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Lyman-α emission from H^+ impact on rare-gas atoms

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Absolute cross sections for the emission of Lyman-α radiation have been measured for low-energy H^+ impact on rare-gas-atom targets. Data were obtained for H^+ energies from 2.0 keV down to 1.0 keV for He targets, to 0.5 keV for Ne targets, to 0.05 keV for Ar and Kr targets, and to 0.013 keV for Xe targets. The polarizations of the emitted Lyman-α radiation were also measured. Using previously measured cross sections for Balmer-α and Balmer-β emission for the same collisions, it was possible to make an approximate determination of the cascade contributions to the total Lyman-α emission, and to extract the cross sections for direct population of the $2p$ state of hydrogen during the collisions. The results are compared with the work of other investigators at higher H^+ energies in an attempt to deduce the best working values of these cross sections for H^+ energies up to 100 keV.

I. INTRODUCTION

The study of Lyman-α (L_α) emission from various ion-atom and ion-molecule collisions has been the subject of numerous experimental and theoretical investigations over the last 25 years. A substantial fraction of this work has been devoted to studying L_α emission resulting from proton (H^+) impact on rare-gas-atom targets, presumably among the simpler and computationally approachable reactions involving electron capture into excited states of the projectile ions.

Of all the available information, however, only two systematic measurements of the absolute L_α-emission cross sections for H^+ impact on the complete sequence of rare-gas atoms have been reported. These are the results of Pretzer *et al.*,[1] who examined the L_α emission for H^+ energies from about 25 keV down to (typically) about 1 keV, and of Andreev *et al.*,[2] who made measurements for H^+ energies between about 10 and 40 keV. These sets of data have assumed an important role in this area of research, because most other workers have used one or the other of these results as a measurement standard to calibrate absolutely their own L_α photon detectors.

The primary purpose of this paper is to provide another independent set of absolute L_α-emission cross-section data for H^+ energies below 2.0 keV. All three sets of data are then evaluated and compared in an attempt to provide a "standard set" of cross-section information for future reference.

The second purpose of this paper is to estimate the extent to which the observed L_α emission from the collisions is influenced by cascade transitions to the $2p$ state of hydrogen from the higher-lying ns and nd states populated during the electron-capture interactions. This analysis, based upon the cross sections for Balmer-α (H_α) and Balmer-β (H_β) emission for the collisions,[3] is made for H^+ energies from 0.1 to 100 keV.

The techniques used to make the measurements reported here, including the all-important procedure for absolute calibration of the L_α photon detector, will not be discussed. They are identical to those employed for similar measurements of the absolute L_α-emission cross section for H + Ne collisions reported earlier by Van Zyl *et al.*,[4] and recently extended to the other rare-gas-atom targets.[5] The serious reader is encouraged to examine this earlier work closely, for it contains not only a discussion of the measurement procedures, but also a description of the computational model used to estimate the cascade contributions to the measured L_α signals.

II. DIRECT RESULTS OF THE MEASUREMENTS

The measured L_α-emission cross sections for H^+ impact on the rare-gas atoms are shown in Fig. 1. The measurement uncertainties are indicated on typical data points, usually being about $\pm15\%$ for Ar, Kr, and Xe targets, and $\pm20\%$ for He and Ne targets. The uncertainties are somewhat larger for Xe, Ne, and He targets at the lower ends of their respective H^+ energy ranges.

It must be stressed that these data are only the "apparent" L_α-emission cross sections measured by viewing the L_α from the collisions at a distance of 4.3 cm into the target cell,[4] and are henceforth denoted by $Q_m(L_\alpha)$. Because of the long radiative lifetimes of the excited ns states of hydrogen ($>1.5\times10^{-7}$s), some of the L_α produced by the $ns\rightarrow2p\rightarrow1s$ cascade decay sequence from the rapidly moving excited hydrogen atoms will escape detection at only 4.3 cm into the target cell. (The same is true for the decay sequence $nd\rightarrow2p\rightarrow1s$, for those transitions originating from the higher nd levels.) Thus, these $Q_m(L_\alpha)$ represent only lower limits on the true L_α-emission cross sections (to be presented in Sec. IV), although this effect is not large in our range of low H^+ energies.

It should also be noted that a slight possibility exists that some of the observed ultraviolet photons resulting from H^+ impact on Kr and Xe targets were not L_α. When the O_2-gas filter used to "isolate" L_α was evacuated, the photon-counting rate increased by a factor of about 2.1 for both these targets (with very little depen-

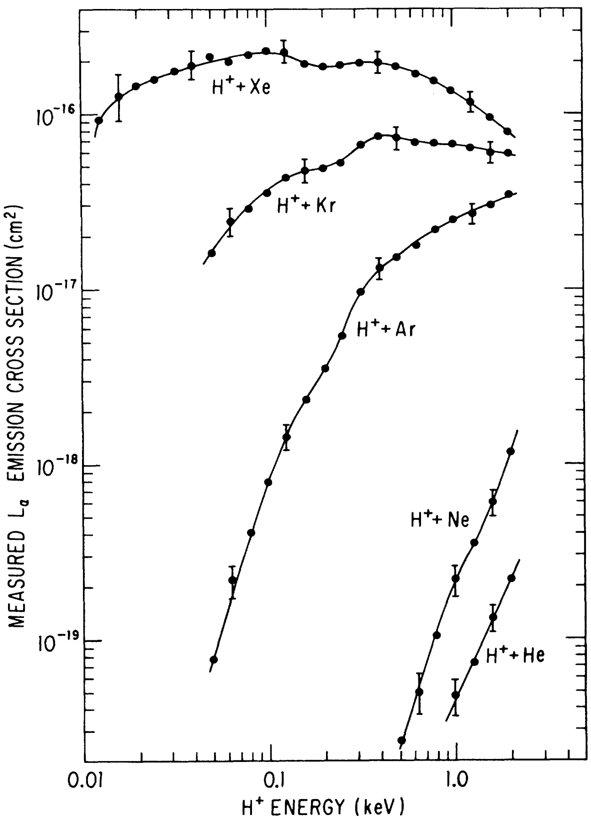

FIG. 1. Measured L_α-emission cross sections for H^+ impact on rare-gas-atom targets.

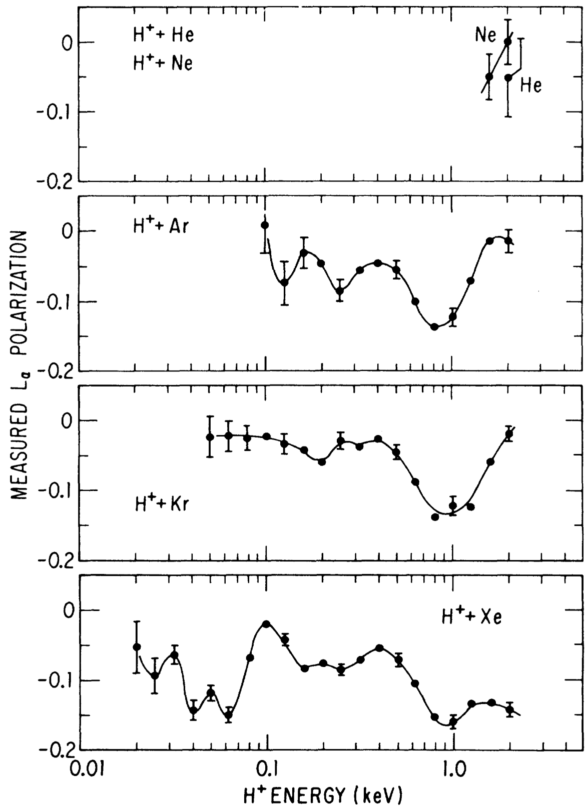

FIG. 2. Measured polarizations of L_α emission from H^+ impact on rare-gas-atom targets.

dence on H^+ energy). The counting-rate increase expected for a pure L_α signal[4] was a factor of 1.79. However, while Kr and Xe and their ions have emission lines within the full bandpass of the unfiltered photon counter, the more intense of these emission lines (at least as produced in gas discharges[6]) do not fall close to the O_2-gas-filter transmission windows.[4] The possibility of substantial L_α-signal contamination is thus considered remote (particularly in view of the very large L_α-emission cross sections for these reactions).

As can be seen, a considerable range of $Q_m(L_\alpha)$ values is represented in Fig. 1. The measured L_α-emission cross sections are quite small for H^+ impact on He and Ne targets, and increase approximately as E^2 with increasing H^+ energy. The data for Ar targets behave similarly for H^+ energies below about 0.3 keV, while those for Kr and Xe targets remain quite large even at very low H^+ energies. Indeed, the $Q_m(L_\alpha)$ for Xe targets is above 10^{-16} cm^2 for H^+ energies down to near 0.014 keV (only 5 eV above the reaction threshold).

Note also that there appear to be structures in these $Q_m(L_\alpha)$ data for the heavier rare-gas-atom targets, suggesting that the interactions leading to population of the $2p$ state of hydrogen during the collisions may be complex. Further evidence of the complexity of these interactions is shown in Fig. 2, where the polarizations (measured at 4.3 cm into the target cell[4]) of the emitted L_α are presented. Note that for these heavier targets, the polarizations are generally negative, but show considerable oscillatory structure, indicating that the relative populations of the $m_l=0$ and ± 1 sublevels of the $2p$ state of hydrogen occupied during the collisions may depend quite strongly on H^+ energy.[7] It seems plausible that the structures in both the emission-cross-section and polarization data result from interference between various interaction channels which can lead to the observed L_α emission.

Unfortunately, the small magnitudes of the L_α signals resulting from H^+ impact on He and Ne targets prevented measurement of the L_α polarizations for these reactions except at the higher H^+ energies. Because such polarization data are required to correct the measured L_α-emission cross sections for the angular dependence of the emitted radiation,[4] we assumed that these polarizations were -0.05 for this purpose, and included a $\pm 8\%$ uncertainty (in quadrature[4]) from this source for the $Q_m(L_\alpha)$ data shown in Fig. 1 for these targets.

III. CASCADE CONTRIBUTIONS TO THE L_α SIGNAL

In order to determine the cascade contributions to the L_α emission resulting from H^+ impact on rare-gas atoms, it is necessary to know the cross sections for electron capture into all the excited *ns* and *nd* states of hydrogen for $n \geq 3$. While all this information is obviously not available, the most important cascade contributions to the L_α signal can be approximately deduced from knowledge of the H_α- and H_β-emission cross sections for the reactions. The status of the cross sections for these Balmer-line emissions has recently been reviewed by Van Zyl *et al.*[3] for H^+ energies up to 100 keV.

Most workers who have examined the H_α emission resulting from H^+ impact on rare-gas atoms[3,8-12] have been able to separate the total H_α emission into its $3s \rightarrow 2p$ and $(3p \rightarrow 2s)+(3d \rightarrow 2p)$ components. While the $3p \rightarrow 2s$ transition does not lead to population of the $2p$ state of hydrogen and, consequently, not to L_α emission, it generally makes a rather small contribution to the total H_α emission because the branching ratio for the $3p \rightarrow 2s$ transition is only 0.118. Thus, at least the most important cascade transitions to the $2p$ state of hydrogen from the $3s$ and $3d$ states can be reasonably estimated.

Unfortunately, the total H_β-emission cross sections are much less well known. No data are available for H^+ impact on He and Ne targets, and results for the heavier rare-gas atoms are only available for H^+ energies up to about 2 keV.[3,8] However, that component of the total H_β resulting from $4s \rightarrow 2p$ transitions has been measured by several workers[13-15] at the higher H^+ energies. This is important information because electron-capture reactions leading to population of the excited ns states of hydrogen generally dominate over capture into other nl states at the higher H^+ energies.[3]

For H^+ energies near 100 keV, it seems likely that the relative amount of electron capture into the excited ns states of hydrogen should obey the n^{-3} scaling law.[3] Following the procedure used to determine the cascade contributions to the L_α emission resulting from H + Ne collisions,[4] we first examine how the predictions of this law are followed at the lower H^+ energies. Figure 3 shows the results of this analysis, where the plotted parameter R, defined in the figure, reflects the departure of the cross-section ratio for electron capture into the $4s$ and $3s$ states of hydrogen from an n^{-3} prediction (i.e., the value of R would be unity if this law were obeyed everywhere).

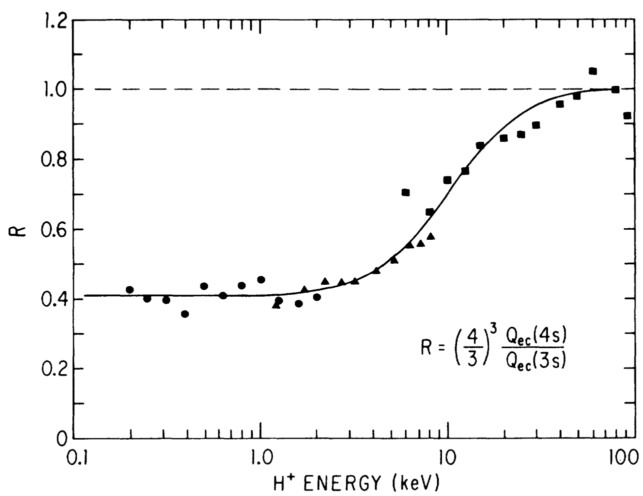

FIG. 3. Dependence of the parameter R (see text) on H^+ energy. The data points are from: ●, Van Zyl *et al.* (Refs. 3, 8, and 16); ▲, Dawson and Loyd (Refs. 9 and 13); ■, Hughes *et al.* (Refs. 11 and 14) and Doughty *et al.* (Refs. 15 and 17).

The data shown in Fig. 3 for H^+ energies below 2 keV obtained in this laboratory,[3,8,16] represent averages of the electron-capture cross-section ratios $Q_{ec}(4s)/Q_{ec}(3s)$ for H^+ impact on Ar, Kr, Xe, N_2, and O_2 targets. For H^+ energies between 1.2 and 8.2 keV, the data presented from Dawson and Loyd[9,13] are averages for He, Ar, Kr, N_2, and O_2 targets. The results shown at the higher H^+ energies are averages for all the rare-gas-atom and N_2 and O_2 targets obtained from Hughes *et al.*[11,14] and Doughty *et al.*[15,17]

The reason for using these average results to determine R (and for including data for N_2 and O_2 targets) is that the data for each individual reaction exhibit considerable scatter as a function of H^+ energy. (This is particularly true for our own results[3,8,16] at the lower H^+ energies, where electron capture into these ns states of hydrogen make fairly small contributions to the total observed Balmer-line emissions, and at the lower ends of the H^+-energy ranges covered by Hughes *et al.*[11,14] and Doughty *et al.*[15,17]) However, with the possible exception of the O_2 data for H^+ energies between about 5 and 30 keV (which give somewhat smaller R values), and the data of Doughty *et al.*[15,17] for Xe targets for H^+ energies below about 30 keV (which give larger R values), the results for each reaction follow the same trend of R with H^+ energy to within measurement uncertainties. (We know of no physical reason, however, why R should have a constant value near 0.41 at the lower H^+ energies.)

It is next assumed[4] that the same values of R give the relative amount of electron capture into all adjacent ns states, i.e., that

$$R = \left[\frac{n+1}{n}\right]^3 \frac{Q_{ec}((n+1)s)}{Q_{ec}(ns)} . \quad (1)$$

Thus, all the $Q_{ec}(ns)$ cross sections can be determined relative to $Q_{ec}(3s)$, for which reasonably good data are available.[3] All these $Q_{ec}(ns)$ are then summed, after multiplication by the appropriate $ns \rightarrow 2p$ branching ratios, to give $Q_{cas}(ns \rightarrow 2p)$, the effective cross section for cascade population of the $2p$ state of hydrogen from electron capture into the various excited ns states.

The assumption of Eq. (1) above has relatively little effect on the calculated total $Q_{cas}(ns \rightarrow 2p)$ at the lower H^+ energies. At 2-keV H^+ energy, for example, this model predicts that about 89% of $Q_{cas}(ns \rightarrow 2p)$ comes from the $3s$ state, about 9% from the $4s$ state, and only about 2% from all the higher ns states. Thus $Q_{cas}(ns \rightarrow 2p)$ is quite insensitive to the assumptions made here about $Q_{ec}(ns)$ for the $n \geq 5$ levels. (Some discussion of the uncertainties assigned to the cascade contributions to the total L_α emission from the reactions is presented in Sec. V.)

The next step in the analysis is to determine what fraction of this cascade component of the total L_α emission was observed by the various workers whose data will be considered here (depending upon the distances into the target cell where measurements were made, and the radiative lifetimes of the excited ns states of hydrogen). This fraction of $Q_{cas}(ns \rightarrow 2p)$ was then subtracted from the various measured $Q_m(L_\alpha)$ results to obtain $Q_{ec}(2p)$ plus the (observed) cascade contribution from $Q_{cas}(nd \rightarrow 2p)$ for each worker's data.

The cascade contribution to the total L_α emission from $nd \rightarrow 2p$ transitions was handled in a generally similar way. However, instead of using the simple n^{-3} scaling law for the relative amount of electron capture into the various *nd* (and *np*) excited states of hydrogen at the higher H^+ energies, a modified scaling law,

$$Q_{ec}(nl) \propto \frac{(n+l)!}{(n-l-1)!n^{2l+4}} , \qquad (2)$$

was used.[4] The right side of this expression is the square of the coefficient of the leading term of the *nl*-state radial wave function for hydrogen, which reduces to the n^{-3} scaling law for *ns* states.

This form of the scaling law predicts that the cross-section ratio $Q_{ec}(4d)/Q_{ec}(3d)=0.601$. While, as noted above, there are no experimental data to support the use of this scaling law here, this value is in excellent agreement with the Born-approximation calculations of Bates and Dalgarno[18] for $H^+ + H \rightarrow H^*(nd) + H^+$ collisions at the higher H^+ energies. This form of the scaling law was also used to perform a similar analysis for *nd*-state population resulting from H impact on rare-gas atoms.[4,5]

The L_α-cascade-modeling calculations then proceeded as follows. Using the measured $(3p \rightarrow 2s)+(3d \rightarrow 2p)$ component of the total H_α emission[3] as a guide, a $Q_{ec}(3d)$ was assumed. The scaling law from Eq. (2) and the same R shown in Fig. 3 were then used to estimate all $Q_{ec}(nd)$ from this $Q_{ec}(3d)$. These cross sections were then combined with the appropriate branching ratios to find $Q_{cas}(nd \rightarrow 2p)$, and with the appropriate *nd*-state radiative lifetimes to determine the fraction of the L_α from $nd \rightarrow 2p$ transitions observed during each L_α-emission cross-section measurement. This allowed an estimate to be made of $Q_{ec}(2p)$. The scaling law from Eq. (2) and the R from Fig. 3 were again applied to find $Q_{ec}(3p)$ from $Q_{ec}(2p)$, obtaining an improved estimate of $Q_{ec}(3d)$ to be made from the H_α-emission cross-section data. The entire process was then iterated until a reasonable convergence was obtained.

It was found, however, that the above procedure tended to overestimate the $Q_{ec}(4d)/Q_{ec}(3d)$ ratio at H^+ energies near 2 keV when compared to the measured H_α- and H_β-emission cross sections.[3,8] In other words, smaller values of the parameter R than those deduced from the $Q_{ec}(4s)/Q_{ec}(3s)$ data plotted in Fig. 3 were needed to fit the *nd*-state cross-section ratios at the lower H^+ energies. (This is also consistent with the trends predicted by Bates and Dalgarno[18] for $H^+ + H$ collisions for these same cross-section ratios at the lower H^+ energies.)

At 2-keV H^+ energy, the R values needed to fit the $Q_{ec}(4d)/Q_{ec}(3d)$ ratios for H^+ impact on Ar, Kr, and Xe targets ranged between about 0.27 and 0.35 (as compared to the value 0.42 shown in Fig. 3 for the *ns*-state cross-section ratio). At H^+ energies above 20 keV, the R values used to determine the *nd*-state cross-section ratios were taken to be the same as those shown in Fig. 3. For H^+ energies below 20 keV, the needed R values were simply deduced from curves drawn to be similar in shape to that shown in Fig. 3, but merging smoothly onto the somewhat smaller values needed to fit the experimental data available below 2-keV H^+ energy. These R values were then used to repeat the analysis described above[19] to find $Q_{cas}(nd \rightarrow 2p)$.

This procedure for estimating $Q_{cas}(ns \rightarrow 2p)$ and $Q_{cas}(nd \rightarrow 2p)$ to allow the determination of $Q_{ec}(2p)$ and $Q_{em}(L_\alpha)$ from each workers $Q_m(L_\alpha)$ data should yield fairly accurate results. For H^+ energies above about 10 keV, $Q_{cas}(ns \rightarrow 2p)$ exceeds $Q_{cas}(nd \rightarrow 2p)$ for all reactions (increasingly so with increasing H^+ energy). This is fortunate, for the simple n^{-3} scaling law and the R values shown in Fig. 3 used for determining $Q_{cas}(ns \rightarrow 2p)$ should be fairly accurate here. For H^+ energies below 10 keV, except for He and Ne targets, the less well determined $Q_{cas}(nd \rightarrow 2p)$ do exceed $Q_{cas}(ns \rightarrow 2p)$. Here, however, the R values are rapidly becoming smaller, so that most of $Q_{cas}(nd \rightarrow 2p)$ comes from $Q_{ec}(3d)$ and $Q_{ec}(4d)$, which are less dependent on the model assumptions than $Q_{ec}(nd)$ for the higher *nd* states.

It should, however, be mentioned that this computational model for estimating the cascade contributions to these L_α emissions becomes increasingly invalid for H^+ energies below 1 keV. Here, for Ar, Kr, and Xe targets, the measured $(np \rightarrow 2s)+(nd \rightarrow 2p)$ parts of the total cross sections for H_α and H_β emission show considerable structure as functions of H^+ energy,[3,8] causing the parameter(s) R to fluctuate markedly with H^+ energy as well. However, there is no reason to expect that such a crude model should even begin to describe the interactions at such low H^+ energies, where basically chemical reactions are occurring.

Finally, it should also be noted that this model was checked against a variety of other available data for these collisions. For example, we can predict $Q_{ec}(3p)$ from $Q_{ec}(2p)$ using the appropriate parameter R and the scaling law of Eq. (2). For $H^+ + Ar$ collisions, this prediction is in reasonable agreement with the measurements of Risley *et al.*[20] for H^+ energies between 2 and 15 keV, and lies between the data of Hughes *et al.*[11] and Ford and Thomas[12] at H^+ energies near 100 keV. This kind of consistency check lends confidence to our use of this model in the application made here.

IV. FINAL L_α-EMISSION CROSS-SECTION DATA

The final L_α-emission cross-section data for H^+ impact on rare-gas-atom targets are shown in Figs. 4–8 for H^+ energies from 0.1 to 100 keV. The measured $Q_m(L_\alpha)$ obtained here are compared with those of Pretzer *et al.*[1] (which have been adjusted in magnitude) and those of Andreev *et al.*[2] at the higher H^+ energies. For He, Ne, and Ar targets, the measured data of Hughes *et al.*[21] (also adjusted) are included in Figs. 4–6 for H^+ energies up to 100 keV.

The $Q_m(L_\alpha)$ data of Pretzer *et al.*[1] were adjusted because, unfortunately, these results were never corrected to account for an increasing loss of L_α signal with increasing H^+ energy due to the effect of Doppler shifting of the L_α wavelength on the transmission of the narrow-bandpass O_2-gas filter used to isolate the L_α signal during the mea-

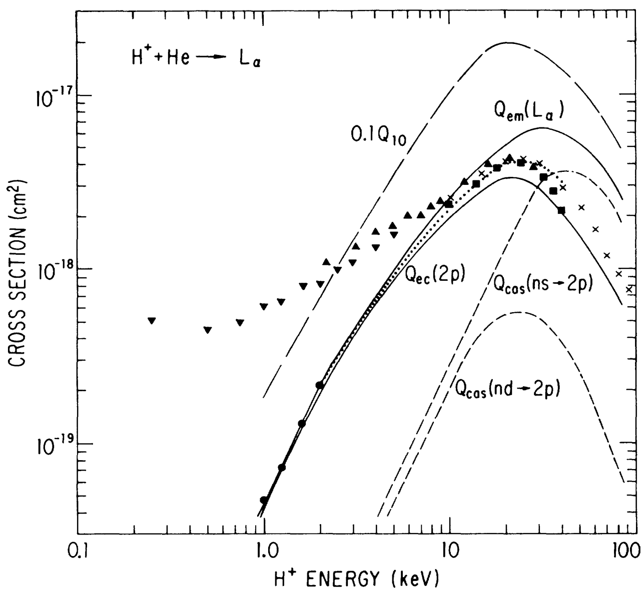

FIG. 4. L_α-emission cross sections for H^+ impact on He targets. The data points are from: ●, present results; ▲, Pretzer *et al.* (Ref. 1); ▼, scaled results for D^+ impact, Pretzer *et al.* (Ref. 1); ■, Andreev *et al.* (Ref. 2); ×, Hughes *et al.* (Ref. 21); · · · ·, Kimura (Ref. 28). Some results have been adjusted (see text).

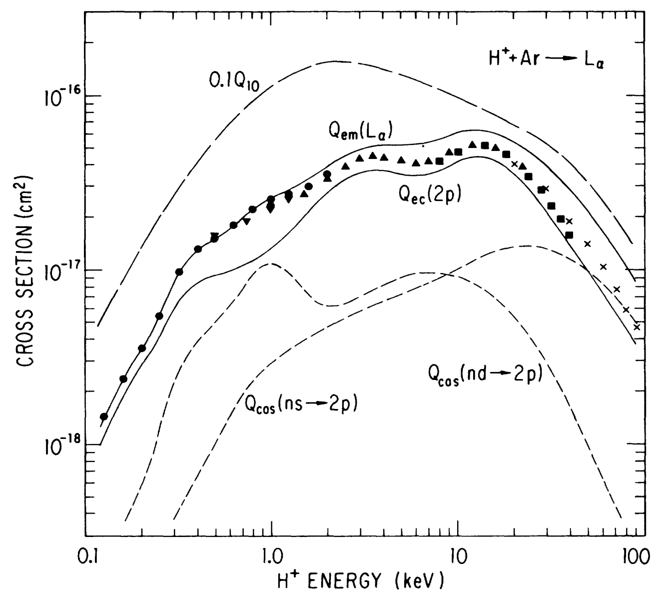

FIG. 6. L_α-emission cross sections for H^+ impact on Ar targets. The data points are from: ●, present results; ▲, Pretzer *et al.* (Ref. 1); ▼, scaled results for D^+ impact, Pretzer *et al.* (Ref. 1); ■, Andreev *et al.* (Ref. 2); ×, Hughes *et al.* (Ref. 21). Some results have been adjusted (see text).

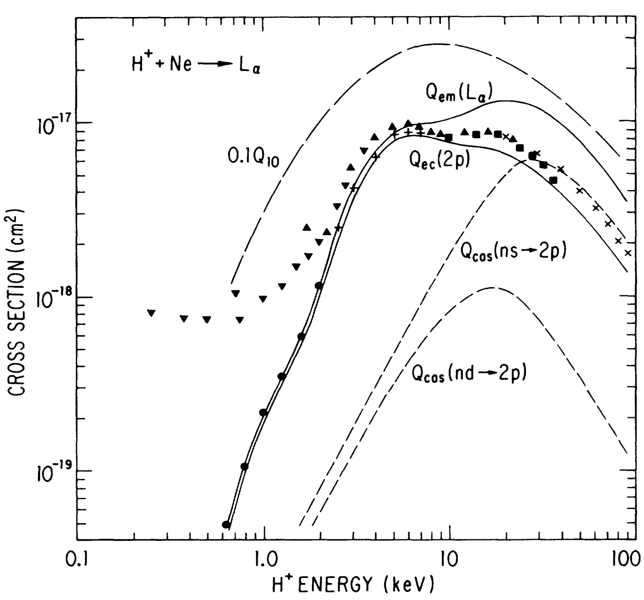

FIG. 5. L_α-emission cross sections for H^+ impact on Ne targets. The data points are from: ●, present results; ▲, Pretzer *et al.* (Ref. 1); ▼, scaled results for D^+ impact, Pretzer *et al.* (Ref. 1); +, Martin and Jaecks (Ref. 29); ■, Andreev *et al.* (Ref. 2); ×, Hughes *et al.* (Ref. 21). Some results have been adjusted (see text).

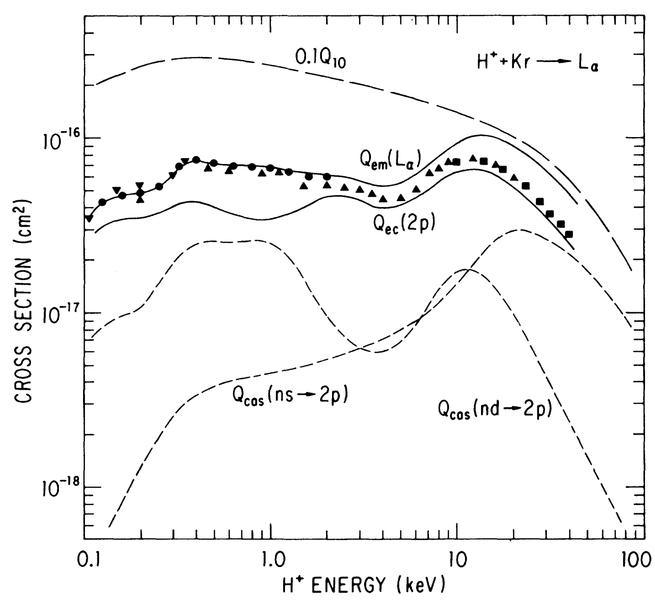

FIG. 7. L_α-emission cross sections for H^+ impact on Kr targets. The data points are from: ●, present results; ▲, Pretzer *et al.* (Ref. 1); ▼, scaled results for D^+ impact, Pretzer *et al.* (Ref. 1); ■, Andreev *et al.* (Ref. 2). Some results have been adjusted (see text).

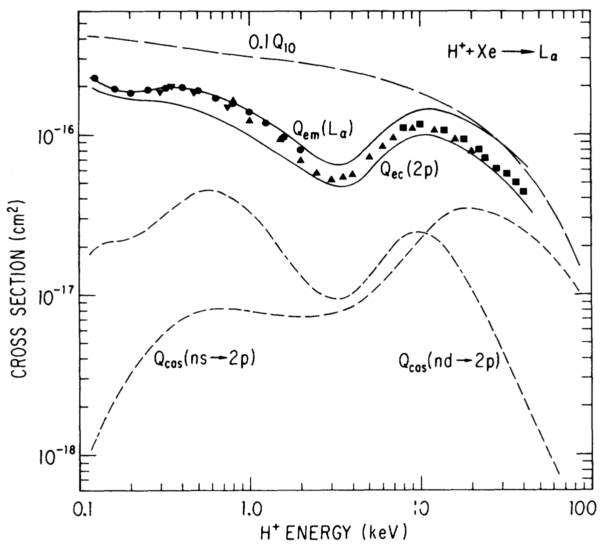

FIG. 8. L_α-emission cross sections for H^+ impact on Xe targets. The data points are from: ●, present results; ▲, Pretzer *et al.* (Ref. 1); ▼, scaled results for D^+ impact, Pretzer *et al.* (Ref. 1); ■, Andreev *et al.* (Ref. 2). Some results have been adjusted (see text).

surements. The (multiplicative) correction applied to these measured data here is 0.976 $(1 + 0.00816E)$, where E is the H^+ energy in keV units.[22] Relative to 3-keV H^+ energy (where these results were normalized in absolute value to earlier work of Dunn *et al.*[23]), the measured $Q_m(L_\alpha)$ were thus increased by 13.5%, for example, at 20-keV H^+ energy. In addition, the $Q_m(L_\alpha)$ data shown here for Ne and Xe targets are slightly different from those published by Pretzer *et al.*,[1] because of a recalibration of their absolute values made at a later time.[24]

The $Q_m(L_\alpha)$ values of Hughes *et al.*[21] were adjusted upward because these data were normalized, in turn, to the results of Pretzer *et al.*[1] at 20-keV H^+ energy. Thus, the Hughes *et al.*[21] data were increased by 13.5% for He and Ar targets, and 8.1% for Ne targets,[24] to preserve their original relative normalization to the adjusted data of Pretzer *et al.*[1]

It should be noted that an additional upward adjustment of the data of Hughes *et al.*[21] may be necessary. These workers measured the L_α from the collisions at a distance of about 5 cm into their target cell, so they would have observed more of the L_α from cascade processes than observed by Pretzer *et al.*[1] at a distance of only about 1.7 cm into the target cell. Thus, the data of Hughes *et al.*[21] shown in Figs. 4—6 may be too small by between 5 and 10%. However, no such additional upward adjustment of these data has been made here, for reasons which will be discussed later.

Also shown in Figs. 4—8 are the $Q_{ec}(2p)$, $Q_{cas}(ns \rightarrow 2p)$, and $Q_{cas}(nd \rightarrow 2p)$ cross sections derived from the measured $Q_m(L_\alpha)$ by the model calculations described in Sec. III. The upper solid-line curve in each graph is the total L_α-emission cross section obtained from $Q_{em}(L_\alpha) = Q_{ec}(2p) + Q_{cas}(ns \rightarrow 2p) + Q_{cas}(nd \rightarrow 2p)$.

Finally, the total electron-capture cross sections (multiplied by 0.1) are shown for H^+ impact on each rare-gas-atom target. These Q_{10} data are more or less the averages of results from a variety of sources,[25] and are presented here to indicate the trends of these cross sections with H^+ energy, as opposed to representing a critical evaluation of the existing data.

A. $H^+ + He$ Collisions

The final L_α-emission cross sections for H^+ impact on He targets are shown in Fig. 4. Although the data of Pretzer *et al.*,[1] Andreev *et al.*,[2] and Hughes *et al.*[21] are in fair agreement at the higher H^+ energies, the present results and those of Pretzer *et al.*[1] are in severe disagreement at the lower H^+ energies. (Some of the low-H^+-energy data shown for Pretzer *et al.*[1] were obtained using D^+ projectiles and are plotted here at 0.5 of the actual D^+ energy.)

Although the uncertainties cited by Pretzer *et al.*[1] are quite large ($\pm 45\%$), this discrepancy is obviously outside the (cited) mutual uncertainties of these low-H^+-energy measurements. We feel that the only reasonable explanation for the very large difference between these results is an impurity contamination of the He-gas target employed[26] by Pretzer *et al.*[1] Indeed, if this target contained, for example, an 0.2% concentration of Xe (the $H^+ + Xe \rightarrow L_\alpha$ cross section being very large at the lower H^+ energies, as seen in Fig. 8), this tailing-off of the "apparent" $Q_m(L_\alpha)$ measured by Pretzer *et al.*[1] could be nicely accounted for. While Xe was not likely to have been the foreign species present, it is probable that such species as H_2O or various hydrocarbon molecules might also be effective targets for copious L_α emission under H^+ impact.[27]

As can be seen in Fig. 4, the cascade contributions to the total L_α emission are very small at the lower H^+ energies. In sharp contrast, for H^+ energies above about 30 keV, the $Q_{cas}(ns \rightarrow 2p)$ contribution exceeds $Q_{ec}(2p)$, becoming the dominant source of L_α emission. As noted earlier, however, the radiative lifetimes of the excited ns states of hydrogen are quite long ($> 1.5 \times 10^{-7}$ s), so that much of this component of the total L_α emission was not detected by Andreev *et al.*[2] and Hughes *et al.*[21] during their measurements (made by observing L_α from the collisions at distances into their respective target cells of about 5 cm). Note also that, for this reaction, $Q_{cas}(nd \rightarrow 2p)$ is quite small. Thus, the considerable uncertainty in our modeling of this L_α contribution for this interaction has little impact on the $Q_{em}(L_\alpha)$ and $Q_{ec}(2p)$ shown.

While our purpose here is not to discuss in detail the theory of these collisions, the recent calculations made by Kimura[28] of $Q_{ec}(2p)$ for $H^+ + He$ collisions are so close to our results that they have been included in Fig. 4. This excellent agreement, we feel, substantiates our own $Q_m(L_\alpha)$ measurements at low H^+ energies, and the H^+-energy dependence of the $Q_{ec}(2p)$ and $Q_{em}(L_\alpha)$ obtained from our analysis of these experimental results.

B. $H^+ + Ne$ Collisions

Figure 5 shows the L_α-emission cross sections for $H^+ + Ne$ collisions. Again, the data of Pretzer *et al.*,[1] Andreev *et al.*,[2] and Hughes *et al.*[21] are in reasonably good agreement at the higher H^+ energies. As for the case of He targets, $Q_{cas}(ns \to 2p)$ becomes the dominant source of L_α for H^+ energies above about 30 keV, and the contribution to the total L_α emission from $Q_{cas}(nd \to 2p)$ is small.

The present data and those of Pretzer *et al.*[1] are again in very poor agreement at the lower H^+ energies. The same gas-contamination problem noted above for He targets may be responsible for this discrepancy. This is substantiated to some extent by the $Q_m(L_\alpha)$ obtained by Martin and Jaecks,[29] whose results are also presented in Fig. 5 for H^+ energies between 2.5 and 7.0 keV. It is these data, in fact, which have been basically used to determine the magnitudes and shapes of $Q_{ec}(2p)$ and $Q_{em}(L_\alpha)$ to connect our low-H^+-energy data with the other results shown near 10-keV H^+ energy.

A word of caution must be included about these Ne-target data. The $Q_{cas}(ns \to 2p)$ and $Q_{cas}(nd \to 2p)$ shown in Fig. 5 for H^+ energies between about 2 and 10 keV are not well established, for no H_α- or H_β-emission cross sections are available here.[3] (The H_α-emission cross sections in this H^+ energy range used for our analyses depend in part on the data of Dawson and Loyd,[9] who, unfortunately, did not investigate the H_α emission from $H^+ + Ne$ collisions.) However, we believe that the maximum in $Q_{em}(L_\alpha)$ occurring at about 6-keV H^+ energy must result from a corresponding maximum in $Q_{ec}(2p)$, as opposed to an inordinately large (and here missed) cascade contribution to the L_α emission in this H^+-energy range.

C. $H^+ + Ar$ Collisions

The data for $H^+ + Ar \to L_\alpha$ are presented in Fig. 6. As can be seen, the character of these results is quite different from those shown above for He and Ne targets.

Note that the present $Q_m(L_\alpha)$ now lie slightly above those of Pretzer *et al.*[1] at the lower H^+ energies. This is as it should be, for Pretzer *et al.*[1] obtained their data by viewing the L_α from the collisions at a distance of only about 1.7 cm into their target cell, and should therefore have measured a smaller fraction of the L_α from the $ns \to 2p$ cascade processes than was observed here (at 4.3 cm into the target cell). Of course, some small fraction of the L_α emission measured by Pretzer *et al.*[1] could still have come from H^+ impact on impurity gases present in their target cell, but the net effect of this problem would be much reduced here because of the much larger L_α-emission cross section for $H^+ + Ar$ collisions at the lower H^+ energies, compared to those for He and Ne targets.

While $Q_{cas}(ns \to 2p)$ still becomes the dominant source of L_α at the higher H^+ energies, its contribution here is less than $Q_{cas}(nd \to 2p)$ for H^+ energies below about 10 keV. In fact, for H^+ energies near 1 keV, $Q_{cas}(nd \to 2p)$ is dominated[3,8] by $Q_{ec}(3d)$, which is nearly as large as $Q_{ec}(2p)$. Furthermore, because the $3d$ state of hydrogen has a reasonably short radiative lifetime (1.5×10^{-8} s), almost all of the L_α from the cascade sequence $3d \to 2p \to 1s$ should have been observed in both the present and the Pretzer *et al.*[1] measurements. Thus both these $Q_m(L_\alpha)$ results should be quite close to the total $Q_{em}(L_\alpha)$ at the lower H^+ energies.

For H^+ energies in the 20-keV range, the (here adjusted) data of Pretzer *et al.*,[1] of Andreev *et al.*,[2] and the (adjusted) results of Hughes *et al.*[21] are again in close agreement. Because none of these experiments should have measured much of the L_α from the dominant $ns \to 2p \to 1s$ cascade sequences at this H^+ energy (about 4% for the Pretzer *et al.*[1] results and 12% for the others), the $Q_{ec}(2p)$ obtained from these various measured $Q_m(L_\alpha)$ all lie within less than $\pm 10\%$ of their average. This fact is rather remarkable, considering the large uncertainties cited by these investigators, and provides at least a consistent (if not correct) set of $Q_{em}(L_\alpha)$ values for this interaction.

D. $H^+ + Kr$ Collisions

Figure 7 shows the results obtained for H^+ impact on Kr targets. These data are generally similar to those for Ar targets discussed above, except that the magnitudes of the various cross sections are larger, particularly at the lower H^+ energies. Again, the contribution to $Q_{em}(L_\alpha)$ from $Q_{cas}(nd \to 2p)$ is much larger than that from $Q_{cas}(ns \to 2p)$ for H^+ energies in the 1-keV range, and the present $Q_m(L_\alpha)$ data and those of Pretzer *et al.*[1] thus approximate the total $Q_{em}(L_\alpha)$.

The data of Pretzer *et al.*[1] and of Andreev *et al.*[2] are also in very nice agreement for $H^+ + Kr$ collisions. Unfortunately, Hughes *et al.*[21] did not examine L_α emission from H^+ impact on Kr (or Xe) targets, but the general H^+-energy dependence of the various cross sections shown in Fig. 7 leaves little doubt about how these data could be extrapolated to 100-keV H^+ energy.

E. $H^+ + Xe$ Collisions

The final L_α-emission cross sections for H^+ impact on Xe targets are shown in Fig. 8. Again, the results of the various $Q_m(L_\alpha)$ measurements are in close agreement, well within their cited mutual uncertainties. However, the striking feature of these data is the very large $Q_{em}(L_\alpha)$ at the lower H^+ energies. Remember that, as indicated in Fig. 1, this L_α-emission cross section remains very large down to an order of magnitude lower H^+ energy than that plotted in Fig. 8.

While the contribution made to $Q_{em}(L_\alpha)$ by $Q_{cas}(nd \to 2p)$ at the lower H^+ energies is not negligible, it is clear that the bulk of the L_α from this interaction comes directly from electron capture into the excited $2p$ state of hydrogen. As noted in Sec. III, our model for evaluating the cascade contribution to the total L_α emission becomes increasingly invalid at the very low H^+ energies. However, the total H_α- and H_β-emission cross sections for this reaction[3] must represent an approximate upper limit for the cascade contributions to this L_α signal, and they lie well below $Q_{ec}(2p)$ at the very low H^+ energies. It is thus apparent that a highly state-selective electron-capture process must be operative here.

V. DISCUSSION OF THE RESULTS

In general, when the data of Pretzer *et al.*[1] are adjusted as described earlier in Sec. IV, the present $Q_m(L_\alpha)$ and those of Pretzer *et al.*[1] and Andreev *et al.*[2] for the heavier rare-gas-atom targets are in quite satisfactory agreement. It must be noted, however, that neither Pretzer *et al.*[1] or Andreev *et al.*[2] accounted for the effects of the L_α polarization on any of their emission-cross-section measurements (both L_α observations being made from a direction normal to their H^+-beam axes).

Gaily *et al.*[30] did attempt to correct the results of Pretzer *et al.*[1] for the effects of the L_α polarization for H^+ impact on He, Ne, and Ar targets. Their measured L_α polarizations, however, are in very poor agreement with those obtained here (see Fig. 2) for H^+ energies near 2 keV (and down to 0.6 keV for Ar targets). In contrast, the L_α polarizations measured by Teubner *et al.*[31] for these same collisions are in fair agreement with our results at the lower H^+ energies, but are frequently of the opposite polarity from those measured by Gaily *et al.*[30] at the higher H^+ energies. We thus have chosen not to apply any correction to the data of Pretzer *et al.*[1] or of Andreev *et al.*[2] for the effect of these L_α polarizations.

It is difficult to make a highly definitive estimate of the uncertainties to be assigned to the $Q_{em}(L_\alpha)$ and $Q_{ec}(2p)$ data resulting from the analysis undertaken here. In our own range of low H^+ energies, where $Q_m(L_\alpha)$ and $Q_{em}(L_\alpha)$ are very similar in magnitude, the uncertainties in $Q_{em}(L_\alpha)$ should be similar to those cited in Sec. II for $Q_m(L_\alpha)$, i.e., about $\pm 20\%$ for He and Ne targets, and $\pm 15\%$ for the heavier targets. For He and Ne targets, the $Q_{ec}(2p)$ uncertainties should also be close to $\pm 20\%$, for $Q_{cas}(ns \rightarrow 2p)$ and $Q_{cas}(nd \rightarrow 2p)$ are here very small and their large uncertainties (almost $\pm 50\%$ at 2-keV H^+ energy) thus have little effect on the determination of $Q_{ec}(2p)$. (Whenever such uncertainties were judged to be uncorrelated, they were combined in quadrature.)

In contrast, for Ar, Kr, and Xe targets, the cascade contributions to the total L_α emission are much larger at these lower H^+ energies. Here, however, we have both the H_α- and H_β-emission cross sections upon which to base our estimates of $Q_{cas}(ns \rightarrow 2p)$ and $Q_{cas}(nd \rightarrow 2p)$, and we believe these results should be accurate to within less than $\pm 20\%$. Thus, we believe that these $Q_{ec}(2p)$ should, in general, be uncertain by no more than about $\pm 20\%$ in this H^+ energy range, except perhaps $\pm 30\%$ at H^+ energies close to 1 keV for Ar and Kr targets, where cascade and $Q_{ec}(2p)$ make comparable contributions to the total L_α emission.

For Ar, Kr, and Xe targets, the good agreement between the measured $Q_m(L_\alpha)$ presented here (after adjusting the Pretzer *et al.*[1] results), suggest that the absolute L_α-detector calibrations used here, by Pretzer *et al.*,[1] and by Andreev *et al.*,[2] must be very similar. Furthermore, at least for $H^+ + Ar$ collisions, the L_α polarizations reported by Teubner *et al.*[31] are quite small for H^+ energies above 2 keV (lying between about -0.06 and 0.05), and it seems improbable that those for Kr and Xe targets should be substantially different. Thus, we would be surprised if the $Q_m(L_\alpha)$ of Pretzer *et al.*[1] and Andreev *et al.*[2] should be in error by more than $\pm 25\%$, even though their cited uncertainties are somewhat larger.

Furthermore, for these heavier rare-gas-atom targets, Figs. 6—8 show that for H^+ energies above 20 keV, the cascade contributions to the total L_α emission are increasingly dominated by $Q_{cas}(ns \rightarrow 2p)$. In this high-$H^+$-energy range, however, where the parameter R is approaching unity (see Fig. 3), there is strong evidence that the n^{-3} scaling law can be used via the model described in Sec. III to predict the $Q_{cas}(ns \rightarrow 2p)$ contributions to the total L_α emission. In fact, use of this scaling law to predict $Q_{ec}(ns)$ for the higher ns states from $Q_{ec}(3s)$ is probably much less uncertain than the uncertainties (taken here to be $\pm 20\%$) in the available measured $Q_{ec}(3s)$ data[3] upon which the predictions are based. Thus, at least at these higher H^+ energies, the uncertainties in $Q_{em}(L_\alpha)$ should not exceed about $\pm 25\%$. The uncertainties in $Q_{ec}(2p)$ should be comparable, for as can be seen, here $Q_{ec}(2p) \approx Q_m(L_\alpha)$.

It is in the H^+-energy range between about 2 and 20 keV, where $Q_{cas}(ns \rightarrow 2p)$ and the more uncertain $Q_{cas}(nd \rightarrow 2p)$ are comparable in magnitude, that an uncertainty estimate is most difficult. However, even here, we think that the estimated $Q_{cas}(nd \rightarrow 2p)$ should be accurate to within about $\pm 50\%$, yielding uncertainties in $Q_{em}(L_\alpha)$ and $Q_{ec}(2p)$ ranging between about ± 25 and $\pm 30\%$.

For He and Ne targets, however, the situation is less clear at the higher H^+ energies. As discussed earlier, the $Q_m(L_\alpha)$ values of Pretzer *et al.*[1] may be everywhere too large because of the influence of target-gas impurities. This would also, therefore, affect the results of Hughes *et al.*[21] via their absolute normalization (which is why we did not upwardly adjust the data of Hughes *et al.*[21] by the additional 5—10% noted near the beginning of Sec. IV). The L_α polarizations for H^+ impact on He and Ne could be larger (between about -0.10 and 0.15, according to Teubner *et al.*[31]), requiring larger corrections, therefore, to the measured $Q_m(L_\alpha)$ for this effect. In addition, the $Q_{cas}(ns \rightarrow 2p)$ contributions made to the total L_α emission for these targets are very large at the higher H^+ energies. Thus, we feel that the uncertainties in the $Q_{em}(L_\alpha)$ and $Q_{ec}(2p)$ estimated here must be set to at least $\pm 30\%$. Indeed, the calculated $Q_{ec}(2p)$ of Kimura[28] for He targets is probably as accurate as that deduced here for H^+ energies in the 20-keV range.

Finally, there is another problem which could increasingly influence all these results with increasing H^+ energy. With the exception of our own low-H^+-energy measurements, none of the other data were acquired using a Helmholtz coil to cancel the Earth's magnetic field in the photon-observation region. Thus, the excited hydrogen atoms produced in the collisions could have experienced $\mathbf{V} \times \mathbf{B}$ electric fields in their rapidly moving reference frames up to about 2 V/cm at 100-keV energy. (The problem could be even worse if stray magnetic fields from analyzing magnets, for example, added to the Earth's field during the measurements, or possibly less severe if there was some accidental field cancellation.)

Electric fields of this magnitude are sufficient to substantially "mix" the $ns_{1/2}$ and $np_{1/2}$ states of hydrogen for all $n \geq 6$, and the $np_{3/2}$ and $nd_{3/2}$ states even at the $n=3$ level.[32] The "mixing" of these states changes their radiative lifetimes, their branching ratios for decay, and, consequently, the $Q_{cas}(ns \to 2p)$ and, in particular, the $Q_{cas}(nd \to 2p)$ calculated here. Indeed, even at 10-keV H^+ energy, this problem is likely to have been the reason why Hughes *et al.*[14] were unable to measure the cross sections for total H_β emission for these collisions using their experimental technique.

Unfortunately, only for the $n=3$ level of hydrogen are the branching ratios for decay of the various excited nlm_l states known when the excitation and decay occurs in small electric fields.[33] However, even if this information was available for all the excited states of hydrogen as a function of electric field magnitude, it would not be possible to correct the available data for this effect because the population of the various m_l sublevels of given nl states are largely unknown, as are the magnetic field magnitudes present during the various measurements.

Remember, however, that at the higher H^+ energies, where this problem is most severe, most of the cascade contributions to the L_α emission come from electron capture into the $3s$, $4s$, and $5s$ states of hydrogen, the dominant parts ($>90\%$) of $Q_{cas}(ns \to 2p)$, which should not be strongly affected by this problem. Furthermore, for H^+ energies below 20 keV, well over 50% of $Q_{cas}(nd \to 2p)$ still comes from the $3d$ state, whose decay appears not to be significantly altered here by this problem.[34] Remember also that we assigned a $\pm 50\%$ uncertainty to $Q_{cas}(nd \to 2p)$ for H^+ energies between 2 and 20 keV, in part because of this problem. Thus, we feel that the uncertainties assigned above to $Q_{em}(L_\alpha)$ and $Q_{ec}(2p)$ are sufficiently large to encompass the magnitude of this problem, although application of such data in a practical environment must be made with considerable care.

As noted earlier, the purpose of this paper is not to describe in detail the theory of these electron-capture reactions. However, the general theoretical approach to understanding the interactions at the lower H^+ energies has been to consider them as basically two-step processes. In this model, an electron capture first occurs to the ground state of the hydrogen atom as the H^+ approach their targets. The ground-state hydrogen atoms then continue toward their (now ionized) targets, where various rotational and radial couplings are responsible for second transitions between the various molecular orbitals near the united-atom limits. These transitions (and perhaps others occurring on the outward legs of the collisions) lead to population of the various excited states of hydrogen which, eventually, decay to produce the observed hydrogen-line emissions.

Even for the simplest case of He targets, analysis of the second transition steps can be quite complicated.[28,35] However, if this model is correct, one might expect some general similarities between the various $Q_{ec}(nl)$ and the total Q_{10} for the interactions. For this reason, these Q_{10} (multiplied by 0.1) have been included as part of the data[25] shown in Figs. 4—8.

As can be seen, these data generally reflect the validity of this model. The structures in the various $Q_{ec}(nl)$ at the lower H^+ energies do indeed seem to fit into the "envelopes" of the plotted Q_{10} data. In particular, the $Q_{ec}(2p)$ for low-energy H^+ impact on Kr and Xe targets seem to represent nice examples of this concept. In fact, the near resonance of the total electron-capture cross sections for these reactions (that for Xe being exothermic) is almost certainly responsible[36] for the large $Q_{eC}(2p)$ for these reactions at the lower H^+ energies.

Finally, it should be noted that the existence of transient-intermediate Coulomb states may be influencing excited-hydrogen-atom formation during collisions of H^+ with the heavier rare-gas-atom targets.[3,8] Thus, such complicated reaction sequences as $H^+ + Xe \to H + Xe^+ \to H^- + Xe^{2+} \to H^* + Xe^+$ may well be operative in such collisions. Indeed, Martin and Jaecks[37] have found that the outgoing reaction channels leading to H^-, $H^*(2s)$, and $H^*(2p)$ formation appear to be coupled for this interaction. In addition, Gallup[38] has recently undertaken (configuration-interaction) calculations directed at explaining the relatively large $H^- + Ar^{2+}$ production resulting from $H^+ + Ar$ collisions, and it seems probable that this intermediate Coulomb state could be influencing excited-hydrogen-atom formation in these collisions as well.

In summary, it appears that production of L_α emission resulting from H^+ impact on rare-gas-atom targets is a rather complicated subject. While the data obtained here are in good agreement with theory[28] for the relatively simple case of He targets, we hope that this work will stimulate additional theoretical interest in understanding these interactions for the heavier rare-gas-atom targets.

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