THE ASTROPHYSICAL JOURNAL, 407:820–825, 1993 April 20

ELECTRON EXCITATION OF THE $H_2(a\ ^3\Sigma_g^+ \rightarrow b\ ^3\Sigma_u^+)$ CONTINUUM IN THE VACUUM ULTRAVIOLET

J. M. AJELLO
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109
AND
D. E. SHEMANSKY
Aerospace Engineering Department, University of Southern California, Los Angeles, CA 90089
Received 1992 July 1; accepted 1992 October 16

ABSTRACT

The electron excitation function for the $H_2(a\ ^3\Sigma_g^+ \rightarrow b\ ^3\Sigma_u^+)$ continuum emission has been measured from 11 to 30 eV at 195.0 nm. The emission cross section data have been combined with electron energy loss cross section measurements (Khakoo & Trajmar 1986) to extend the experimental data to 60 eV. The excitation cross section has been estimated by normalizing the data to the electron energy loss cross section at 20 eV and using a model to account for emission from the entire band system (120–500 nm). The spin forbidden excitation of the $a\ ^3\Sigma_g^+$ state is a major dissociative channel of H_2 at low energy with a peak cross section of $1.7 \pm 0.85 \times 10^{-17}$ cm^2 at 15.5 eV. The full width at half-maximum (FWHM) of the cross section is 7 eV. The high energy dependence of the cross section has a rapid $1/E^3$ fall off with electron energy, E, above 50 eV. A modified Born approximation analysis was applied to the data to provide an analytic model.

Subject heading: molecular processes

1. INTRODUCTION

Planetary exploration has pointed out the need for accurate electron impact excitation cross sections for H_2. The partitioning of energy in deposition processes in the outer planet atmospheres (Shemansky & Hall 1992) requires accurate measures of dissociation rates in H_2 particularly at low electron energies. A contributing process is the release of two fast H atoms in the $H_2(a\ ^3\Sigma_g^+ \rightarrow b\ ^3\Sigma_u^+)$ transition. The quantum yield in the threshold energy region between vacuum ultraviolet (VUV) emission production by the band systems of the singlet and triplet states and dissociative production of fast H(1s) atoms by the triplet states is essential for energy budget modeling in planetary atmospheres and astronomy. The $H_2(a\ ^3\Sigma_g^+ \leftarrow b\ ^3\Sigma_u^+)$ continuum is also a source of absorption in stellar atmospheres of main-sequence stars (Doyle 1968a, b).

Laboratory measurements of electron impact cross sections for H_2 in the threshold region are also needed to provide basic constraints for ab initio calculations. A broad definition of the threshold region extends to 100 eV. This region is consistent with the wide separation of vibrational levels in H_2 leading to measurable threshold effects to almost 100 eV (Ajello & Shemansky 1985). The experiment described here provides the excitation function for the emission continuum in the reaction chain

$$H_2(X\ ^1\Sigma_g^+) + e \rightarrow H_2(a\ ^3\Sigma_g^+) + e\ , \quad (1)$$

$$H_2(a\ ^3\Sigma_g^+) \rightarrow H_2(b\ ^3\Sigma_u^+) + h\nu\ , \quad (2)$$

which subsequently leads to

$$H_2(b\ ^3\Sigma_g^+) \rightarrow 2H(1s)\ . \quad (3)$$

The product in reaction (1) contains a number of excited states that cascade to the a-state in the triplet system. Our measurements do not distinguish between cascade and direct contributions to the excitation of the a-state. We assume the contributions by cascade do not significantly affect the shape of the excitation function. An attempt has not been made to establish an absolute cross section internally consistent with this experiment. An absolute scale has instead been established by normalizing to the Khakoo & Trajmar (1986) electron energy loss measurements at 20, 30, 40, and 60 eV, giving the direct excitation cross section for reaction (1). The singlet state excitation cross sections of Khakoo & Trajmar (1986) are in basic agreement with the emission measurements (Shemansky, Ajello, & Hall 1985a; Shemansky et al. 1985b; Ajello et al. 1988), suggesting consistency in results of the two experimental methods.

The excitation function is established in analytic form within the framework of the modified Born approximation introduced by Shemansky et al. (1985a, b). The $a\ ^3\Sigma_g^+$ excitation cross section result is compared to ab initio results of Rescigno et al. (1976), Chung, Lin, & Lee (1975), Chung & Lin (1978), and Lima et al. (1988).

2. EXPERIMENTAL

The experimental apparatus and VUV calibration techniques have been described in detail in earlier papers (Ajello et al. 1984, 1988, 1989, 1990, 1991; Ajello & Shemansky 1985; James et al. 1990; Tripp et al. 1991; Ratliff et al. 1991). There are two independent sets of experimental apparatus in our laboratory with differing spectral resolutions. Each of these systems consists of an electron impact collision chamber in tandem with either an extreme-ultraviolet (EUV) spectrometer which operates from 40–140 nm or a far-ultraviolet (FUV) spectrometer which operates from 110–300 nm. The system utilized is a low-resolution apparatus in whch spectra were obtained at 0.5 nm resolution.

A magnetically collimated beam of electrons is crossed with a beam of gas formed by a capillary array or a static gas target at a background pressure that can be varied from 1×10^{-8} to 3×10^{-4} torr. The capillary array is used for obtaining spectra and the static target mode is used for taking cross section

measurements. The energy width of the electron beam is 0.3 eV. The measurements reported here were made at an angle of 90° between the electron beam axis and optic axis. The absolute energy scale for the electron beam was established by setting the voltage scale to the appearance potential for Ar II (91.96 nm) at 29.24 eV (Ajello et al. 1990).

3. THE $H_2(a\ ^3\Sigma_g^+ \rightarrow b\ ^3\Sigma_u^+)$ CONTINUUM

The triplet states of H_2 are a source of fast H(1*s*) atoms, principally at electron impact energies below 30 eV. The $b\ ^3\Sigma_u^+$ state potential curve is repulsive releasing two H(1*s*) atoms with about 3 eV of kinetic energy per atom (Weingartshofer et al. 1970). The process $H_2(X\ ^1\Sigma_g^+) + e \rightarrow H_2(b\ ^3\Sigma_u^+) + e$ is spin forbidden with a peak cross section at ~15 eV (Nishimura & Danjo 1986). Above 30 eV the doubly excited singlet states of H_2 are a source of fast H(2*s*, 2*p*) atoms (Ajello et al. 1991).

Electron impact excitation of all triplet states leads to production of fast H atoms by direct or cascade excitation of the $b\ ^3\Sigma_u^+$ state. The $a \rightarrow b$ transition is a continuum first extensively studied in emission during the 1930's by Coolidge and coworkers (Coolidge, James, & Present 1936; James, Coolidge, & Present 1935; Coolidge 1944).

The total cross section for electron impact dissociative excitation into fast H atoms from 8–100 eV was measured by Corrigan (1965). An important result of this study is that the maximum cross section for dissociation occurs at 16.5 eV with a value of 9×10^{-17} cm^2. The electron impact excitation cross section for the *b*-state from 12 to 60 eV has been measured by Nishimura & Danjo (1986). Khakoo et al. (1987) have also measured the electron impact cross section for the *b*-state at 20, 30, 40, and 100 eV. Except at 30 eV the agreement for the two sets of measurements of the *b*-state is better than 6%. Although the *b*-state (cross section of 6×10^{-17} cm^2 at 15 eV) is the dominant source of fast atoms (Nishimura & Danjo 1986), transitions through the *a*-state must account for the remainder of the dissociative cross section.

Figure 1 shows the FUV spectrum of electron excited H_2 at 20 eV. The cross-hatched area in the spectrum indicates the bandpass and location for the excitation function measurement of the *a*–*b* emission. The measured excitation function is shown in Figure 2. It is shown with the results of Khakoo & Trajmar (1986) normalized to unity at 20 eV. The excitation function represents emission from the $v' = 1$, 2, 3, and 4 levels of the *a*-state as determined by the location of the spectral bandpass. The Khakoo & Trajmar (1986) data represent the excitation of the entire *a*-state. However we compare the two sets of data on the same basis because threshold effects have little influence on excitation shapes at energies greater than 20 eV. The data are compared in Table 1 together with a model. Table 1A gives the cross section values as a function of energy. Table 1B lists the Franck-Condon factors and excitation energies. The peak cross section is at 15.5 eV. The ratios of the cross sections of the two experiments at 20 and 30 eV are the same within 6%. Beyond 30 eV there is a large discrepancy. The measured emission cross section is larger than the measured excitation cross section by a factor of 3 at 60 eV. The differences may arise from experimental problems inherent in both experiments. It was necessary for Khakoo and Trajmar to extrapolate the differential cross sections from 10°–120° to 0°–180°. In addition the analysis depends on unfolding the energy-loss spectra in the 12–14 eV energy-loss region where many states overlap. On the other hand, the emission experiment with the large electron beam currents (~100 μA) is particularly susceptible to secondary electron excitation at high impact energies where cross sections have fallen by an order of magnitude relative to the low-energy peak. Our conclusion from the analysis of the shape of the energy dependence of the cross section shows that the latter effect is dominant. The effect of the former is to cause a 50% uncertainty into the absolute cross section value. For this reason it was decided to merge the two data sets at 30 eV, using the Khakoo and Trajmar values at 40 and 60 eV. The synthesis of the two fundamentally different data types is valid if cascade cross sections are small or if the energy dependence of cascading and direct excitation is similar. The energy dependence of the laboratory data is compared to theory and experiment for triplet state excitation in Table 2. The available data, theory, and experiment vary as $1/E^3$ for large energy. In Table 2 the relative cross section values are normalized to unity at 30 eV.

The modeling of the data in Table 1A followed a two step process. First, the partial emission cross section represented by

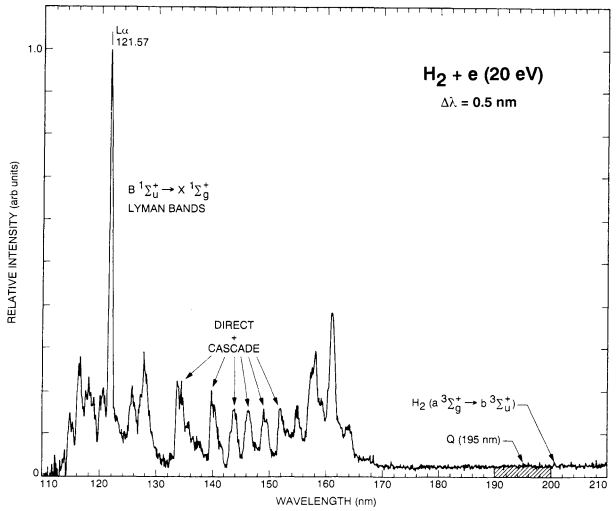

FIG. 1.—FUV spectrum of electron excited H_2 at 20 eV. The calibrated spectrum is obtained at a spectral resolution of 0.5 nm from 110 to 210 nm. The hatched region indicates the wavelength and bandpass for the excitation function measurement.

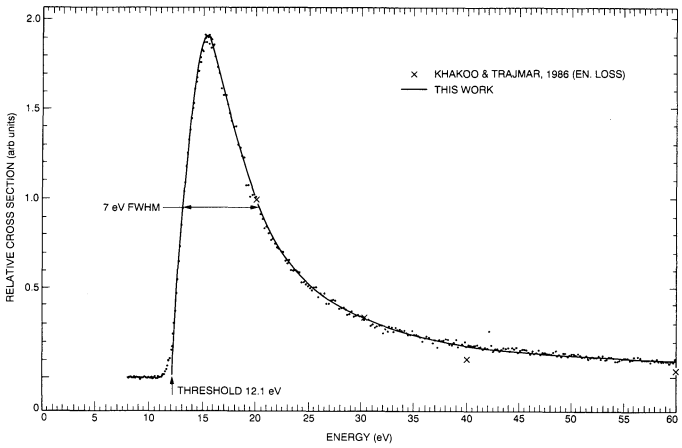

FIG. 2.—$H_2(a \rightarrow b)$ excitation function measured from 0 to 60 eV. The laboratory data are normalized to the relative cross section value at 20 eV of Khakoo & Trajmar (1986). The data from 8 to 15 eV were acquired every 0.0977 eV and the data from 15 to 60 eV were acquired every 0.195 eV. The threshold for $v' = 1$ is indicated.

TABLE 1A

COMPARISON OF RELATIVE EMISSION CROSS SECTIONS AT 195.0 nm FOR $H_2(a\ ^3\Sigma_a^+ \rightarrow b\ ^3\Sigma_u^+)$ AND EXCITATION CROSS SECTIONS FOR $H_2(a\ ^3\Sigma_g^+ \leftarrow X\ ^1\Sigma_g^+)$

Energy (eV)	Emission Cross Section Data[a]	Excitation Cross Section Data[b]	Model[c]
12.1	0.0		0.0
12.5	0.19		0.12
13.0	0.58		0.55
14	1.45		1.39
15	1.85		1.79
15.5	1.90		1.83
16	1.85		1.80
17	1.62		1.63
18	1.41		1.40
19	1.19		1.18
20	1.0	1.0	1.0
21	0.86		0.85
22	0.75		0.74
23	0.65		0.65
24	0.59		0.58
25	0.51		0.52
30	0.33	0.36	0.32
35	0.24		0.19
40	0.19	0.11	0.11
45	0.15		0.073
50	0.13		0.038
60	0.09	0.030	0.026

[a] Data, this work, normalized to unity at 20 eV at 195.0 nm.
[b] Data, Khakoo & Trajmar 1986, normalized to unity at 20 eV.
[c] Model based on modified Born approximation (Shemansky et al. 1985a, b) with $C_0 = 0.3108497$, $C_1 = 5.140471$, $C_2 = -150.4288$, $C_3 = 4642.62$, $C_4 = -26995.5$, $C_8 = 1.9861$. The formula for total electronic collision strength, $\Omega(E)$, in 1/2 au is given by

$$\Omega(E) = \sum_{v'} q_{v'o}\Omega_{v'o}(X_{v'o}),$$

where $\Omega_{v'o}(X_{v'o})$ is given by

$$\Omega_{v'o}(X_{v'o}) = C_0(1 - 1/X_{v'o})(X_{v'o}^{-2}) + \sum_{k=1}^{4} C_k(X_{v'o} - 1)\exp(-kC_8 X_{v'o}),$$

where $X_{v'o}$ is the electron energy in threshold units, $E/E_{v'o}$. $E_{v'o}$ is the excitation energy in ryd units given in Table 1B and $q_{v'o}$ is the Franck-Condon factor given in Table 1B. The excitation cross section, $\sigma_{v'}(X_{v'o})$, in atomic units for each vibrational level is given by $\sigma_{v'}(X_{v'o}) = q_{v'o}\Omega_{v'o}(X_{v'o})(E_{v'o}X_{v'o})^{-1}$. The model cross section is normalized to unity at 20 eV.

TABLE 1B

THE FRANCK-CONDON FACTORS[a] AND EXCITATION ENERGIES FOR $H_2(a\ ^3\Sigma_g^+ \leftarrow X_{v'o}\ ^1\Sigma_g^+)$

v'	$q_{v'o}$	$E_{v'o}$(ryd)
0	0.208E + 00[b]	0.86655
1	0.255E + 00	0.88956
2	0.202E + 00	0.91134
3	0.134E + 00	0.93193
4	0.820E − 01	0.95140
5	0.482E − 01	0.96979
6	0.279E − 01	0.98715
7	0.162E − 01	1.00353
8	0.953E − 02	1.01898
9	0.567E − 02	1.03355
10	0.343E − 02	1.04729
11	0.210E − 02	1.06026
12	0.128E − 02	1.07250
13	0.750E − 03	1.08406
14	0.383E − 03	1.09500
15	0.140E − 03	1.10535
16	0.600E − 04	1.11519
17	0.320E − 04	1.12454
18	0.173E − 04	1.13347
19	0.849E − 05	1.14203
20	0.353E − 05	1.15026

[a] Kwok et al. 1986.
[b] E + 00 = 10°.

the vibrational levels in the bandpass of the instrument at 195.0 nm is calculated. The continuum transition probabilities allow us to calculate the fraction of $v' = 1$, 2, 3, and 4 in the excitation function measurement to be 0.248, 0.683, 0.311, and 0.0379, respectively. The slightly different thresholds (~0.3 eV) cause a shape difference between the experimental excitation function measurement at 195.0 nm and total electronic cross section from a sum of vibrational cross sections. A modified Born cross section model was prepared with these fractional contributions. The fit comparison of collision strength between model and data is shown in Figure 3. The constants for the modified Born approximation are given in Table 1A together with the model relative cross sections, for the partitioned upper vibrational levels in the experiment given above.

TABLE 2

COMPARISON OF ENERGY DEPENDENCE OF RELATIVE CROSS SECTIONS FOR TRIPLET STATE EXCITATION OR EMISSION

		States									
Energy (eV)	$1/E^3$	a^1	a^2	b^2	c^2	d^2	e^2	$d \rightarrow a^3$	Lab $a \rightarrow b^4$	Model $a \rightarrow b^4$	b^5
30	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
40	0.42	0.31	0.47	0.48	0.45	0.44	0.47	0.47	0.56	0.36	0.39
50	0.22		0.25	0.26	0.24	0.23	0.25	0.24	0.38	0.15	0.18
60	0.13	0.086						0.15	0.27	0.075	
70	0.079		0.096	0.10	0.092	0.086	0.097	0.11		0.045	
80	0.053							0.060		0.031	
90	0.037							0.047			
100	0.027		0.034		0.032	0.030	0.034	0.037		0.016	
150	0.0080		0.010		0.012	0.0097	0.0092	0.0098		0.0049	
200										0.0021	

[1] Khakoo & Trajmar 1986.
[2] Chung et al. 1975.
[3] Mohlmann & de Heer 1976.
[4] This work.
[5] Nishimura & Danjo 1986.

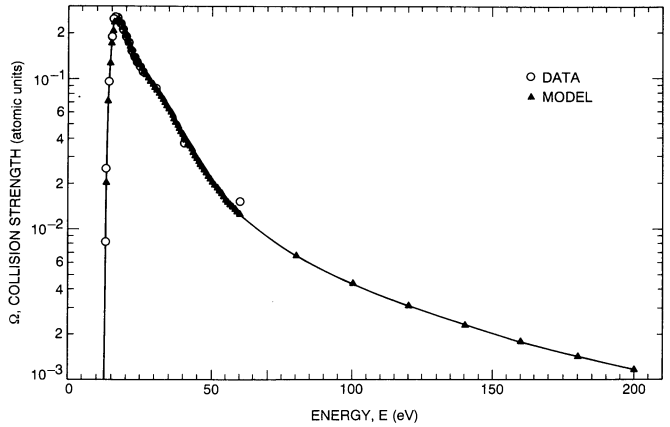

FIG. 3.—Laboratory data of Fig. 2 are fitted to the modified Born approximation formulation (Shemansky et al. 1985a, b). The laboratory data are shown as a collision strength. The constants for the approximation are given in Table 1A.

Second, the absolute excitation cross section is determined for $v' = 0$ and for the total electronic cross section using the modified Born approximation constants in Table 1A. The cross section values are listed in Table 3 from 11.8 to 200 eV. The total absolute cross section is based on the normalization to the 20 eV value of Khakoo & Trajmar (1986). A comparison of the two model cross sections is shown in Figure 4. The peak cross section for $v' = 0$ is at 15.0 eV with a value of 3.9×10^{-18} cm^2. The peak total cross section is at 15.5 eV with a value of 1.73×10^{-17} cm^2. The model is compared to ab initio calculations in Figure 5. The unusually narrow FWHM = 7 eV is indicated in Figure 5. The asymptotic energy dependence of the model follows $1/E^3$ beginning at 50 eV. The ab initio calculations in Figure 5 show a broader FWHM than that of the experimental data. None of the calculations correctly predict the shape of the a-state cross section energy dependence. The most recent two state close coupling calculations of Lima et al. (1988) almost exactly predict the experimental peak value, but differ by ~40% from the current work at 30 eV. Ongoing theoretical work with five to 10 state close coupling calculations may improve the threshold cross section shape (V. McCoy, 1992 private communication).

TABLE 3

EXCITATION MODEL TOTAL CROSS SECTION OF $H_2(a\ ^3\Sigma_g^+ \leftarrow X_{v'o}\ ^1\Sigma_g^+)$

ENERGY (eV)	CROSS SECTION[a] (10^{-18} cm^2) $v' = 0$	Total
11.8	0.0	0.0
12.1	0.486	0.486
12.5	1.326	2.201
13.0	2.350	5.608
14.0	3.643	12.79
15.0	3.924	16.71
15.5	3.820	17.33
16.0	3.627	17.27
17.0	3.124	15.92
18.0	2.618	13.87
19.0	2.188	11.79
20.0	1.851	10.00
22.0	1.393	7.406
24.0	1.108	5.791
26.0	0.902	4.697
28.0	0.736	3.864
30.0	0.598	3.181
35.0	0.349	1.924
40.0	0.206	1.158
50.0	0.0838	0.470
60.0	0.0435	0.238
70.0	0.0267	0.143
80.0	0.0180	0.0956
100.0	0.00948	0.0502
150.0	0.00293	0.0156
200.0	0.00126	0.00671

[a] Model cross section based on modified Born approximation model constants of Table 1A and Franck-Condon factors of Kwok et al. (1986) given in Table 1B.

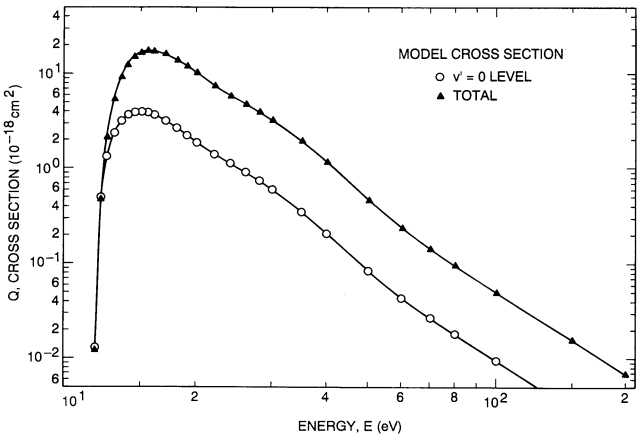

FIG. 4.—Model excitation cross sections for $v' = 0$ and for the total cross section for the $H_2(a–b)$ continuum. The constants for the modified Born approximation are given in Table 1A and the Franck-Condon factors are from Kwok et al. (1986). The digital values for the cross section are given in Table 2.

The good agreement shown in Figure 2 between the direct excitation function of Khakoo & Trajmar (1986) and the direct + cascade excitation function data points of this experiment at 20 and 30 eV shows that the cascade contribution to the emission (cascade + direct) excitation function is small or that the cascade component has a similar energy dependence. The major source of cascade is the $c \rightarrow a$ transition. The cross section of the c-state at 20 eV is 1.47×10^{-17} cm^2 from the results of Khakoo & Trajmar (1986). However, the c-state does not contribute in this experiment from time-of-flight considerations. The lifetime of the $v' > 1$ vibrational levels is 0.1 ms

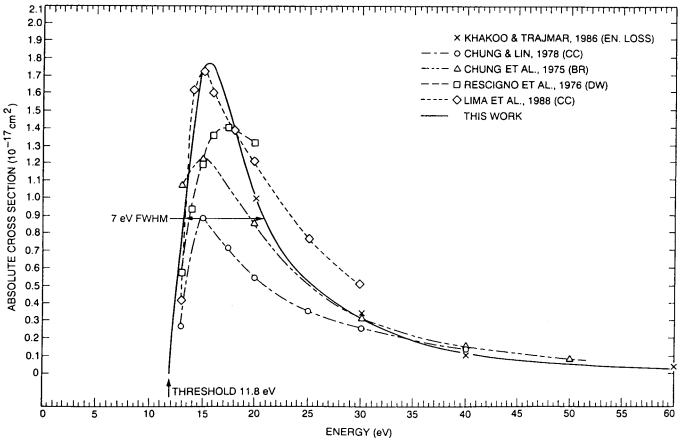

FIG. 5.—Ab initio calculations (Chung & Lin 1978; Chung et al. 1975; Rescigno et al. 1976; Lima et al. 1988) of the H_2 a-state excitation cross section compared to the model cross section from the laboratory study.

(Freis & Hiskes 1970; Johnson 1972). The distance the excited molecule travels in this interval is 15 cm for a 300 K gas and is lost to the spectrometer field of view (Ajello & Shemansky 1985; Dang et al. 1987). The dipole allowed cascade transitions of significance are $d\,^3\Pi_u \rightarrow a\,^3\Sigma_g^+$ and $e\,^3\Sigma_u^+ \rightarrow a\,^3\Sigma_g^+$ (Huber & Herzberg 1979, p. 250). On this basis our emission experiment will include a contribution from other singlet-triplet excitation processes.

According to calculation and measurement the contributions of the *d*- and *e*-states to the population rates of the *a*-state should be significant in the current experiment. Mohlmann & de Heer (1976) measured the *d*-state cross section at 15.6 eV and obtained 0.42×10^{-17} cm^2. The *e*-state cross section at 15 eV has been estimated in close coupling calculations at 0.91×10^{-17} cm^2 (Chung & Lin 1978) and 0.33×10^{-17} cm^2 with the Born-Rudge method (Chung et al. 1975). The measured and calculated cross sections for these states are substantially wider than the current measurement of the *a*-state. The cascade contribution should be significant if the magnitudes quoted above are correct, requiring that the higher states have narrow cross sections with peaks closely aligned with the *a*-state. Since theory currently cannot account for the narrow *a*-state cross section it seems likely that the calculations would be inadequate for the higher states as well. There is a small bump in the *a*-state emission excitation function $\sim$20 eV (Fig. 2), possibly from cascade. The effect of a cascade contribution near 20 eV would be of order 10% and presumably not related to the *d*- or *e*-states.

The excitation cross section of the *a*-state at 15.5 eV is 1.73×10^{-17} cm^2. To this cross section we can add cascade contributions of 4.2×10^{-18} from the *d*-state (Mohlmann & de Heer 1976) and 3.3×10^{-18} cm^2 from the *e*-state (using the Born-Rudge cross section). Thus cascade appears to be important, contributing about 33% at 15.5 eV of the total emission cross section. We feel both these cascade contributions should be the subject of further laboratory investigations. In the case of the $d \rightarrow a$ (Fulcher-bands) electron impact induced fluorescence measurement, the background subtraction of the $a \rightarrow b$ continuum must be carefully examined (Mohlmann & de Heer 1976). Background gas pressures in this experiment are an order of magnitude lower than used in the Mohlmann and de Heer *d*-state measurement. Low background pressure is an important consideration in accurate cross section measurements of singlet-triplet cross sections.

The 20 and 30 eV cross section points of Khakoo & Trajmar (1986) for the *c*-state lie on the *a*-state curve measured in this experiment. We can estimate the peak *c*-state excitation cross section to be 2.5×10^{-17} cm^2, assuming it has the same shape. The total cascade contribution to the *a*-state, including the *c*-state, at 15.5 eV is 3.3×10^{-17} cm^2 or 65% of the *a*-state total emission cross section. The total emission cross section at 15.5 eV is 5.0×10^{-17} cm^2.

Nishimura & Danjo (1986) measured the *b*-state cross section to be 6.04×10^{-17} cm^2 at 15 eV. The sum of all these triplet state cross sections (*b*-direct + *a*-direct + *a*-cascade) is 11.0×10^{-17} cm^2. Corrigan (1965) has measured a value near 9×10^{-17} cm^2 for dissociation into neutral atoms. This dissection of the total triplet state cross section into individual cross sections is an important corroboration of the Corrigan result to the 20% accuracy level. The major uncertainty to the components of the total cross section is the cascade contribution to the *a*-state. At 15.5 eV energy, the singlet state predissociation process for slow H atoms [H(1*s*) + H(2*l*)] with a threshold at 14.7 eV is much less than 1×10^{-18} cm^2 (Ajello et al. 1991). The H_2 Lyman continuum contributes roughly 1×10^{-18} cm^2 to H(1*s*) + H(1*s*) production.

4. DISCUSSION

The model UV spectrum of the direct *a*–*b* transition is shown in Figure 6. It is based on the continuum transition probabilities, ω_λ, of Kwok, Dalgarno, & Posen (1986). The individual continuum irradiances of the first five vibrational levels (Kwok et al. 1986) are shown in Figure 6*a*; and the total UV spectrum from all 20 vibrational levels at 50 eV including threshold effects is shown in Figure 6*b*. Our excitation function measured at 195.0 nm shown in Figure 1 through Figure 3 is weighted (see hatched area in Fig. 1) most heavily by $v' = 2$ level followed by the $v' = 1$, 4, and 3 levels, respectively. The modified Born approximation of the laboratory data at 195.0 nm was constructed on the basis of these weight factors. We have obtained a calibrated spectrum of the *a*–*b* transition of H_2 below 210 nm. The *a*–*b* continuum emission extends from 121.6 to 500 nm. We have studied the wavelength region from 121.6 to 210 nm, a region which encompasses the peak of the broad *a*–*b* continuum. A comparison of the H_2 Lyman bands cross section to the *a*–*b* continuum from a spectral model at 20 eV will serve to provide an independent absolute cross section. This analysis is now being pursued.

It is clear from Figure 5 that ab initio calculations fail to account for the narrow 7 eV FWHM of the excitation function

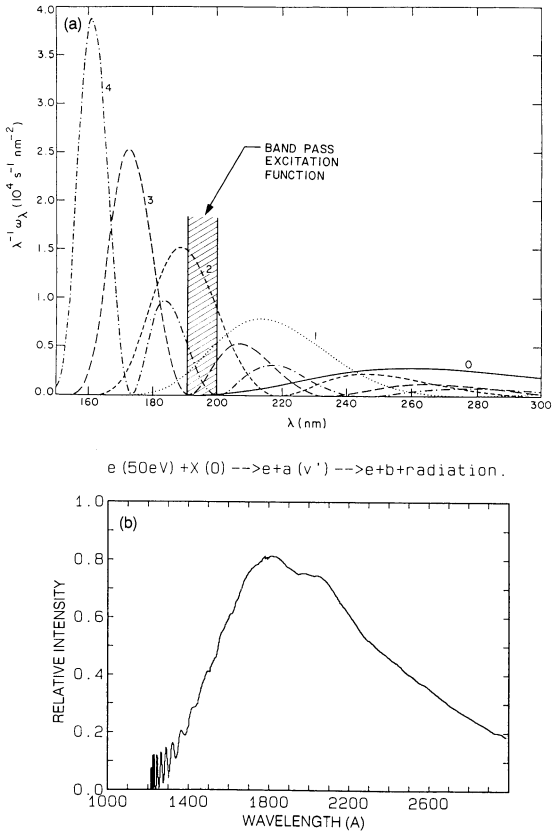

FIG. 6.—(*a*) Spontaneously emitted spectrum from each vibrational level of the $a\,^3\Sigma_g^+$ state from 0 to 4 (Kwok et al. 1986). These are the levels contributing to the 195.0 nm excitation function of Figs. 2 and 3; and the wavelength region in the instrumental bandpass is shown as the hatched region. (*b*) Total spontaneously emitted spectrum of the $a\,^3\Sigma_g^+$ state from all vibrational levels 0 to 20 at an electron energy of 50 eV.

near the threshold, although there is excellent agreement with Lima et al. (1988) in both absolute magnitude and energy value of the peak cross section from their two state close coupling calculation. Since all excited triplet states cascade to the *b*-state through the *a*-state as an intermediate product, the *a*-state has a very large cascade contribution totaling 65% of the total emission cross section. The estimated and published cross sections at 15.5 eV for the *a*-, *b*-, *c*-, *d*-, and *e*-states are within 20% of the Corrigan (1965) measurement for the dissociative production of fast H atoms. We have constructed a modified Born approximation model of the excitation cross section for the *a*–*b* continuum, which accurately models the excitaion cross section measurements from threshold to arbitrary high energy.

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology and the University of Southern California and was sponsored by the Air Force Office of Scientific Research (AFOSR), the Aeronomy Program of the National Science Foundation under grant ATM 9296090, and the NASA Planetary Atmospheres, Space Physics, and Astronomy Program Offices through an agreement with the National Aeronautics and Space Administration. We have benefitted from discussions with S. Trajmar and I. Kanik. We are also thankful for the collaboration with T. L. Kwok, now deceased, for his assistance in obtaining the experimental data and participating in the analysis.

REFERENCES

Ajello, J. M., et al. 1988, Appl. Opt., 27, 890
Ajello, J. M., James, G. K., Franklin, B. O., & Shemansky, D. E. 1989, Phys. Rev. A, 40, 3524
Ajello, J. M., James, G. K., Franklin, B. O., & Howell, S. J. 1990, J. Phys. B, 23, 4355
Ajello, J. M., & Shemansky, D. E. 1985, J. Geophys. Res., 90, 9845
Ajello, J. M., Shemansky, D. E., & James, G. K. 1991, ApJ, 371, 422
Ajello, J. M., Shemansky, D. E., Kwok, T. L., & Yung, Y. L. 1984, Phys. Rev., 29, 636
Chung, S., & Lin, C. C. 1978, Phys. Rev. A, 17, 1874
Chung, S., Lin, C. C., & Lee, T. P. 1975, Phys. Rev., 12, 1340
Coolidge, A. S. 1944, Phys. Rev., 65, 236
Coolidge, A. S., James, H. M., & Present, R. D. 1936, J. Chem. Phys., 4, 193
Corrigan, S. J. B. 1965, J. Chem. Phys., 43, 4381
Doyle, R. O. 1968a, ApJ, 153, 987
———. 1968b, J. Quant. Spectros. Rad. Transf., 8, 1968
Freis, R. P., & Hiskes, J. R. 1970, Phys. Rev., 2, 573
Huber, K. P., & Herzberg, G. 1979, Molecular Spectra and Molecular Structure. IV. Constants of Diatomic Molecules (NY: Van Nostrand Reinhold)
James, G. K., Ajello, J. M., Franklin, B., & Shemansky, D. E. 1990, J. Phys. B, 23, 2055
James, H. M., Coolidge, A. S., & Present, A. D. 1935, J. Chem. Phys., 3, 122
Johnson, C. E. 1972, Phys. Rev., 5, 1026
Khakoo, M. A., & Trajmar, S. 1986, Phys. Rev., 34, 146
Khakoo, M. A., Trajmar, S., McAdams, P., & Shyn, T. W. 1987, Phys. Rev. A, 35, 2832
Kwok, T. L., Dalgarno, A., & Posen, A. 1986, Phys. Rev., 34, 1962
Lima, M. A. P., Gibson, T. L., Huo, W. M., & McKoy, V. 1988, Phys. Rev., 38, 4527
Mohlmann, G. R., & de Heer, F. J. 1976, Chem. Phys. Lett., 43, 240
Nishimura, H., & Danjo, A. 1986, J. Phys. Soc. Japan, 55, 3031
Pang, K. D., Ajello, J. M., Franklin, B., & Shemansky, D. E. 1987, J. Chem. Phys., 86, 2750
Ratliff, J. M., James, G. K., Trajmar, S., & Ajello, J. M. 1991, J. Geophys. Res., 96, 17,559
Rescigno, T. N., McCurdy, C. W., Jr., & McKoy, V. 1976, Phys. Rev., 13, 216
Shemansky, D. E., Ajello, J. M., & Hall, D. T. 1985a, ApJ, 296, 765
Shemansky, D. E., Ajello, J. M. Hall, D. T., & Franklin, B. 1985b, ApJ, 296, 774
Shemansky, D. E., & Hall, D. T. 1992, J. Geophys. Res., 97, 4143
Tripp, T. M., Shemansky, D. E., James, G. K., Ajello, J. M., & James, G. K. 1991, ApJ, 368, 641
Weingartshofer, A., Erhardt, H., Herman, V., & Linder, F. 1970, Phys. Rev., 2, 294