In Fig. 2 is shown the experimental H_α-line profile of Birkeland *et al.*[6] for an electron density of 1.5×10^{17} electrons/cm^3 and electron temperature of 1.74×10^4°K. Also shown for comparison are several theoretical line profiles calculated from Eq. (1) using different approximations. From this figure one can see the relative importance of the various effects on the theoretical profile. The GKS curve neglects the strong interaction, considers only broadening of the upper level and the central component of the lower level, and uses the Ecker distribution function. Substituting the Mozer-Baranger distribution function for the Ecker function (everything else unchanged) has only a small effect on the line shape as shown by the curve marked "BE-without strong interaction." It is expected that the distribution function proposed by Hooper[10] would also have a small effect at the center and near wings of the line. The effect of considering only broadening of the central component in the lower level is about the same as considering broadening of all the components in the lower level. This profile would coincide with the curve marked "BE-without strong interaction" and is not shown. When the strong-interaction effects, the Mozer-Baranger distribution functions, and broadening for both the upper and lower levels with cross terms are included there is close agreement between the experimental and theoretical profiles. The theoretical profile is then given by the curve marked "BE-with strong interaction." Neglecting strong interaction and broadening of the lower level, but with the Mozer-Baranger distribution function, the profile (not shown in Fig. 2) would have a half-width about 30% smaller than the experimental half-width. From Fig. 2 one can see that the major effects on the profile are the strong interaction and the broadening of the central components in the lower level. It is to be expected that the strong-interaction effects will be appreciable for those lines having an unshifted central component (L_α,L_γ,H_α,H_γ, etc.) and have a smaller effect on those lines with a shifted central component (L_β,L_δ,H_β,H_δ, etc.).

H_α-line profiles have been calculated[11] using this modified theory for electron densities and temperatures within the range from 10^{16} to 10^{20} electrons/cm^3 and 10^4 to 10^5 °K, respectively, wherever the ion-distribution functions of Mozer and Baranger and the GKS II theory are valid. These higher densities and temperatures correspond to typical values in the laser-produced plasmas reported by Edwards and Litvak.[12] Using the ion-field distributions of Hooper[10] should yield more accurate results than the Mozer-Baranger functions, especially for the high-density high-temperature plasmas. Lyman-α profiles were also calculated[11] using this same modified theory. Experimental profiles of L_α corrected for self-absorption were not available for making a comparison similar to that made for H_α. This modified theory is also being used to calculate H_γ profiles in an attempt to find closer agreement between theory and experiment.[3]

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[10] C. F. Hooper, Phys. Rev. **149**, 77 (1966).

[11] M. E. Bacon and D. F. Edwards, Colorado State University, Physics Department Technical Report No. TR-68-1 (unpublished).

[12] M. M. Litvak and D. F. Edwards, J. Appl. Phys. **37**, 4462 (1966); IEEE J. Quant. Electron. **QE-2**, 486 (1966).

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Vacuum Ultraviolet Emission Produced by Proton and H-Atom Impact on H_2†

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The spectrum in the wavelength range 1200 to 1700 Å excited by proton and hydrogen-atom collisions with hydrogen molecules has been investigated under thin-target conditions. The prominent features of the spectrum are bands originating from the B and C states of H_2 and the Lyman α line of atomic hydrogen. Relative cross sections are presented for the emission of Lyman α and the Lyman band emission from the B state of H_2 due to proton and hydrogen-atom impact in the energy range 20–130 keV. Absolute values of these cross sections are estimated by comparison with known cross sections for Lyman α. A calculation of the cross section for proton excitation of the sum of the B and C states of H_2 in the first Born approximation is presented and compared with the experimental results for the B state.

INTRODUCTION

THE homonuclear diatomic molecule is one of the simplest molecular structures. A collision between the proton and H_2 is the least complex ion-molecule interaction and the collision between the hydrogen atom and H_2 is the simplest atom-molecule

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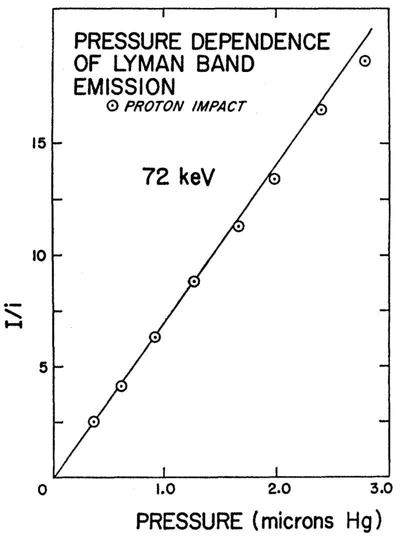

FIG. 1. Light intensity per incident proton as a function of energy for the Lyman bands of H_2 centered around 1606 Å.

interaction. These facts have influenced extensive work in collisions involving this molecule and are responsible for the study of the optical emissions presented in this paper.

Spectral scans of the light in the spectral region from 1200 to 7000 Å emitted in the collisions of protons and hydrogen molecules indicated which band systems were strongly excited by these collisions and the extent of the dissociation resulting in excited hydrogen atoms. These scans indicated that the most intense optical emissions were in the vacuum ultraviolet region of the spectrum and that it was possible to measure relative emission cross sections for the Lyman bands ($B2p\sigma{}^1\Sigma_u{}^+ - X1s\sigma{}^1\Sigma_g{}^+$) and the Lyman α line at 1216 Å. The cross sections for these emissions were measured as a function of incident-particle energy for both protons and hydrogen atoms in the energy range 20–130 keV. The experimental apparatus and procedure are described in a previous paper.[1]

Preliminary experiments revealed a linear relationship between the light intensity per incident particle and pressure of the target gas for sufficiently low pressures. Figure 1 shows the linear relationship between light intensity per incident proton and pressure for a group of bands centered around 1606 Å.

RESULTS

The emission spectrum produced by protons incident upon hydrogen molecules was scanned with a monochromator from 1200 to 7000 Å. The scans above 1700 Å are not shown since, excepting the Balmer lines, the emissions that appeared were weak. Below 1700 Å the Lyman bands (B–X), the Werner bands (C–X), and the Lyman α line dominated the spectrum (Fig. 2). The molecular bands have a total intensity that is the same order of magnitude as the intensity of Lyman α. The complexity of the band spectrum and the low light intensity did not permit resolution of individual lines in the spectrum. A study of the wavelengths indicated which vibrational bands contributed to the observed emissions. These conclusions will be discussed later.

Lyman Band System

Relative emission cross sections were measured as a function of incident-particle energy for two groups of bands in the Lyman system. The experimental emission cross section (shown as a solid curve) for the group of bands centered about 1606 Å is shown in Fig. 3. The emission cross section for hydrogen-atom impact was measured for a single energy because of the ineffectiveness of hydrogen atoms in producing excitation.

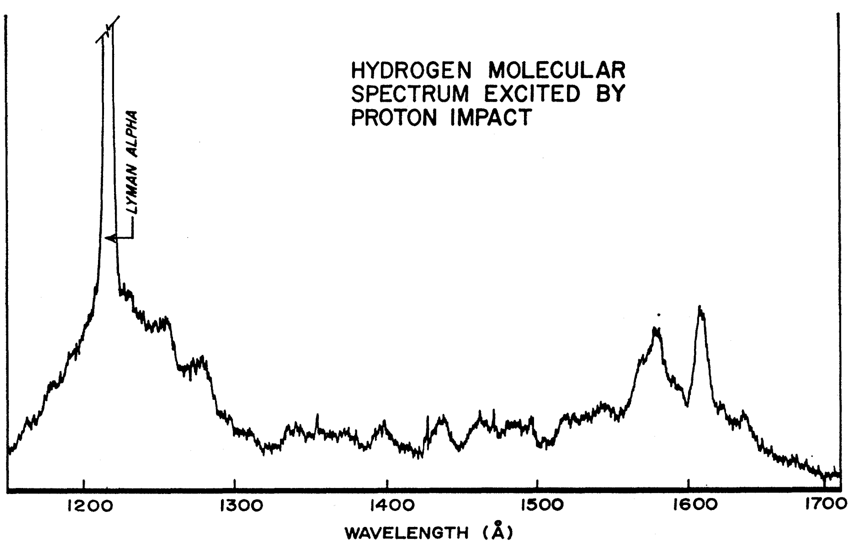

FIG. 2. Spectrum produced by a 10-μA beam of 55-keV protons incident on hydrogen gas at a pressure of 27 μ of Hg. Monochromator slits equivalent to 5.5 Å. (The relatively high pressure is used to enhance the spectrum.)

[1] D. A. Dahlberg, D. K. Anderson, and I. E. Dayton, Phys. Rev. 164, 20 (1967).

To obtain these data the monochromator, with a slit width equivalent to 16 Å, was set to include a group of bands centered at 1606 Å. This group included the (4,11), (5,12), and (6,13) vibration bands.[2]

The absolute cross section for excitation of the B state is impossible to obtain directly from emission measurements of a group of bands. The total-relative-emission cross section can be estimated from a study of the spectral scan and a knowledge of the slit width of the monochromator. Absolute-cross-section measurements for the production of Lyman α in the collision of protons with H_2 and N_2 have been reported by Van Zyl *et al.*[3] These data have been used to estimate the absolute value for the cross section for the 1606 Å bands shown in Fig. 3. No correction has been made for spectral dependence of the monochromator efficiency or for cascading, since the longer-wavelength transitions populating the B state were observed to be weak.

The emission cross section for the bands in the spectral region around 1575 Å were also measured as a function of proton energy. The probable bands contributing to this emission are the (5,11), (6,12), and (7,13). These measurements showed the same energy dependence as did the bands around 1606 Å. Therefore the energy dependence of these cross sections should not differ significantly from the cross section for the excitation of the B state.

Lyman α

The emission-cross-section measurements for Lyman α for both proton and hydrogen-atom impact are shown in Fig. 4. These data are normalized at 25 keV to the Lyman α data of Van Zyl *et al.*[3] In the case of proton impact the Lyman α intensity is due to electron capture into excited states by the proton as well as dissociation of the molecule into excited atomic states. In the case of hydrogen-atom impact the direct excitation of the projectile also contributes to the Lyman α intensity, especially at the higher energies. For proton impact at the higher energies, the main contribution to the Lyman α emission is expected to be the dissociation of the hydrogen molecule. This expectation is based upon the fact that the charge-exchange cross section decreases rapidly with energy. This interpretation is supported by proton excitation of the nitrogen molecule where excitation of the projectile can easily be distinguished from that of the target.[1] The experimental cross sections for the emission of the Lyman α line and an atomic nitrogen line due to proton impact on N_2 are presented in Fig. 5 where they are compared to the Lyman α cross section for proton impact on H_2. The sum of the two N_2 cross sections gives a curve that is similar to the H_2-cross-section curve.

[2] G. Herzberg and L. L. Howe, Can. J. Phys. **37**, 636 (1959).
[3] B. Van Zyl, D. Jaecks, D. Pretzer, and R. Geballe, Phys. Rev. **158**, 29 (1967).

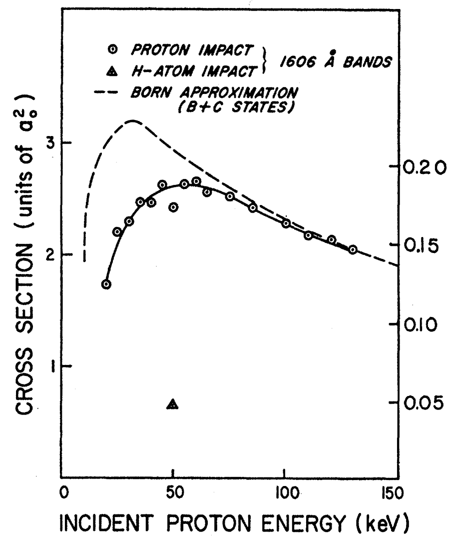

FIG. 3. Cross sections for the emission of the Lyman bands centered at 1606 Å produced by proton and hydrogen atom impact (right-hand scale). The dashed line is the result of evaluating formula (3) (left-hand scale). a_0 is the Bohr radius.

DISCUSSION

The excitation of the B state of the hydrogen molecule by proton impact is evidently a simple and direct process without complications due to dissociation and charge exchange. The Bethe-Born approximation[4] for dipole excitation predicts a cross section that depends on the projectile energy E as $E^{-1}\ln E$ for high energies. The domain of validity for this formula can be determined experimentally by noting the onset of a linear region in a plot of QE against $\ln E$ where Q is the observed cross section. In the case of the B state of the hydrogen

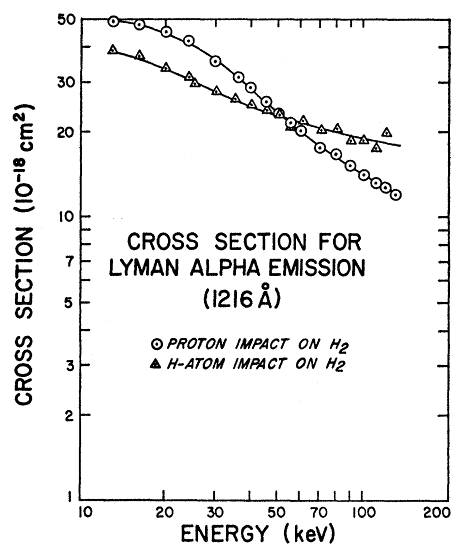

FIG. 4. Cross sections for the production of Lyman α by protons and hydrogen atoms incident on H_2.

[4] H. Bethe, Ann. Physik **5**, 325 (1930).

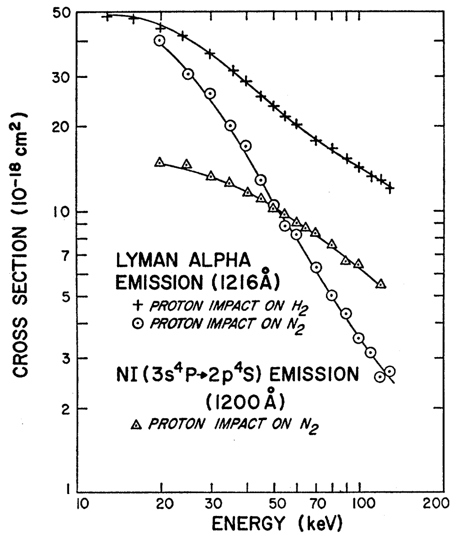

FIG. 5. A comparison of Lyman-α emission and atomic nitrogen emission under proton impact.

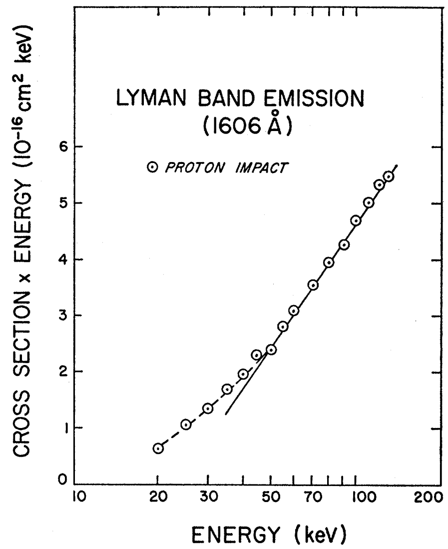

FIG. 6. Cross section for the emission of the Lyman bands centered at 1606 Å produced by proton impact, plotted in terms of QE as a function of $\ln E$.

molecule such a plot reveals a linear behavior for proton energies above 60 keV (Fig. 6). Green[5] has pointed out that the first Born approximation for proton excitation may be evaluated without detailed knowledge of the molecular wave functions by utilizing the generalized oscillator strengths (or form factors) measured by inelastic scattering of high-energy electrons. The differential cross section for the scattering of 25-keV electrons resulting in the excitation of the sum of the B and C states of H_2 has been measured by Geiger.[6] The cross section Q for proton excitation is

$$Q=\int \frac{dQ}{d\Omega}d\Omega. \tag{1}$$

This can be converted to an integration over the momentum transfer K by using for the differential solid angle $d\Omega$ the relation

$$d\Omega=\left(\frac{2\pi}{V^2}\right)KdK. \tag{2}$$

Here V is the velocity of the proton in atomic units. The cross section is then

$$Q=\left(\frac{2\pi}{V^2}\right)\int_{K_{\min}}^{K_{\max}} \frac{dQ}{d\Omega}KdK. \tag{3}$$

Here, $K_{\min}=k-k_n$, where k is the initial momentum and k_n is the final momentum.

$$k_n=[2m_p(E-\Delta E)]^{1/2}, \tag{4}$$

where m_p is the mass of the proton, E is the initial energy of the proton, and ΔE is the energy loss due to the collision. For the excitation of the B and C states Geiger[6] gives $\Delta E=12.6$ eV. Since $E\gg\Delta E$, it is a very good approximation to use $K_{\min}=\Delta E/V$. This limit is thus independent of the projectile mass.

$$K_{\max}=[2M/(m_p+M)]k,$$

where M is the mass of the target molecule. A numerical integration of Eq. (3) using these limits and Geiger's experimental values for the integrand gives the total cross section for proton excitation of the B and C states of H_2. These results are shown in Fig. 3 along with the experimental results for the excitation of a group of bands centered around 1606 Å. The data show a significant deviation from the shape of the Born approximation for proton energies below 60 keV. A crude comparison of the magnitudes of the experimental and theoretical cross sections can be obtained from the total intensity of the molecular spectrum in Fig. 2. Such a comparison gives order-of-magnitude agreement at 55 keV.

ACKNOWLEDGMENTS

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[5] T. A. Green, Phys. Rev. **157**, 103 (1967).
[6] J. Geiger, Z. Physik **181**, 413 (1964).