Lyman-α emission from low-energy $H+H_2$ and H^++H_2 collisions

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Absolute cross sections for the emission of Lyman-α radiation have been measured for $H+H_2$ and H^++H_2 collisions. The projectile energies ranged from 2.5 to 0.05 keV for H projectiles, and from 2.0 to 0.08 keV for H^+ projectiles. The polarizations of the emitted Lyman-α radiation were also measured. Arguments are made to suggest that most of the observed Lyman-α emission from these reactions results from production of fast excited hydrogen atoms during the collisions, as opposed to dissociative excitation of the target H_2 molecules.

I. INTRODUCTION

In a series of recent papers,[1–4] we have presented the results of cross-section measurements for the emission of Lyman-α (L_α) radiation resulting from low-energy hydrogen-atom (H) and proton (H^+) impact on rare-gas atoms and N_2 and O_2 molecules. We report here on similar measurements for $H+H_2$ and H^++H_2 collisions.

The basic atomic-beam apparatus,[5] the method of target pressure measurement,[6] and the details of the L_α detector and its absolute calibration[1] will not be reviewed here. As in all these earlier studies, the observed L_α signals were measured as functions of target pressure (typically 0.5×10^{-4} to 3.0×10^{-4} Torr) and extrapolated to zero pressure when necessary. The L_α emissions were again observed at right angles to the fast-beam axis at a distance of 4.3 cm into the target cell, and the measured polarizations[1] of the L_α emissions were used to correct for the anisotropies of the L_α signals.

In contrast to our earlier studies, however, the source of the L_α emitted from the collisions of interest here could not be determined uniquely. Dissociative excitation of the target H_2 (or of collisionally produced $H_2{}^+$) can occur during these reactions, and no experimental provisions were available to separate such a L_α emission from that resulting from direct projectile excitation (for H-impact collisions) or electron-capture processes (for H^+-impact collisions). Thus the detailed unfolding of the observed L_α emission into the parts associated with direct projectile-2*p*-state population and cascade population of the projectile 2*p* state from higher-lying *nl* states that was made in the earlier studies is not possible here. Nevertheless, it is still possible to deduce the total L_α-emission cross sections for these reactions from the available experimental information, as will be discussed below.

In spite of this limitation of the detailed understanding of the source of the L_α emission from $H+H_2$ and H^++H_2 collisions, it is important to know the total L_α-emission cross sections for these reactions. They can occur in various astrophysical environments, and during proton auroras in the atmospheres of the Jovian planets. A knowledge of these L_α-emission cross sections should also find applications in studies of a variety of hydrogen-discharge phenomena, and in quantifying the projectile-energy-loss mechanisms operative in the cooler regions (and injection sources) of magnetically confined fusion reactors.

II. RESULTS OF THE MEASUREMENTS

The L_α-emission cross sections, measured by observing photons from the collisions at a distance of 4.3 cm into the target cell and subsequently called $\sigma_m(L_\alpha)$, are plotted as the circular data points in Fig. 1. The uncertainties[7] in these $\sigma_m(L_\alpha)$ values are everywhere about $\pm15\%$ for the H-impact data and for the H^+-impact data down to 0.2-keV H^+ energy, below which they increase to about twice this value. While not shown in Fig. 1, the $\sigma_m(L_\alpha)$ values for H^++H_2 collisions closely follow an E^3 dependence on H^+ energy down to 0.08 keV, referenced to the value 5.5×10^{-19} cm^2 at 0.16-keV H^+ energy. These plotted $\sigma_m(L_\alpha)$ have been corrected for the polarizations of the L_α radiation,[1] using the polarization data shown in Fig. 2.

The $\sigma_m(L_\alpha)$ plotted in Fig. 1, however, are not the total L_α-emission cross sections for these reactions. Because the radiative lifetimes of the excited *ns* states of hydrogen are quite long ($>1.5\times10^{-7}$ s), some of the L_α produced by the $ns\rightarrow2p\rightarrow1s$ cascade decay sequences from the rapidly moving excited H atoms produced in the reactions will escape detection at only 4.3 cm into the target cell. In contrast, most such L_α from the (shorter-lived) *nd*-state-cascade terms will be observed at 4.3 cm into the cell,[8] as will virtually all the L_α resulting from direct projectile-2*p*-state population or from any target-dissociation processes.

For the case of $H+H_2$ collisions, the (projectile-velocity-dependent) fractions of L_α not observed during the measurements for this reason were calculated from the cross sections for (fast) $H^*(3s)$ and $H^*(4s)$ production for this reaction reported by Van Zyl *et al.*,[9] and estimated for the still-higher-lying *ns* states using the cross-section-scaling procedures developed earlier.[1] This component of the L_α emission was then added to the measured $\sigma_m(L_\alpha)$ values to obtained the total L_α-emission cross section, shown by the solid-line curve la-

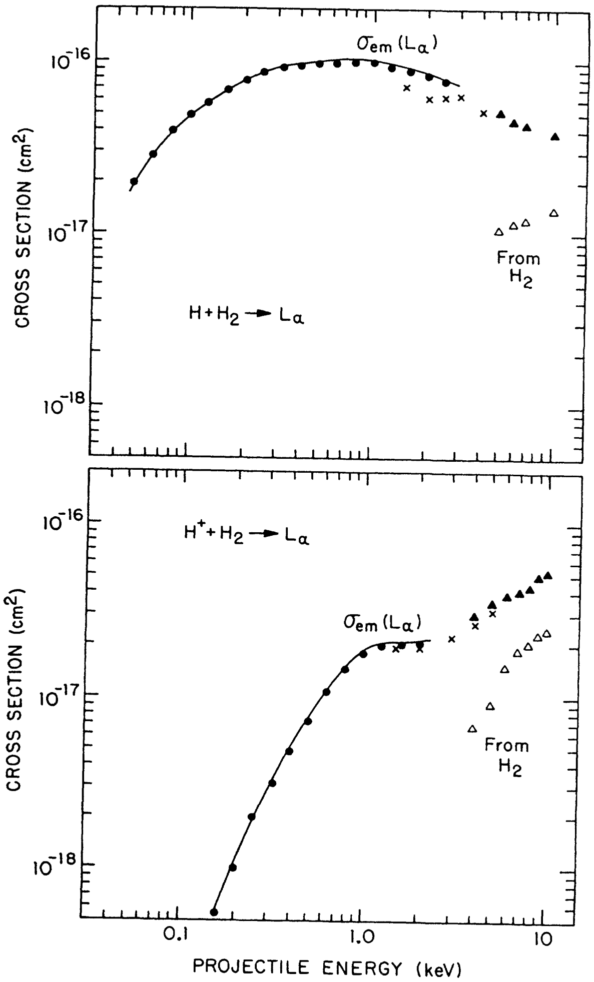

FIG. 1. Cross sections for L_α emission from $H+H_2$ and $H^+ + H_2$ collisions. The data points shown are from: ●, present results; and ×, ▲, △, Birely and McNeal (Ref. 14).

beled $\sigma_{em}(L_\alpha)$ in Fig. 1. As can be seen, the upward revision of $\sigma_m(L_\alpha)$ made to obtain $\sigma_{em}(L_\alpha)$ by this procedure is quite small, being everywhere less than 4%.

Unfortunately, no comparable data for (fast) $H^*(3s)$ and $H^*(4s)$ formation are available for the case of $H^+ + H_2$ collisions. However, Williams *et al.*[10] have measured the $H^*(3s)$-production cross section for this reaction down to 1.5-keV H^+ energy. This cross section exhibits a (secondary) maximum near 3-keV H^+ energy, below which it begins to decrease with H^+ energy in a way very similar to those found for H^+ impact on N_2 and Ar targets,[11,12] approaching an E^2 dependence on H^+ energy near 0.5 keV. Because N_2 and Ar have ionization potentials close to that for H_2, the energy defects for all these reactions are about the same, so such similarities in the H^+-energy dependences of these cross sections are not unreasonable.

We have thus assumed here that the (fast) $H^*(3s)$-production cross section for $H^+ + H_2$ collisions has the values, in units of 10^{-19} cm^2, of 9.0 at 2 keV (as given by Williams *et al.*[10]), 5.7 at 1 keV,and 1.9 at 0.5 keV, and decreases in proportion to E^2 with decreasing H^+ energy below 0.5 keV. We have then used the *ns*-state cross-section scaling laws found for H^+ impact on Ar, Kr, Xe, N_2, and O_2 targets[3] to estimate the higher $H^*(ns)$-production cross sections for $H^+ + H_2$ collisions. Using these assumed data, we calculated the fractions of the L_α emission produced via these cascade processes missed by the measurements made at 4.3 cm into the target cell in the same way as described above for $H+H_2$ collisions.

The $\sigma_{em}(L_\alpha)$ for $H^+ + H_2$ obtained by this procedure is again plotted as a solid-line curve in Fig. 1. Here, the increase in the measured $\sigma_m(L_\alpha)$ values required by this analysis is even smaller than for the case of $H+H_2$ collisions discussed above, being only about 2%, for example, at 1-keV H^+ energy. Thus, for the low H and H^+ energies of interest here, the fractions of the total L_α emission from such $ns \rightarrow 2p \rightarrow 1s$ cascade processes not observed during the measurements is quite small.

We have made a similar (but much more approximate) analysis of the fractions of the total L_α emission resulting from $nd \rightarrow 2p \rightarrow 1s$ cascade processes[8] that might have been missed during the measurements made at 2-keV projectile energy. This study suggested upper limits for these fractions on the order of a few percent for these reactions, so some small additional upward revision of the $\sigma_{em}(L_\alpha)$ shown in Fig. 1 at the higher projectile energies might be required.

However, it is also possible that some small fraction of the total uv emission observed to come from these collisions was not L_α. Indeed, both the Lyman and Werner systems of H_2 have emission bands in the spectral region near L_α, some of which can be transmitted by the O_2-gas filter[13] used to spectrally isolate the L_α emission in the measurements made here. While our studies of the relative photon signals observed with the filter containing 720 Torr of O_2 and subsequently evacuated[1] suggest that this contribution to the total photon signal should be quite small (particularly for $H+H_2$ collisions), the possibility of such emission contamination at the level of a few percent cannot be eliminated. This would require a small downward revision of both the $\sigma_m(L_\alpha)$ and $\sigma_{em}(L_\alpha)$ shown in Fig. 1.

The effects of the two potential problems discussed above thus appear to be quite small (and, in fact, tend to cancel one another). We therefore believe that the

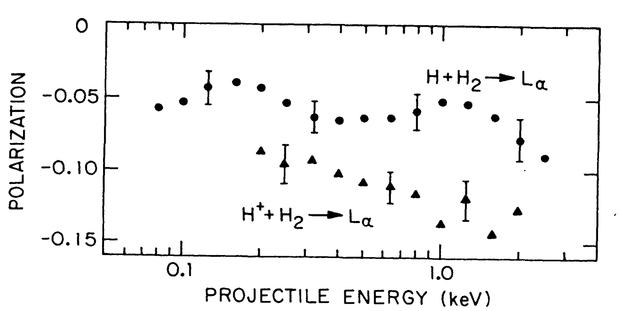

FIG. 2. Measured polarizations of L_α emission from $H+H_2$ and $H^+ + H_2$ collisions.

$\sigma_{em}(L_\alpha)$ curves shown in Fig. 1 should be accurate to within ±18% for $H+H_2$ collisions, and to within ±20% for $H^+ + H_2$ collisions.

Although our purpose here is not to compare these L_α-emission cross sections with the numerous other measurements that have been made (most at much higher projectile energies), we do show in Fig. 1 the data obtained by Birely and McNeal[14] for projectile energies below 10 keV. These studies were made by observing the L_α from the collisions at 5 cm into a target cell, so that their $\sigma_m(L_\alpha)$ should be similar to those obtained here. Their data shown by the solid triangles in Fig. 1 were obtained by viewing the L_α emission at the magic angles (54.7° and 125.3° to the beam axis) where no radiation-polarization corrections are needed. However, they also made measurements down to 1.5-keV projectile energy by observing the L_α emission at 90° to the fast-beam axis, which results are plotted as crosses in Fig. 1.

While these data of Birely and McNeal[14] in the 2-keV projectile-energy range should be adjusted slightly upward (because of the negative polarizations of the L_α emission shown in Fig. 2), their results for $H+H_2$ collisions are still about 20% below those obtained here. This is quite typical of similar comparisons made for H impact on other target species,[2,4] and we have attributed[2] this difference to the method used by Birely and McNeal[15] to calibrate their L_α detector. Surprisingly, however, this discrepancy appears not to be present for the case of L_α emission from $H^+ + H_2$ collisions, even though it is present for similar comparisons involving H^+ impact on N_2 and O_2 targets.[4] We can offer no satisfactory explanation for this inconsistency here.

However, the basic reason for showing these data of Birely and McNeal[14] here is to include their measurements of that part of the total L_α emission from these reactions that results from target H_2 dissociative excitation. These data are shown by the open triangles in Fig. 1. Note that this part of the total L_α emitted from these reactions is less than 50% at 10-keV projectile energy, and appears to be headed towards much smaller fractions at the lower projectile energies of interest here.

This situation, in addition to the considerable similarities exhibited by these data and those for the same reactions involving H and H^+ impact on other targets,[2–4] leads us to the conclusion that most of the total L_α emission observed during these measurements results from the production of fast excited H atoms during the collisions. In particular, the large cross section for (projectile) H-atom excitation in $H+H_2$ collisions at projectile energies below 1 keV is typical of what has been found for many of the other targets investigated, and may again be the result of the transient existence of Coulomb ion-pair states[2] during the interactions.

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[7]The uncertainties cited here were determined by quadrature combination of all the known individual uncertainties influencing these measurements. The uncertainties are dominated by that associated with the absolute calibration of the L_α detector (see Ref. 1).

[8]This is true for cascading transitions originating from the 3*d* and 4*d* states of hydrogen, but becomes increasingly invalid for higher *nd* states because of their longer radiative lifetimes.

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