exchange takes place, it is of much shorter range.

IV. DISCUSSION

The results obtained in this paper for the charge-exchange reaction

$$H + Be^{++} \to H^{+} + Be^{+}$$

are of interest from several points of view.

First, the methods which we have employed yield cross sections at low energies for which conventional linear-trajectory methods are not at all applicable. In this connection it is worth noting that our technique may be extended in a straightforward manner to more complex systems. The proton–hydrogen-atom exchange reaction previously studied represented a "six-state" calculation and an application to atom-molecular collisions is currently under way.

From the point of view of understanding a reaction process our method is particularly suitable. The phenomenon of multiple electron exchange characterizing charge-exchange reactions is a simple analogue of the type of process commonly conceived for more complex reactions. For example, it is thought that a "transition state" may execute several vibrations before energy is distributed in such a way as to facilitate the conversion from reactants to products. It is hoped that the present methods may be applied to such processes in the near future.

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Cross Sections for the Production of Lyman-α Radiation by Fast-Proton Impact on H_2†

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Absolute cross sections have been measured for the production of Lyman-α radiation by proton impact on H_2 in the energy range from 20 to 120 keV. Radiation from slow H atoms produced by dissociative excitation of the H_2 molecule was separated from the radiation from fast hydrogen atoms produced by electron capture by using a Doppler-shift technique. Reasonable agreement is obtained with other investigators where the cross sections overlap. The fast-atom emission exhibits a sharp monotonic decrease with energy, characteristic of charge transfer. The slow-atom emission also monotonically decreases with energy but not nearly as rapidly. It is estimated that about 4% of the total charge transfer goes into producing fast atoms in the $2p$ state.

INTRODUCTION

Lyman-α ($2p \to 1s$) radiation from fast-proton impact on H_2 can be produced by several reactions. They are

$$\underline{H}^{+} + H_2 \to \underline{H}^{+} + H + H(2p) \tag{1}$$

$$\to \underline{H}^{+} + H^{+} + H(2p) + e \tag{2}$$

$$\to \underline{H} + H^{+} + H(2p) \tag{3}$$

$$\to \underline{H}(2p) + H_2^{+} , \tag{4}$$

where the underlined species represent the fast particle. Reactions (1), (2), and (3) produce slow Lyman-α emitters by dissociative excitation of the target H_2 molecule. Reaction (4) produces a fast-atom emitter through the process of electron capture by the incident proton.

Production of Lyman-α radiation by proton impact on H_2 has been experimentally studied by several investigators. Van Zyl *et al.*[1] have measured the radiation emitted perpendicular to the proton-beam direction, using an oxygen-filtered helium-and-iodine-filled counter, in the range from 1 to 25 keV. Andreev *et al.*[2] separated the fast-atom emission [reaction (4)] from the slow-atom emission by using the Doppler effect. The emissions were viewed at an angle to the proton beam with a vacuum monochromator spectrally resolving the slow- and fast-atom emissions. Their range was from 10 to about 35 keV. Dahlberg *et al.*[3] also used a vacuum monochromator but no attempt was made to resolve the fast and slow emissions since they observed only at 90° to the beam. Their energy range was from 20 to 130 keV. McNeal and Birely[4] have measured both the fast and slow emissions by observing them both at 90° and at an angle of 54.5° with their oxygen-filtered detector. Since the Doppler shift at 54.5° is appreciable relative to the band pass of the O_2 filter, the fast-atom emission is greatly attenuated at this angle. The O_2 transmission coefficients for the unshifted emissions and the shifted emissions were determined for each energy by the observation of the transmission of the filter for H^+ impact on Ar at 90° and 54.5°.

EXPERIMENTAL TECHNIQUE

Our technique for separate determinations of the fast- and slow-atom emission cross sections is similar to that of McNeal and Birely since we also used an O_2 filter for isolating the Lyman-α radiation. The Doppler-shift technique using an O_2-filtered counter was also used by Stebbings *et al.*[5] for studying proton impact on H.

The counter was a helium-and-iodine-filled counter,[6] similar to the one used by Stebbings *et al.*[5] The fast-atom emission was attenuated when the counter was positioned to detect photons emanating at an angle of 75° to the beam direction by Doppler shifting the fast-atom emissions to the short-wavelength side of the unshifted Lyman-α wavelength. Shifting the radiation to the short-wavelength side takes advantage of a very rapid increase in absorption of the O_2 filter as the wavelength decreases from the Lyman-α wavelength.[7]

The transmission coefficients for the filter (an absorption path of 1.5 cm at 1 atm) were determined for the Doppler-unshifted radiation and the Doppler-shifted Lyman-α radiation by observing signals from the 90° and 75° positions using the radiation from H^+ on Ne which contains no Ne emissions within the spectral window of the unfiltered counter.[8]

The analysis of the Doppler-shift technique used in this investigation with the O_2 filter is as follows. Let

$$Q_0(H_2) = Q_0(fH) + Q_0(SH) + Q_0(BG) = [Q_0(H_2)/Q_0(Ne)][Q_0(Ne)] , \tag{5}$$

$$Q_1(H_2) = a_1 Q_0(fH) + b_1 Q_0(SH) + c_1 Q_0(BG) = [Q_1(H_2)/Q_1(Ne)][Q_1(Ne)] , \tag{6}$$

$$Q_1'(H_2) = a_1' Q_0(fH) + b_1 Q_0(SH) + c_1 Q_0(BG) , \tag{7}$$

$$Q_1(Ne) = a_1 Q_0(Ne), \tag{8}$$

$$Q_1'(Ne) = a_1' Q_0(Ne) , \tag{9}$$

$$b_1 \approx [Q_1(Ne)]/[Q_0(Ne)]\big|_{20\,\mathrm{keV}} , \tag{10}$$

where $Q_0(H_2)$ and $Q_0(Ne)$ are the apparent cross sections for the production of radiation by H^+ impact on H_2 and Ne, respectively, that is passed through the unfiltered detector spectral window (1050 to 1317 Å); $Q_0(fH)$ and $Q_0(SH)$ represent the no-filter apparent Lyman-α cross sections for fast H atoms and slow H atoms, respectively; $Q_0(BG)$ is the no-filter apparent cross section for producing background radiation other than Lyman α that passes through the counter spectral window. The apparent cross sections designated by the subscript "1" are the corresponding filter cross sections. The unprimed and primed filter cross sections are the apparent cross sections at 90° and 75°, respectively. It is assumed that the no-filter apparent cross sections (subscript "0") are independent of the angle (the no-filter detector sensitivity does not change appreciably over the small Doppler-shift range in wavelength). The coefficients a_1, b_1, and c_1 are the filter transmission coefficients at the unshifted Lyman-α wavelength from the fast atoms, unshifted Lyman α from the slow atoms, and the (unshifted) background wavelengths, respectively; a_1' is the filter transmission coefficient at the shifted Lyman-α wavelength and is generally much less than a_1. [Generally $a_1 < b_1$, because of the Doppler-broadening effects in the fast-atom emission caused by the finite cone of radiation accepted by the detector. However, at 20 keV the Doppler correction is small, hence, Eq. 6.]

Subtracting Eq. (7) from Eq. (6) we obtain

$$Q_0(fH) = \left[\frac{Q_1(H_2) - Q_1'(H_2)}{Q_1(Ne) - Q_1'(Ne)}\right] Q_0(Ne) . \tag{11}$$

This gives the fast-atom Lyman-α emission cross section.

We now define a slow-atom emission cross section

$$Q_0(\mathrm{slow}) = (1/b_1)[b_1 Q_0(SH) + c_1 Q_0(BG)] \tag{12}$$

which is related to the emission passed by the O_2 filter. It is generally expected that $c_1/b_1 \ll 1$ so that $Q_0(\mathrm{slow}) \approx Q_0(SH)$. However, this statement may not be true if the molecular background radiation is appreciable and is located near one of the O_2

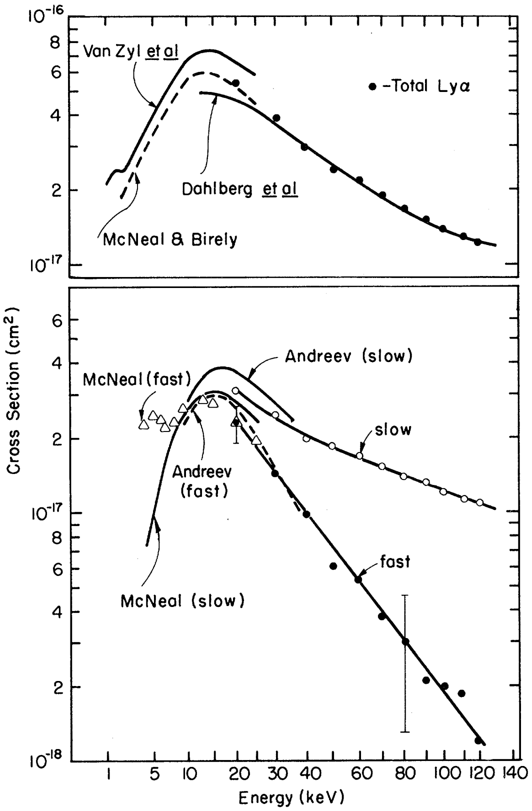

FIG. 1. Upper plot is a graphical display of the total Lyman-α cross sections along with the results of Refs. 1, 3, and 4. The uncertainty in the absolute value of the present cross sections is about ±40%. The lower plot is a graphical display of the fast- and slow-atom emissions along with the results of Refs. 2 and 4. (Energy is plotted on a square root scale.)

transmission windows. It follows from Eq. (7) that

$$Q_0(\text{slow}) = (1/b_1)\,[Q_1'(\text{H}_2) - a_1'\,Q_0(\text{fH})]\,; \qquad (13)$$

since generally $a_1'/b_1 \ll 1$ for our case, $Q_0(\text{slow}) \approx (1/b_1)\,[Q_1'(\text{H}_2)]$.

We further define a "total Lyman-α" cross section

$$Q_T(\text{Ly-}\alpha) = Q_0(\text{slow}) + Q_0(\text{fH})\ . \qquad (14)$$

The cross sections were placed on an absolute basis by determining the ratio $Q_0(\text{H}_2)/Q_0(\text{Ne})$ at 20 and 30 keV. Previously determined absolute values for $Q_0(\text{Ne})$[9] were then used to obtain $Q_0(\text{H}_2)$. The ratio $Q_1(\text{H}_2)/Q_1(\text{Ne})$ was also determined at these energies. It was discovered that $Q_0(\text{H}_2)/Q_0(\text{Ne}) = Q_1(\text{H}_2)/Q_1(\text{Ne})$ to within a reproducibility of 10% with no systematic discrepancy. Thus, values of $Q_1(\text{H}_2)/Q_1(\text{Ne})$ were also averaged in to determine $Q_0(\text{H}_2)/Q_0(\text{Ne})$. The fact that the no-filter ratio is the same as the filter ratio implies that the molecular background is small compared to the Lyman-α radiation $[Q_0(\text{BG}) \ll Q_0(\text{SH}) + Q_0(\text{fH})]$ at 20 and 30 keV in the spectral window of the unfiltered counter.

The ratio $Q_1'(\text{Ne})/Q_1(\text{Ne})$ was nearly 0.06 and 0.05 at 20 and 30 keV, respectively. The ratio rapidly decreased to a negligible fraction at the higher energies. Thus, to a good approximation Eq. (11) becomes

$$Q_0(\text{fH}) \approx [Q_1(\text{H}_2) - Q_1'(\text{H}_2)\,]\,Q_0(\text{Ne})/Q_1(\text{Ne}). \qquad (15)$$

The ratio $Q_0(\text{Ne})/Q_1(\text{Ne})$ is energy dependent because of the Doppler-broadening effect. The ratio at 120 keV differs from that at 20 keV by about 30%. [Equation (11) was actually used in evaluating $Q_0(\text{fH})$ even though the difference between Eq. (11) and Eq. Eq. (15) is only about 6% at 20 keV and is less at the higher energies.]

RESULTS AND DISCUSSION

Figure 1 includes a plot of our total Lyman-α cross sections which include a Doppler correction for the fast-atom emission. The uncertainty in the absolute value of the cross sections is estimated to be about 40%. Also plotted are the results of Dahlberg *et al.*[3] from 20 to 130 keV. Their experiment involved measurements at 90° to the beam with a spectrometer. Since they could scan through the background radiation at the Lyman-α wavelength, they presumably could subtract off the molecular background and actually obtain Lyman-α radiation free from the molecular background. According to Ref. 3, they normalized to the value obtained by Van Zyl *et al.*[1] at 25 keV, which was obtained with an O_2 filter. However, there appears to be a discrepancy between the two sets of data at this energy. It is unclear how Dahlberg *et al.* reached calibration; however, there is good agreement between the shape of their curve and our curve from 30 to 120 keV. If our conjecture is correct that there is little molecular background compared with Lyman-α in the unfiltered detector spectral window at 20 and 30 keV, then the agreement with the shape of Dahlberg's curve at the higher energies implies that the background is also small at the higher energies. Figure 1 also shows excellent agreement with McNeal and Birely at 20 keV where the two sets of data overlap. Such agreement is to be expected since the two laboratories have essentially the same optical calibration. The apparatus of Birely and McNeal was calibrated[9] by normalizing to the measurements of Pretzer *et al.*[10] and Andreev *et al.*[8] for the production of Lyman-α radiation by H^+ impact on Ar. The present apparatus was calibrated[11] by normalizing to Pretzer *et al.*[10] for H^+ on He, Ne, and Ar. This procedure produced cross sections in good agreement with Andreev.[8] Lyman-α measurements for H^+ impact on O_2 and N_2 taken with the present apparatus[11] are

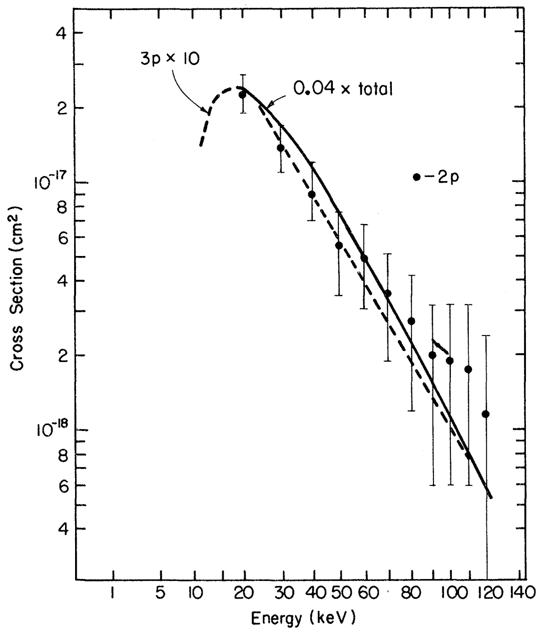

FIG. 2. Plot of the direct $2p$ capture cross sections (cascade corrected) along with a scaled version of the $3p$ cross sections (Ref. 12) and the total capture cross sections (Ref. 13).

also in agreement with those taken by Birely and McNeal.[9]

Also shown in Fig. 1 are our fast-atom cross sections [Q_0(fH)] which are measures of charge capture into the $2p$ state, and our slow-atom cross sections [Q_0(slow)] which are measures of the dissociative excitation of the target H_2 molecule producing H atoms in the $2p$ state. Plotted also are the fast- and slow-atom cross sections as determined by McNeal and Birely[4] and by Andreev *et al.*[2]

Error bars on the fast-atom cross-section curve indicate the estimated relative error in subtracting the slow-atom curve from the total Lyman-α curve. The error gets very large at the high energies where the fast-atom emissions are small compared with the slow-atom emission.

Figure 2 shows our values for direct capture into the $2p$ state. This curve is the fast-atom curve corrected for cascade based on $3s$ and $3d$ measurements.[12] (Cascade from the d states is negligible compared with s cascade.) The cascade correction was always less than 10%.

Also shown are the $3p$ cross sections scaled up by a factor 10. If the capture followed an n^{-3} behavior, then it would be expected that scaling the $3p$ by a factor of 3.4 would superimpose the two curves. There is considerable error in both the $3p$ and $2p$ curves, but it does indicate that an n^{-3} scaling of p-state capture, unlike the s-state capture, may not be a particularly valid procedure for all gases.[11] Also plotted is a scaling of the total charge-capture cross-section curve which seems to indicate that about 4% of the total capture[13] for H^+ on H_2 goes into the $2p$ state. This percentage is very close to that obtained for H^+ impact on the diatomic gases O_2 and N_2.[11]

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