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Spectra Induced by 200-kev Proton Impact on Nitrogen*

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Spectra induced by 200-kev proton impact on nitrogen have been observed in the spectral region from λ3000 A to λ6000 A. The principal feature was the strong excitation of the N_2^+ first negative band systems. Absolute cross sections for excitation were determined for the principal bands of this system as well as for two NII atomic lines. A relatively weak Doppler-shifted H_β line was detected, and the cross section for the charge-exchange electron-capture into the $n=4$ excited state of hydrogen was estimated. Second positive N_2 bands were observed at higher pressures.

I. APPARATUS

A MAGNETICALLY analyzed 200-kev proton beam from the University of Arkansas Cockcroft-Walton accelerator was allowed to enter a differentially pumped collision chamber containing the target gas, nitrogen. The beam was collimated by passing through two holes each $\frac{1}{16}$ in. in diameter, spaced 2 in. apart. The light resulting from the proton impact was then observed spectroscopically at an angle of 25° to the beam direction, which permitted the observation of possible Doppler-shifted radiation from fast hydrogen atoms formed by electron-capture collisions.

The necessary spectral resolution was accomplished through the use of a Jarrell-Ash 82-000 Ebert scanning spectrometer with an EMI 6256B photomultiplier as a detector. The absolute efficiency of the detecting system was determined by means of a standard lamp whose emission was absolutely calibrated in terms of number of photons per second per steradian per angstrom. The beam current was measured by using the insulated collision chamber as a Faraday cup while the collision chamber pressure was monitored by a Pirani gauge. By knowing these quantities, the cross section of the excitation processes concerned in this paper can then be readily calculated.

The apparatus and calibration procedure has been described elsewhere.[1]

II. RESULTS AND DISCUSSION

One of the typical spectrograms is shown in Fig. 1. The spectrograms were obtained with a spectral slit

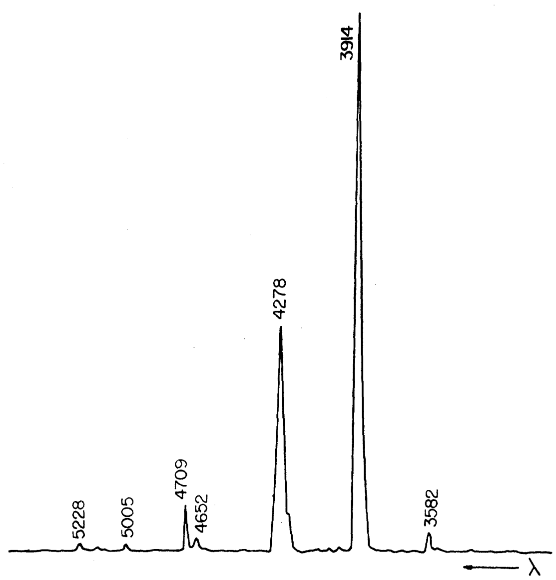

Fig. 1. Spectrogram of 200-kev proton impact on N_2 (19-μ pressure and 0.04-μa beam current).

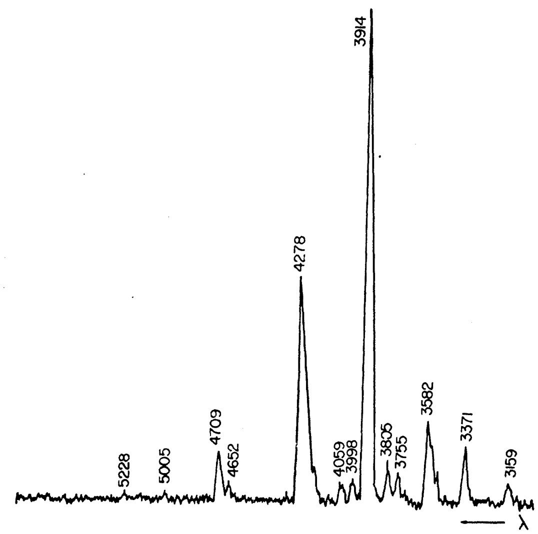

Fig. 2. Spectrogram of the radiation from the edge of the proton beam (20-μ pressure and 0.15-μa beam current). Much of the radiation shown here is coming from the area outside the proton beam. Compare with Fig. 1 which represents about the same pressure. Note that here the λ3371-A band of the N_2 second positive system produced deflection about equal to the N_2^+ λ4709-A band. In Fig. 1, the λ4709-A band is clearly visible but the λ3371-A band is not apparent.

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[1] R. H. Hughes, R. C. Waring, and C. Y. Fan, Phys. Rev. **122**, 525 (1961).

TABLE I. Cross sections for spectral excitation of nitrogen by 200-kev proton impact.

λ (A)	Transition	σ (10^{-19} cm^2)
	$v'v''$	
3914	N_2^+ 0−0	330
	1st negative	
4278	0−1	93
4709	0−2	17
5228	0−3	2.5
3582	1−0	33
3884	1−1	(Unresolved satellite of λ3914-A band)
4236	1−2	16
4652	1−3	4.7
5149	1−4	0.9
5005	N II $3p\,^3D-3d\,^3F^0$	2.6
5680	$3s\,^3P^0-3p\,^3D$	≈ 2.4
4772	H_β (charge-exchange)	$\approx 0.1_2$

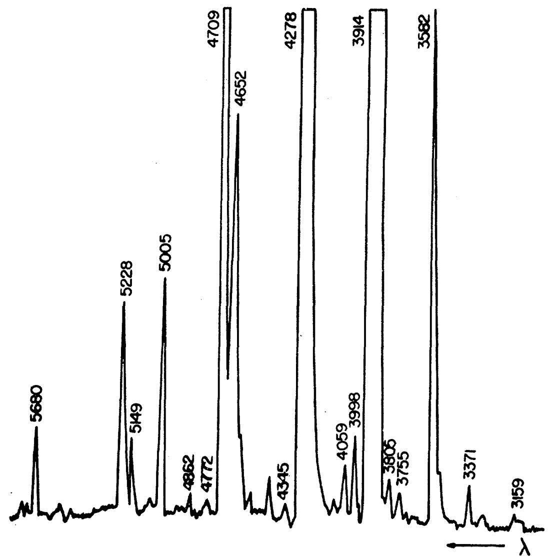

FIG. 3. Spectrogram of 200-kev proton impact on N_2 (17μ pressure and 0.14 μa beam current).

width of 25 A at pressures ranging from 1 μ to 30 μ and proton currents from 0.04 μa to 0.18 μa.

Except for the second positive system, all of the prominent emissions appeared to be linear with both current and pressure within the experimental error. This implies that these linear features were excited by a primary process for which the number of photons emitted from a cubic centimeter, n, is given by the following equation:

$$n=\sigma\rho F, \tag{1}$$

in which F is the proton flux, ρ is the molecular density of the nitrogen in the collision chamber, and σ is the cross section of the excitation process.

The intensity of the second positive system of N_2 depends linearly on the current but quadratically on the pressure, indicating a two-step process. This is not surprising, since this system cannot be excited directly by proton impact according to the spin conservation rule. We were able to apply an electric field transverse to the beam and observe its effect on various lines in the spectra. Only the N_2 second positive system was affected, which indicated that electron excitation could be a contributing factor for this system. (The intensity increased when the field was applied.) We were able to take spectrograms of the region near the beam edge, and found that much of the radiation from this region came from the N_2 second positive system (see Fig. 2). Therefore, we conclude, as did Fan[2] and Nicholls,[3] that the most probable excitation mechanism for this system is secondary-electron impact at these energies. Recombination as a primary process is ruled out experimentally by the linearity with current.

The cross sections for the excitation of the various systems calculated from Eq. (1) are given in Table I.

The uncertainty in the measurement of the intensity of the Doppler-shifted H_β line (see Fig. 3) was enhanced by background difficulties. The measured cross section for the excitation of the line is approximately 1.2×10^{-20} cm^2. This line cross section, $\sigma(H_\beta)$, can be used to estimate the electron-capture cross section into the $n=4$ levels of hydrogen, $\sigma(n=4)$. This requires knowledge of the relative capture cross sections into the $4s$, $4p$, $4d$, and $4f$ levels. We assume that the relative capture cross sections into these levels will not differ appreciably from capture from helium and Mapleton's calculations[4] for capture from helium can be extrapolated to $n=4$. We let

$$\frac{\sigma(4p)}{\sigma(4s)}=\frac{\sigma(3p)}{\sigma(3s)}=R_1;\quad \frac{\sigma(4d)}{\sigma(4s)}=\frac{\sigma(3d)}{\sigma(3s)}=R_2;$$

and

$$\frac{\sigma(4f)}{\sigma(4s)}\approx 0.$$

R_1 and R_2 are determined using Mapleton's values for $\sigma(3s)$, $\sigma(3p)$, and $\sigma(3d)$ in helium at the appropriate proton energy. Thus, we obtain

$$\sigma(n=4)=\sigma(H_\beta)\left\{\frac{\sum_{n=2}^{n=3}A(4s\rightarrow np)+R_1[A(4p\rightarrow 3d)+\sum_{n=1}^{n=3}A(4p\rightarrow ns)]+R_2[\sum_{n=2}^{n=3}A(4d\rightarrow np)]}{A(4s\rightarrow 2p)+R_1[A(4p\rightarrow 2s)]+R_2[A(4d\rightarrow 2p)]}\right\},$$

[2] C. Y. Fan, Phys. Rev. **103**, 1740 (1956).
[3] R. W. Nicholls, Proc. Phys. Soc. (London) **74**, 87 (1959).
[4] R. A. Mapleton, Phys. Rev. **122**, 528 (1961).

where the A's are indicated hydrogen transition probabilities. Using this expression and neglecting cascade effects, we obtain $\sigma(n=4)\approx 6.6\times 10^{-20}$ cm^2 which is not incompatible with the total capture cross section 1.5×10^{-17} cm^2 at 200 kev.[5] The same quantities for protons in helium are 1.3×10^{-20} cm^2 and 3.6×10^{-18} cm^2, respectively.[6,5]

One note must be added to the excitation of this H_β line. It can also be produced by a two-step process, namely, an electron capture into the ground state and then excitation by a subsequent collision. However, the line recorded in the spectrogram is not a result of this process, since the emission was observed at a distance of about 2 cm from the entrance slit of the collision chamber, which is much less than the mean free path for the process of electron capture at these pressures (more than 100 cm). A linear dependence of the emission on pressure would also support this statement, but because of background problems at the lower pressures it is difficult to attest to the exact linearity although it appears likely to be linear.

An attempt was made to determine the population cross section for the $v'=0$ and the $v'=1$ levels associated with the $B\,^2\Sigma$ state of the N_2^+ molecule using Herzberg's transition probabilities[7] and neglecting cascade effects. Within experimental error, fairly consistent results were obtained by using this procedure on our measurements for λ3914-A, λ4278-A, and λ4709-A bands giving a population cross section for $v'=0$ of 42×10^{-18} cm^2. Of course, simply summing the transition cross sections from the $v'=0$ state found in Table I will give the population figure also. This indicates a cross section of about 44×10^{-18} cm^2. Difficulty arose, however, in trying to apply Herzberg's transition probabilities to the $v'=1$ state. Very consistent results were obtained using our λ54236-A and λ4652-A data which gave a population cross section of 4.3×10^{-18} cm^2 for $v'=1$. However, the application to the λ3582-A data gives a population three times larger than this figure. We hesitate to draw conclusions since there is a possibility of unresolved structure in the λ3582-A band and because of the fact that we had to extrapolate our calibration curves from λ3800 A to this region. However, the extrapolation should not have produced much error. We did not resolve the N_2 second positive λ3577-A band which gave the appearance of pressure dependence to the λ3582-A band. The cross section quoted in Table I, however, represents measurements at low pressure where we can state with some degree of confidence that the N_2 second positive contribution is negligible. There remains the possibility of the unresolved $2-1$ N_2^+ first negative band at λ3564 A but the weakness of other members of this progression indicates that its contribution is small. Unless there are foreign lines present it would appear that the transition probability associated with the $1-0$ transition may be relatively larger than Herzberg's measured value. Aurora visual-intensity measurements[7] tend to support such a statement.

It is of some interest to compare our results of the excitation of the $v'=0$ level of the $B\,^2\Sigma$ state of the N_2^+ molecule with the corresponding excitation by electron impact with electrons of the same velocity. The ratio of the cross section for the excitation of this level by 200-kev proton impact to the corresponding cross section for 100-ev electron impact[8] is 42×10^{-18} cm$^2/9.5\times 10^{-18}$ cm$^2=4.4$. On the other hand, the ratio of the cross section for total ionization by 200-kev proton impact[9] to the cross section for total ionization by 100-ev electron impact[10] is about 5.3×10^{-16} cm$^2/2.9\times 10^{-16}$ cm^2 which is a little less than 2. Thus, it would seem that an argument could be presented that proton impact may be more effective in exciting the $v'=0$ level than electron impact. (Unfortunately, this last statement loses some significance when the experimental uncertainties in these quantities are realized.) Further, it would appear in the case of 200-kev proton impact that about 10% of N_2^+ ions are produced in the excited state.

Carleton and Lawrence[11] have measured the excitation of the $0-0$ N_2^+ first negative band system by proton impact in the energy range from 1.5 to 4.5 kev. At these lower energies charge exchange is the dominant feature, while here the ionization reaction $H^+ + N_2 \rightarrow H^+ + N_2^+ + e$, is the dominant feature. They found at their highest energy, 4 kev, that the cross section for excitation of the $0-0$ first negative band was 7% of the total charge-exchange cross section, which is about the ratio of our measured cross section for this band at 200 kev to the total ionization cross section.

ACKNOWLEDGMENTS

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[5] S. K. Allison, Revs. Modern Phys. **30**, 1137 (1958).

[6] Obtained from H_β data in reference 1. A value $\sigma(n=4)\approx 0.8\times 10^{-20}$ cm^2 is quoted in this reference but was obtained using mean hydrogen transition probabilities.

[7] See tables of R. W. B. Pearse, Proceedings of the Conference on Auroral Physics, edited by N. C. Gerson, T. J. Keneshea, and R. J. Donaldson, Air Force Cambridge Research Center AFCRC-TR-54-203, 1954 (unpublished), p. 341. Transition probabilities quoted from G. Herzberg, Ann. Phys. Lpz. **86**, 191 (1928).

[8] D. T. Stewart, Proc. Phys. Soc. (London) **A69**, 437 (1956).

[9] Obtained by extrapolating the plot of the results of R. N. Il'in, V. V. Afrosimov, and N. V. Fedorenko, J. Exptl. Theoret. Phys. (S.S.R.) **36**, 41 (1959). Roughly 80% of this figure is the cross section for the production of N_2^+ ions, while the remainder represents atomic ion production.

[10] J. T. Tate and P. T. Smith, Phys. Rev. **39**, 270 (1932).

[11] N. P. Carleton and T. R. Lawrence, Phys. Rev. **109**, 1159 (1958).