisions between energetic protons or deuterons and hydrogen atoms by the processes

$$H^+ \text{ (or } D^+) + H(1S) \rightarrow H^+ \text{ (or } D^+) + H(2P) \quad \text{(direct excitation)} \qquad (1)$$

and

$$H^+ \text{ (or } D^+) + H(1S) \rightarrow H(2P) \text{ [or } D(2P)] + H^+ \quad \text{(charge transfer)} \qquad (2)$$

have been measured in the equivalent proton energy range from 0.75 to 29 keV. Because of their simplicity these processes have been extensively studied theoretically, with numerous approximations being applied.[1–16] The wide range of both magnitude and shape of the calculated cross-section curves attest to the sensitivity of calculated results on the specific approximations used in the solutions. Previous experiments of Stebbings *et al.*[17] and of Gaily and Geballe[18] have not succeeded in clarifying matters since both experiments contained rather large experimental uncertainties and even then disagreed by amounts larger than the combined experimental uncertainties. The present experiments, using more sophisticated experimental techniques, including cryogenic vacuum production in order to reduce noise, attempt to clarify the experimental situation and at the same time provide reliable results. Concurrent with our experiments, Morgan *et al.*[19] have measured the same cross sections and have obtained results which agree reasonably well with our present data, where the energy ranges overlap.

II. EXPERIMENTAL TECHNIQUE

The basic experimental apparatus (Fig. 1) is almost identical to that used in another paper[20] except for the use of liquid-helium (LHe) cryopumping in the present experiments, and a different mounting of the Lyman-α detector.

As shown in Fig. 1, atomic hydrogen was produced by thermal dissociation in a heated tungsten tube (2700 °K) located in the first of three differentially pumped vacuum chambers. A beam effused from an aperture (1.0 mm diameter) in the tube and was modulated at 270 Hz by a rotating toothed chopper wheel at the second chamber. The modulated beam was then introduced into the third chamber where it was crossed by a proton (or deuteron) beam at 90 deg. After crossing the proton (or deuteron) beam, the modulated beam was fractionally ionized by electron impact, and the ions were analyzed using a quadrupole mass filter in order to monitor fractional dissociation (F) of the atomic hydrogen in it.

F was determined by comparing peak intensities of the ion peaks at masses 1 and 2 amu, and using the formula[21]

$$F = \frac{1}{1 + \sqrt{2}(Q_1^i/Q_2^i)(S_2^i/S_1^i)} \,, \qquad (3)$$

where S_1^i and S_2^i are atomic and molecular peak strengths in the quadrupole mass filter and Q_1^i/Q_2^i is the ratio of cross sections for ionization of the atom and the molecule as determined by Fite and Brackmann.[22] With an ionizing electron energy of 100 eV the factor $\sqrt{2}\ (Q_1^i/Q_2^i)$ becomes 0.93. Operating conditions were normally set so that F ranged between 0.7 and 0.85.

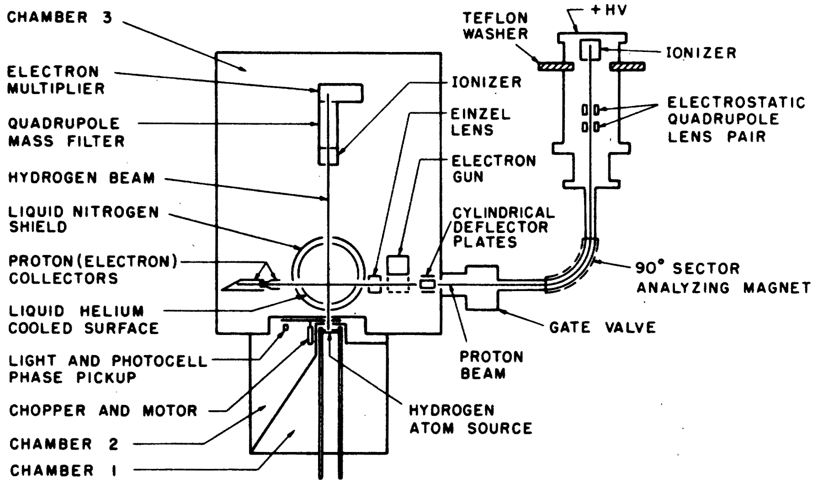

FIG. 1. Schematic diagram of the basic experimental apparatus.

Hydrogen ions, prepared from electron impact on H_2O (or D_2O), were accelerated and focused into a beam by a series of electrostatic lenses in an electron-bombardment ion source. This ion beam was then steered and shaped by an electrostatic quadrupole lens pair and analyzed by a 90° sector magnetic field. The analyzed proton (or deuteron) beam then passed between final steering electrodes and an einzel lens located in the third chamber. The ion beam was aligned and focused by these lenses in such a way that all ions in the beam would pass through the neutral beam. Assurance for this was obtained in the following manner: A deep Faraday cup with an aperture diameter smaller than the neutral beam diameter served as a central collector for protons (or deuterons) passing through the atomic beam while the remainder of the ions were collected by an outer concentric collector. Under normal operating conditions, the ion currents to the outer collector were 10^{-3} times smaller than those to the central one. In order to suppress slow secondary electrons, the outer collector was biased −25 V with respect to the central one which was grounded through a current-measuring electrometer (Keithley 621). The ion beam currents ranged from 2×10^{-8} A at the lowest energy to 3×10^{-7} A at the most favorable region. The fluctuations in the proton beam current appeared to be at the shot-noise level. The fact that fluctuations in the proton-beam current at the atom-beam modulation frequency cause noise in the experiment through charge transfer between the protons and residual gas in the vacuum, recommends electron impact sources even though the ion currents are quite low.

The deuteron beam was utilized at energies below the equivalent proton energy of 6 keV because of its greater stability and intensity. Since commercially available heavy water, from which D^+ was made, contains some amounts of light water in it, the deuteron beam contains some H_2^+ as an impurity. In order to estimate the amount of H_2^+ in the beam, a procedure described in a previous paper[21] was used. First, ion currents of masses at 1, 2, and 4 amu (I_1, I_2, and I_4, respectively) were measured by tuning the magnetic field of the 90° sector magnet. The currents of H_2^+ and D^+ ($I_{H_2^+}$ and I_{D^+}) then are given by an expression (see Ref. 21)

$$I_{H_2^+} = CI_1\,, \tag{4}$$

$$I_{D^+} = I_4/C\,, \tag{5}$$

$$C = [I_2 - (I_2^2 - 4I_1I_4)^{1/2}]/2I_1\,. \tag{6}$$

Because of the high purity of the heavy water used in this experiment, the ratio $I_{H_2^+}/I_{D^+}$ was less than 10^{-4}. The total cross sections for $H + H_2^+$ must be of the same order of magnitude for $H + D^+$; therefore the H_2^+ species contributed negligible correction to the total cross section data for the process studied here.[23] The interaction region was enclosed by two cold walls cooled by liquid nitrogen (LN_2) and LHe, respectively, in order to reduce background gas pressure. The Lyman-α detector was positioned at 90° and 54.7° with respect to the proton (or deuteron) beam direction for the purpose of distinguishing the direct excitation process from the charge transfer one, as will be discussed later (see Fig. 2).

The LHe cryopump used in this experiment was a stainless-steel container of LHe which was thermally shielded by another container filled with LN_2. On the bottom of the cryopump, closed concentric copper cylinders were attached to the LHe and LN_2 containers, respectively. The intersectional region of the atomic hydrogen beam and the proton (or deuteron) beam was located in the inner

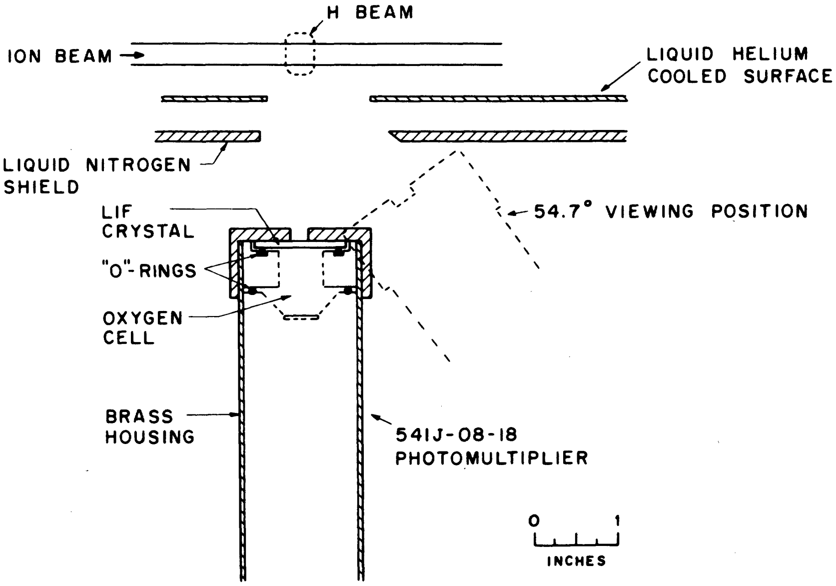

FIG. 2. Schematic of the Lyman-α detection system. The interaction region was surrounded by a cold wall at LHe temperature. The H beam is normal to the plane of the figure.

cylinder where walls, which condensed residual gases, were at 4.2 °K. Reduction of background gas pressure greatly reduced the Lyman-α radiation from charge transfer between proton and residual gases. This constitutes the major difficulty in an experiment of this type.

The Lyman-α detector employed in this experiment consisted of a photomultiplier tube (EMR-541J-08-18) sensitive to the radiation between 1050 and 1600 Å, preceded by a molecular oxygen filter which has a sharp window near the energies of the Lyman-α line.[24-28] The detector was mounted on a rotatable support so as to rotate about an axis coincident with that of the atomic hydrogen beam while always viewing the beam intersection point.

A synchronous single-photon counting method was utilized to measure the intensity of the Lyman-α signals. A pair of phase-locked scalers were gated by the chopper-wheel reference signal, so that one of the scalers (A) registered the output n_A when the H atom beam was on, while the other (B) registered the output n_B when it was off. The value $(n_A - n_B)$ gives the intensity S, of the signals. The ratio S/n_B, indicative of the signal-to-background ratio, was greatly improved by the LHe cryopumping, ranging around the value of 2.5; the ratio was only about 0.1 without the cryopumping.

In the energy range below 3 keV, almost 5 h were required to acquire sufficient signals to attain a satisfactory data point with one-standard-deviation statistical uncertainties of 5% and 8% of the mean values for the direct excitation and the charge transfer processes, respectively. In the high energies above 6 keV, 2 h was sufficient for this accuracy because larger ion currents could be extracted from the ion source. Under normal operating conditions, the count rates were typically 10 and 30 counts/min in the low and the high energy ranges, respectively.

Because the neutral beam always contained 15% to 20% molecular hydrogen, the over-all signal S had to be corrected to determine the desired atomic signal S_H. With effusive flow conditions in the neutral beam source,

$$S_H = S - (1-F)(T_R/T)^{1/2} S_{H_2}, \tag{7}$$

where T is the operating temperature of the hydrogen furnace in degrees Kelvin, F is the dissociation fraction defined in Eq. (3), and S_{H_2} represents the intensity of countable ultraviolet radiation due to collisions of protons with molecular hydrogen at a low enough furnace temperature T_R, such that no dissociation occurs. The neutral-beam flow was ascertained to be effusive because $S_{H_2}T^{1/2}$ remained constant below the temperature of 1500 °K, where $F = 0$. T_R in the present experiments was normally 300 °K.

Several precautions were taken to ensure that only the desired Lyman-α radiation was being observed. The nearest surfaces which radiation could be reflected from were coated with colloidal graphite. Since the LHe-cooled copper walls enclosing the beam intersection region were grounded, the entire volume was free of electric fields, and metastable hydrogen atoms could not be quenched by Stark effect in the region viewed by the Lyman-α detector.

In order to distinguish the Lyman-α radiation resulting from the direct excitation process as opposed to the charge transfer process, the detector was positioned at two angles, 90° and 54.7° with respect to the proton (or deuteron) beam direction. Since the radiation from the charge transfer collision is emitted by rapidly moving hydrogen atoms (or deuterium atoms), the wavelength of the observed radiation will be Doppler-shifted according to the expression

$$\Delta\lambda = \lambda_L (v/c)\cos\theta , \qquad (8)$$

where $\Delta\lambda$ represents amounts of the shift in wavelength, λ_L is the wavelength of the normal Lyman-α line, v is the velocity of the fast hydrogen atoms, c is the speed of light, and θ is the angle of detection measured from the proton beam direction. The absorption of the molecular oxygen filter is such that the unshifted Lyman-α radiation from direct excitation lies near the bottom of a narrow transmission window and as a result, the Doppler-shifted Lyman-α radiation from charge transfer is absorbed more strongly by the filter than the Lyman-α radiation from the direct excitation process. Therefore, the signal observed at 54.7° arises mainly from the direct excitation process from which the unshifted Lyman-α radiation is emitted. However, the Doppler-shifted radiation due to the charge transfer process is not completely absorbed by the oxygen filter at lower ion energy range where the wavelength shift $\Delta\lambda$ is not large enough to discriminate the charge transfer radiation from the direct excitation radiation. Therefore, it is necessary to make the correction required by the incomplete attenuation of the charge transfer radiation. Prior to the discussion of this correction, the angular distribution of the observed intensity of radiation is introduced for the sake of clarity.

In the case of dipole radiation, the observed radiation intensity, S_{H}^{θ}, per unit solid angle per unit ion current in a direction making an angle θ with the ion beam axis is expressed, at a given energy of the ion beam, by

$$S_{\mathrm{H}}^{\theta} = \frac{\eta}{4\pi}\left(T(90^\circ) q_d \frac{1 - P_d \cos^2\theta}{1 - \frac{1}{3}P_d} + T(\theta) q_c \frac{1 - P_c \cos^2\theta}{1 - \frac{1}{3}P_c} \right), \qquad (9)$$

where q_d and q_c are the total intensities of the direct excitation and the charge transfer radiations, respectively; P_d and P_c are the polarization fractions for these two radiations, respectively; $T(\theta)$ denotes the transmittance of the charge transfer radiations in the oxygen filter at the angle θ; and η is the quantum efficiency of the detector. Here, the polarization fraction P is defined as[29]

$$P = \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}} , \qquad (10)$$

where $I_{\parallel}$ and $I_{\perp}$ are intensities of radiation polarized parallel and perpendicular to the ion beam direction when observed at the 90° position. The intensities q_d and q_c in Eq. (9) are expressed in terms of S_{H}^{90} and $S_{\mathrm{H}}^{54.7}$ which are the radiation intensities at the 90° and 54.7° positions, respectively, defined in Eq. (9), as

$$\frac{\eta T(90^\circ)}{4\pi} q_d = S_{\mathrm{H}}^{54.7} - \frac{\gamma}{R_c - \gamma R_d}\left(S_{\mathrm{H}}^{90} - R_d S_{\mathrm{H}}^{54.7}\right), \qquad (11)$$

$$\frac{\eta T(90^\circ)}{4\pi} q_c = \frac{S_{\mathrm{H}}^{90} - R_d S_{\mathrm{H}}^{54.7}}{R_c - \gamma R_d} , \qquad (12)$$

where

$$R_{d,c} = 1/(1 - \tfrac{1}{3}P_{d,c}) , \qquad (13)$$

$$\gamma = T(54.7^\circ)/T(90^\circ) . \qquad (14)$$

Since q_d and q_c are proportional to the absolute cross sections Q_d and Q_c for the direct excitation and the charge transfer processes respectively, $Q_{d,c}$ is given by

$$Q_{d,c} = A q_{d,c} , \qquad (15)$$

where A is a constant depending only on conditions of the atomic hydrogen source and the geometry of the crossed beams.

The value γ in Eq. (14), indicative of the previously mentioned correction required by the incomplete attenuation of the charge transfer radiation in the oxygen filter, was obtained from the absorption coefficients of O_2 at wavelengths near the normal Lyman-α line measured by us, Gaily,[26] Ogawa,[25] and Watanabe.[24] The transmittances, $T(90^\circ)$ and $T(54.7^\circ)$ can be expressed in terms of the absorption coefficients of the unshifted and the shifted Lyman-α lines (k_{α}^{H} and k, respectively) in the molecular oxygen of 760 Torr, as $T(90^\circ) = e^{-k_{\alpha}^{\mathrm{H}} x}$ and $T(54.7^\circ) = e^{-kx}$, where x stands for the thickness of the filter (1.9 cm atm in the present experiment). The coefficients k_{α}^{H} and k were measured in the present experiment by observing the Lyman-α radiation emitted in proton-argon collisions where the Lyman-α radiation arises solely from a charge transfer process. The ratio of the signal intensity with the oxygen filter evacuated, to that with dry O_2 of 760 Torr in it, yielded k and k_{α}^{H} at the 54.7° and the 90° positions of the detector, respectively. Variation of the proton energy allowed the absorption coefficients of O_2 to be measured as a function of the wavelengths of the shifted radiation as seen in Fig. 3. It was found that our values of k agreed well with Gaily's[26] in the vicinity of 1215 Å (see Fig. 3). At wavelengths shorter than 1214 Å, our measurement agreed with Watanabe's data.[24] Since γ was found to be less than 4% at the energies higher than 3 keV, the correction was only made below 3 keV. The absorption coefficients of the

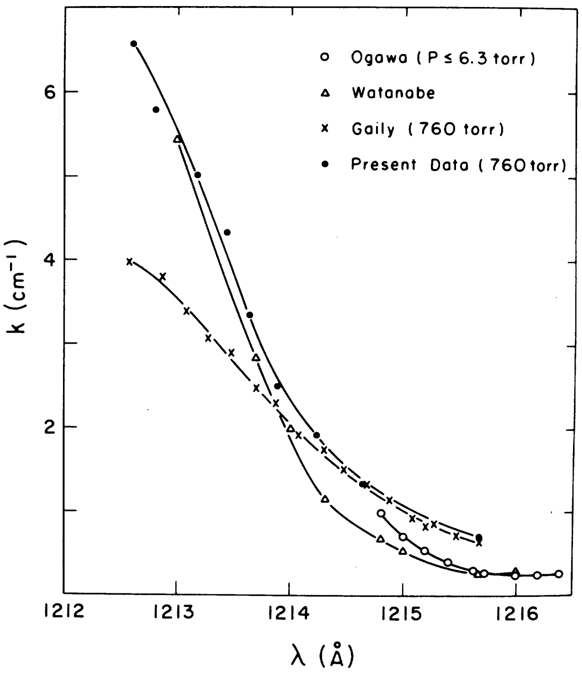

FIG. 3. Absorption coefficients of molecular oxygen in the vicinity of the normal Lyman-α line. The values of the pressures in the parentheses in this figure represent the pressures of O_2 at which these measurements were performed.

unshifted Lyman-α (k_α^{H}) was found to be 0.699 ±0.032 cm^{-1} (1 atm of O_2), while Gaily's[26] is 0.64 cm^{-1}.

Because an excited deuterium atom in the $2p$ state $[\mathrm{D}(2P)]$ emits the radiation with wavelength about 0.3 Å less than the normal Lyman-α line from $\mathrm{H}(2P)$, the absorption coefficient of the radiation from $\mathrm{D}(2P)(k_\alpha^{\mathrm{D}})$ is different from k_α^{H}, and an extra correction is necessary in the experiment of the charge transfer collision between $\mathrm{H}+\mathrm{D}^+$. The correction factor defined as $e^{(k_\alpha^{\mathrm{D}}-k_\alpha^{\mathrm{H}})d}$ is 1.25 according to Watanabe's[24] and Ogawa's data,[25] and 1.26 on the basis of our and Gaily's data.[26]

The other coefficients required in Eqs. (11) and (12) for the evaluation of the ratios of absolute total cross sections for the processes of interest are $R_{d,c}$ which are related to the polarizations of the radiations. In the present experiments, the values of both polarizations, $P_{d,c}$, were taken to be zero over the entire energy range, so that $R_{d,c}=1$.

Below 10 keV this assumption is well justified for the direct excitation polarization P_d by the experimental data of Kauppila *et al.*[20]; and although their data indicate a slight rise of P_d between 10 and 20 keV, the experimental uncertainties are large enough to admit near-zero values for P_d. Over either of these ranges both the four-state Sturmian calculations of Gallaher and Wilets[5] and the four-state and seven-state calculations of Rapp and Dinwiddie[13] are in fair agreement with the experimental results. This agreement is taken, in the absence of sufficiently precise direct experimental results, as justification for using the same calculations for the charge transfer polarization P_c. However, the two calculations differ for charge transfer, one giving slightly positive and the other slightly negative values for P_c for energies up to about 15 keV. An average value would give a value of $P_c \simeq 0$. Taking either set of calculations gives corrections on the order of 5% in the total cross section ratios up to about 15 keV. By 20 keV the theories diverge and the correction using the Gallaher and Wilets calculations would be about 19%, while using those of Rapp and Dinwiddie causes only about 4% correction. Above 20 keV, where no experimental data exist, and where the theories give divergent results, there is no good way to estimate the polarization corrections. Using values of assumed P_c and P_d in the present analysis permits later correction of the values reported here as either better experimental or theoretical results on polarization are obtained.

A final consideration is the finite lifetime of the $2P$ state (1.595×10^{-9} sec); some of the fast moving $\mathrm{H}(2P)$ produced in the charge transfer process would decay outside the field of view of the detector. However, even at 30 keV where the velocity of $\mathrm{H}(2P)$ is 2.4×10^{8} cm/sec, the fraction of the fast $\mathrm{H}(2P)$ which decays outside the field of view of the detector was estimated to be no more than 4% for the geometry used in the present experiments.

III. DETERMINATION OF ABSOLUTE CROSS SECTIONS

An approach used to determine the absolute cross sections was to measure the relative cross sections requiring normalization at 6 keV by comparing a known absolute cross section for Lyman-α production in e-H collisions.

For the purpose of obtaining the relative cross sections, the signals were normalized by S_{H}^{90} at 6 keV which was taken every day. The relative cross sections were determined from the following equations derived from Eqs. (11) and (12)

$$\frac{Q_D}{Q_T(6\ \mathrm{keV})}=\frac{1}{S_{\mathrm{H}}^{90}(6\ \mathrm{keV})}\times\left(S_{\mathrm{H}}^{54.7}-\frac{\gamma}{1-\gamma}\left(S_{\mathrm{H}}^{90}-S_{\mathrm{H}}^{54.7}\right)\right) \qquad (16)$$

and

$$\frac{Q_C}{Q_T(6\ \mathrm{keV})}=\frac{1}{S_{\mathrm{H}}^{90}(6\ \mathrm{keV})}\,\frac{1}{(1-\gamma)}\left(S_{\mathrm{H}}^{90}-S_{\mathrm{H}}^{54.7}\right), \qquad (17)$$

where $Q_T(6\ \mathrm{keV})$ represents the sum of Q_d and Q_c

at 6 keV where γ was practically zero. In Eqs. (16) and (17), P_d and P_c were set to be zero as discussed in the previous section. The absolute cross sections were finally obtained from these relative cross sections combined with the absolute cross section for the direct process at 6 keV.

With the aid of Lyman-α emission from e-H collisions, $S_{\mathrm{H}}^{54.7}$ at 6 keV was normalized by the following procedure: (i) Signals were registered on the scalers at the 54.7° viewing position with the proton beam (6 keV) traversing through the atomic beam; (ii) after replacement of the proton beam by an electron beam of 1000 eV energy, measurement (i) was repeated under identical conditions; and (iii) the ratio of these two signals, (i) and (ii), was obtained. This ratio provides the relative cross section for the direct excitation process at 6 keV, with respect to the cross section for production of Lyman-α emission in e-H collisions at 1000 eV. This measurement was achieved by a removable electron gun located on the axis of the proton beam. As illustrated in Fig. 1, the gun was moved away from the proton beam path in the measurement of the case (i), while it was returned to the path for measurement (ii). The absolute e-H cross section was taken to be the Born approximation value of $0.14\pi a_0^2$ at 1000 eV[30] and we found Q_{D} at 6 keV to be 3.08×10^{-17} cm^2. The normalization was also performed by comparing the known cross section for the Lyman-α production at 1000 eV with the direct excitation cross section of the $\mathrm{H}+\mathrm{D}^+$ collision at the equivalent proton energy of 3 keV. The two procedures of normalization produced the same results within the errors of 2.5%. The probable error in this normalization procedure was estimated to be 2.5%. This error originated mainly from the statistical error in the signals of $\mathrm{H}^+ + \mathrm{H}$ collisions since the Born approximation does not include errors in it.

IV. OVER-ALL ERRORS OF THE ABSOLUTE CROSS SECTIONS

The uncertainty in the absolute cross sections is considered to arise from the statistical errors of the individual measurements of the ratios of signals, and from uncertainties in the measurement of dissociation fraction, transmission of the oxygen filter, and reading errors of current meters.

For the direct excitation process, the uncertainty (one standard deviation) in the measurements of ratios of signals ranged from 2.3% to 4%, and we estimate the over-all uncertainty in the values of the absolute cross sections obtained to be 5% to 6% over the entire energy range.

For the charge transfer process, the statistical uncertainties in the measurements of the ratios of signals ranged from 5% at energies less than 3 keV, to 7% at energies between 3 and 20 keV, and as high as 8% to 10% at energies in excess of 20 keV, where the charge transfer cross section had to be obtained by subtraction of the large signal due

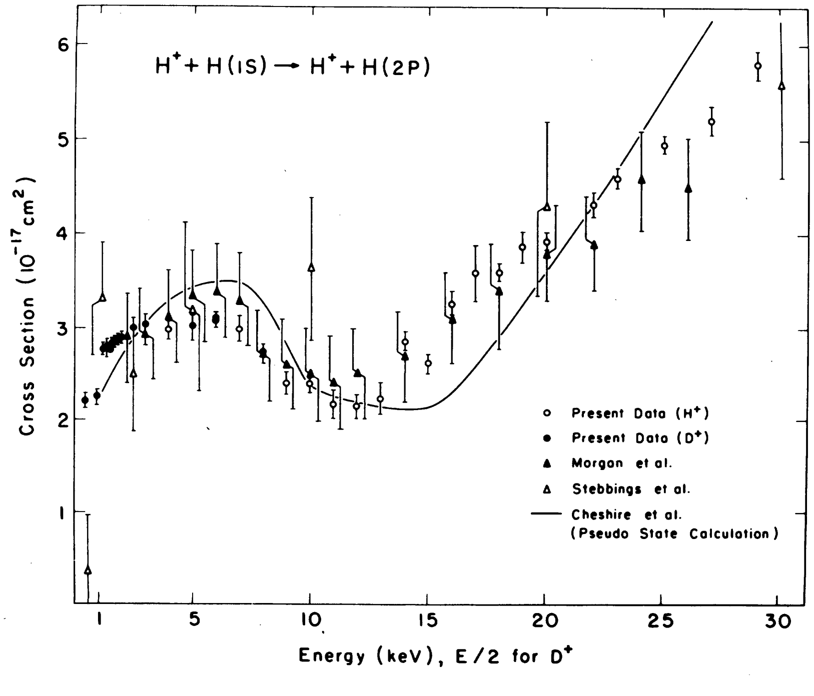

FIG. 4. Absolute cross sections for the direct process plotted against the equivalent proton energies of the incident beam. The error bars represent one standard deviation.

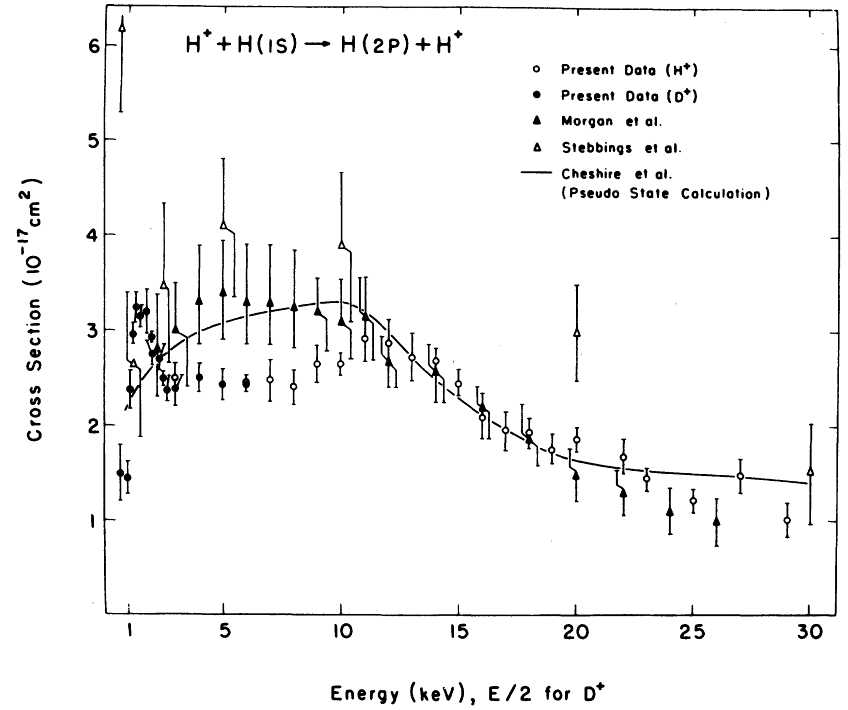

FIG. 5. Absolute cross sections for the charge transfer process plotted against the equivalent proton energies of the incident beam. The error bars represent one standard deviation.

to direct excitation from the sum of signals from both processes. Considering the other measurement uncertainties, we estimate the over-all uncertainty in the cross sections over the three energy ranges listed above at 6%, 8%, and 9% to 11%, respectively.

As noted in Sec. II, above, the cross sections have not been corrected for systematic errors due to polarization of the radiation. While we believe that below 15 keV such corrections would lie within the quoted over-all experimental uncertainties, this may not be the case at higher energies.

V. RESULTS AND DISCUSSION

Figures 4 and 5 represent the cross sections of the direct and the charge transfer processes, respectively. The error bar of each point shows plus and minus one standard deviation. A typical percentage error is approximately ±4% for the direct excitation and ±7% for the charge transfer process. For comparison, the work done by other groups is also illustrated as well as the theoretical curve by Cheshire *et al.*[9] using the pseudostate expansion.

Figures 6 and 7 represent the comparisons of the present experiments with various theoretical predictions for the direct excitation and the charge transfer processes in a logarithmic scale respectively, so that one can obtain general concepts about the experimental and the theoretical situa-

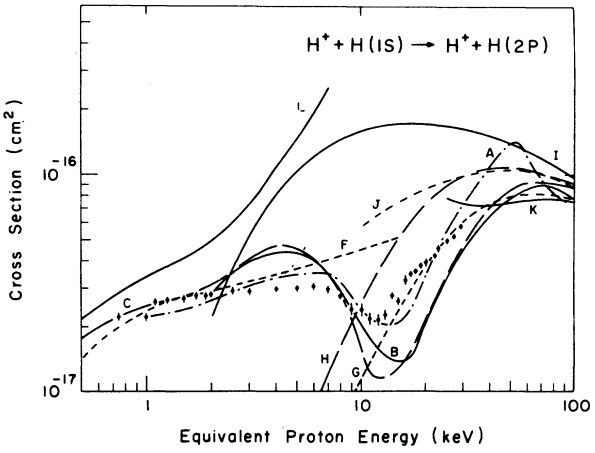

FIG. 6. Comparisons of the experimental cross sections of the present experiment with various theoretical calculations for the direct excitation process: curve A, pseudostate expansion by Cheshire *et al.* (Ref. 9); curve B, seven-state hydrogenic expansion by Rapp *et al.* (Ref. 13); curve C, four-state hydrogenic expansion by Rapp *et al.* (Ref. 13); curve F, molecular treatment by Rosenthal (Ref. 10); curve G, Glauber method by Franco *et al.* (Ref. 12); curve H, four-state close-coupling expansion by Flannery (Ref. 8); curve I, Born approximation by Bates *et al.* (Ref. 16); curve J, 20-state diagonalization by Baye *et al.* (Ref. 16); curve K, four-state second-order potential by Sullivan *et al.* (Ref. 14); curve L, four-state close-coupling hydrogenic by Gaussorgues *et al.* (Ref. 11).

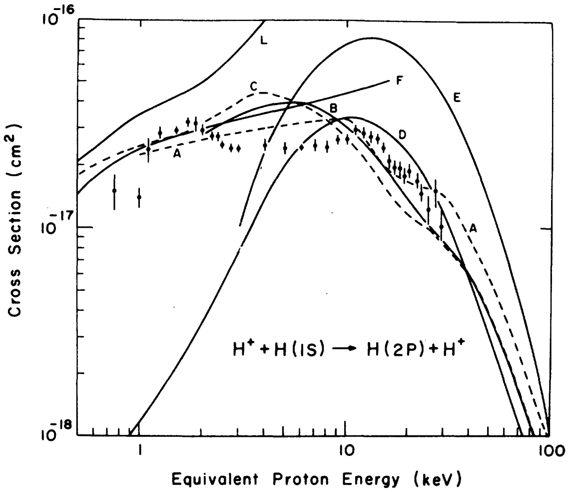

FIG. 7. Comparisons of the experimental cross sections of the present experiment with various theoretical calculations for the charge transfer process: curve A, pseudostate expansion by Chesire *et al.* (Ref. 9); curve B, seven-state expansion by Rapp *et al.* (Ref. 13); curve C, four-state expansion by Rapp *et al.* (Ref. 13); curve D, impulse approximation by Coleman *et al.* (Ref. 6); curve E, Born approximation by Bates *et al.* (Ref. 2); curve F, molecular treatment by Rosenthal (Ref. 10); curve L, four-state close-coupling hydrogenic by Gaussorgues *et al.* (Ref. 11).

tions.

Prior to discussing the present data, it is necessary to evaluate the cascade contribution to the observed emission cross sections. For the direct excitation of H atoms, the Born approximation calculations of Van den Bos and de Heer[31] provide an estimate of the cross sections for direct excitation into the $n \geq 3$ sublevels, where n stands for the principal quantum number of H atoms. The contribution to the observed cross sections for the direct excitation process from the $n = 3$ to 6 levels was approximately 15% at both 5 and 25 keV. In the charge transfer process, since the excited atoms produced are moving fast in the direction of the proton beam and some of them radiate outside the field of view of the detector, the lifetime of the upper levels should be taken into consideration. After this consideration, the cascade contribution in the charge transfer cross sections was about 2% at 5 keV and 3% at 25 keV according to the Born approximation.[31] Hughes *et al.*[32] have reported the cross sections for production of H(3S) and H(3D) in proton-inert gas collision. On the assumption that these cross sections can be applied in the proton-hydrogen-atom collision, the contribution from these states was estimated to be 3% at the proton energy of 10 keV. These estimations suggest that the cross sections might be too large by 15% for Q_d, and by 2% to 3% for Q_c.

In the case of the direct excitation, as shown in Fig. 4, a peak appears at 6 keV, and after passing the minimum at around 12 keV, the cross section increases with increasing energy of the incident beam. Seemingly, there is a structure around 1.3 keV as shown in Fig. 8 which has been obtained by enlarging the lowest energy range of Fig. 4. Because of the greater efforts and time invested in this energy range, the error bars are reduced appreciably. There is general agreement in shape with the data of Stebbings *et al.*[17], and excellent agreement with the work of Morgan *et al*.[19] except for the appearance of the structure at 1.3 keV. The theoretical calculation by Cheshire *et al*.[9]

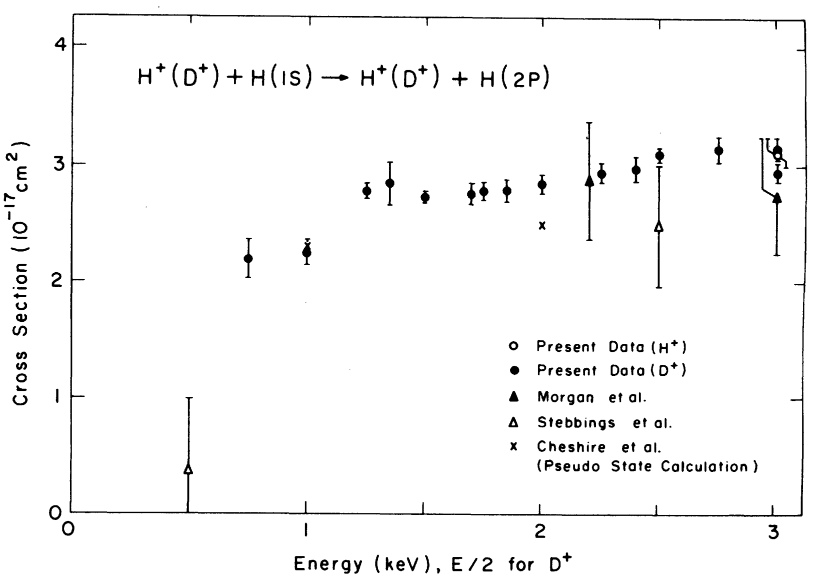

FIG. 8. Absolute cross sections for the direct excitation as a function of the equivalent proton energy of the incident beam in the energy range between 0.75 and 3 keV. The error bars are plus and minus one standard deviation.

(pseudostate expansion) reproduces the experimental points well in the energy range lower than 23 keV, deviating higher above this energy. Figure 6 shows that the Glauber approximation by Franco and Thomas[12] is in rather good agreement with the present work at energies higher than 15 keV in spite of its relative simplicity. The Born approximation is known to give incorrect cross section values for optically allowed excitation processes at energies less than 120 keV.[1,2] The agreement of the Glauber approximation[12] with the experimental values above 15 keV demonstrates the usefulness of this approximation. Evidently, the pseudostate expansion by Cheshire *et al.*[9] predicts the cross sections well at relatively low-energy range.

As shown in Fig. 5, the charge transfer excitation function has two maxima at 1.7 and 11 keV, sinking abruptly in the energy range lower than 1.7 keV and decreasing gently at the high energy side of the 11-keV peak. Our data agree excellently with the data of Morgan *et al.*[19] at the energy range higher than 11 keV, and the data have similarity in shape to the work of Stebbings *et al.*[17] In order to ascertain the existence of the 1.7-keV peak, the energy range between 0.75 and 3 keV was intensively investigated and the results are shown in Fig. 9.

Our data make it appear that again the pseudostate calculations by Cheshire *et al.*[9] give acceptable predictions extending over a broad energy range; in the energy range above 11 keV the experimental values agree well with this theoretical prediction. In the energy range between 3 and 10 keV, the shape of our cross section curve is similar to the curve obtained from the pseudostate calculation, although our magnitude is less than the theoretical value. In addition, the maximum of the cross sections around 11 keV that we observed is predicted by the calculations of the pseudostate expansion. It should be noted that the present charge transfer cross sections appear to have a shoulder at the energies around 24 keV which is predicted by the pseudostate expansion by Cheshire *et al.*[9], as seen in Fig. 7.

The structure at energies around 1.7 keV is not due to instrumental effects. As stated in the previous sections, the uncertainty in the cross sections is believed to be no more than 6% in this energy range. It is highly unlikely that the structure emerges due to molecular hydrogen existing in the atomic hydrogen beam because of the high dissociation fraction used (0.7 to 0.8), and the small cross sections for producing Lyman-α radiation in $H^+ + H_2$ collisions.[33] The fact that cross sections for excitation and charge transfer into states with $n \geqslant 3$ are small compared to processes leading to the $n = 2$ state[31,32] would seem to eliminate structure in excitation of higher-lying states followed by cascade as an explanation for the peak. The fact that the results in the present experiments compare well with other experiments at only slightly higher energies than 1.7 keV is perhaps the best reason for believing that the structure ob-

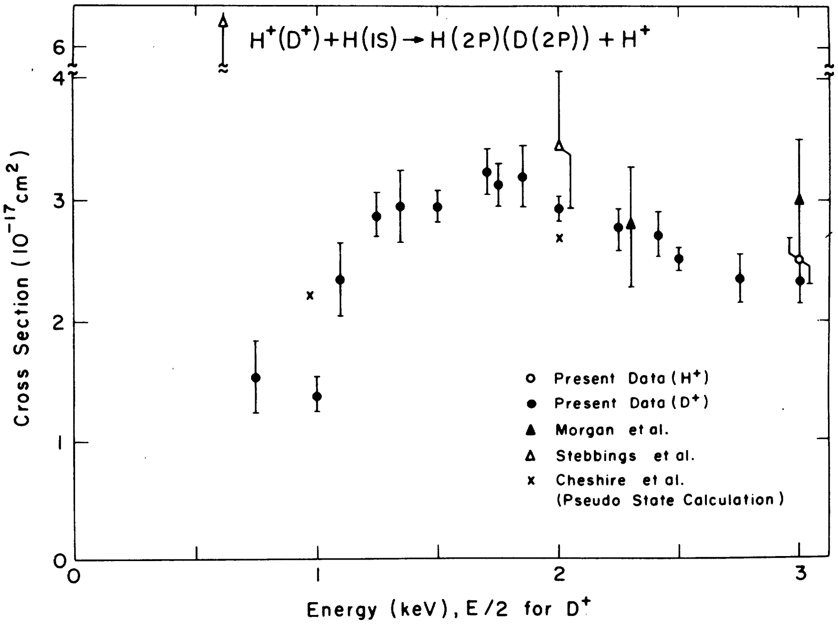

FIG. 9. Absolute cross sections for the charge transfer as a function of the equivalent proton energies of the incident beam in the energy range between 0.75 and 3 keV. The error bars give plus and minus one standard deviation.

served at this energy in the charge transfer excitation process is real and not due to instrumental effects.

We can offer no explanation at present for this unexpected structure in the cross section curve, and to the best of our knowledge such structure has not been predicted in any of the theoretical work to date.

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