Measurements of the Electron Impact Excitation Cross Section of N_2^+ First Negative Bands*

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Emission cross sections for the N_2^+ first negative bands produced by electron impact on N_2 have been measured using a photon counting technique in the energy range 70 eV to 4 keV. The maximum cross section for the $v'=0$ vibrational level of the $B\ ^2\Sigma_u^+$ excited state of N_2^+ is 2.38×10^{-17} cm^2. The ratio of cross sections for the (0, 0), (0, 1) and (0, 2) bands of first negative system is 1: 0.34: 0.065. The total emission cross section for the $v'=0$ vibrational level accounts for 10% of the total ionization cross section of N_2.

1. INTRODUCTION

The present study of the excitation of molecular nitrogen by the impact of electrons on nitrogen gas was undertaken with two objectives. First, there is of course a need to provide information which will lead to the understanding of the basic phenomena. In the case of the heavier gases no quantum-mechanical predictions are available, and it is necessary to provide data which may stimulate and test the development of semiclassical theories which rely heavily on the availability of experimental data. Secondly, the information is of considerable importance to the understanding of the phenomena occuring in the upper atmosphere of the earth,[1-3] especially aurora and airglow.

In a previous paper[4] hereafter referred to as I, we reported an experimental value of the emission cross section for the λ3914 (0, 0) N_2^+ first negative band produced by electron impact on N_2 in the energy range 70 eV to 2.5 keV. The present paper is a report of the extension of the λ3914 results and a fresh measurement of the cross sections for λ4278 (0, 1) and λ4709 (0, 2) N_2^+ first negative radiation produced by the impact of 70 eV to 4 keV electrons on nitrogen gas.

The absolute emission cross sections for all the (0, 0), (0, 1), and (0, 2) bands of the first negative system have been measured twice previously.[5-6] Both measurements, those of Stewart[5] and McConkey and Latimer,[6] are in a very limited energy range (25–300 eV). Also not only are the cross sections of McConkey and Latimer[6] a factor of 2 to 3 higher than those of Stewart,[5] but the measured relative intensities of the progression are in disagreement.

2. EXPERIMENTAL APPARATUS

Figure 1 shows the apparatus used for measuring the excitation functions. The apparatus is essentially the same as that described in paper I. Only the electron collector system was modified to eliminate the reflection of electrons and escape of secondary electrons formed in the Faraday cage at higher energies. The collector assembly consists of three elements, namely, S_2, F_C and F_P. The element F_C is a 15-cm–long tapered cage and was biased 90 V positive with respect to shield S_2, which was kept at the ground potential. Plate F_P was biased 45–90 V positive with respect to cage F_C. A magnetic field up to 250 G in the beam direction was used for the additional collimation. The electron currents were monitored at the collision chamber C_1 and the shield S_1. The total sum of the currents at C_1 and S_1 was always less than 1% of the total beam current.

The radiation was detected at right angles to the beam direction in a static system through a quartz window and narrow band interference filters. The electron beam was at the focal plane of lens L_1 (focal length 14.6 cm) of the collimator assembly (see Fig. 1). Only 1.15-cm beam path radiation was recorded by the photometer. The beam length viewed was determined by the slit's width placed at the mouth of the photomultiplier housing, where the beam image (0.87 magnification) was focused by the collimator. The solid angle of radiation viewed by the photometer was determined by the diameter of the aperture in the collimator and its distance from the beam path. The maximum angle of incidence of radiation at the interference filter was less than 2°. An RCA 7265 photomultiplier tube was employed to record the emission. It was

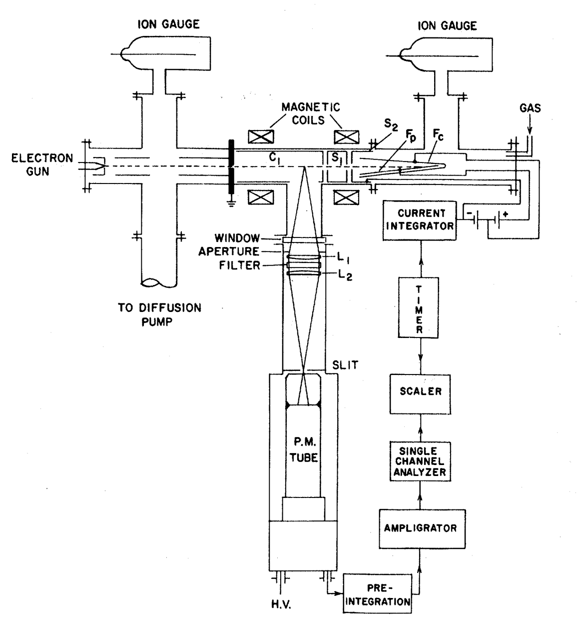

FIG. 1. Schematic view of the apparatus used for measuring excitation cross section by electron impact.

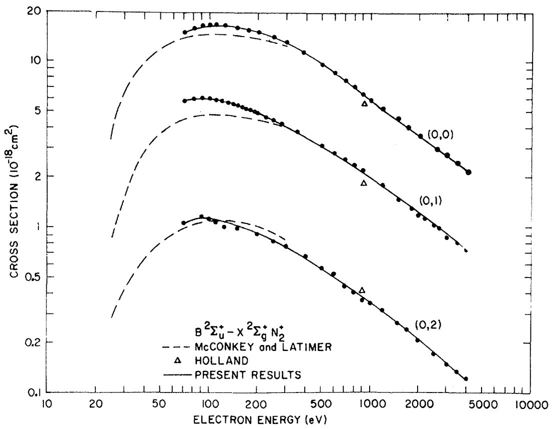

FIG. 2. Emission cross sections of the (0, 0), (0, 1) and (0, 2) first negative bands of N_2^+ by electron impact.

cooled by dry air passing through ice. All measurements were made at a target pressure near 3×10^{-4} Torr and the energy of electrons was varied from 70 eV to 4 keV. In this pressure range light intensity was proportional to both electron current and gas pressure. Photon counting techniques have been used in the present measurements. The beam current was integrated for 50 sec. The typical dark current count was 4.5×10^2 counts/sec, and signal counts were always greater than 2×10^3 counts/sec.

3. PHOTOMETER AND PRESSURE CALIBRATIONS

The photomultiplier tube was calibrated against a standard tungsten ribbon lamp. The details of calibration have been outlined in I and will be reviewed briefly here. During calibration of the photometer, an image (unit magnification) of the tungsten lamp ribbon was focused at the slit by a 5° cone of light (see Fig. 2 of I). The slit area was 1.17 mm^2. The photometer, including the collimator assembly and the quartz window, was placed at a distance from the slit equal to the distance between the electron beam and the quartz window. Thus the slit (lamp ribbon image) was at the focal plane of the lens L_1 of the collimator, and light from the slit passed through the optical elements of the collimator under the same conditions as those in effect during observations. The light from the slit passed unobstructed through the aperture and slit of the collimator assembly.

The pressure in the collision chamber was measured by a Veeco RG-75 ionization-gauge tube. The ion-gauge tube calibration was effected using a Consolidated Vacuum Corporation high-vacuum McLeod gauge, Model GM-110, having a volume of 2193 cc (about 75 lbs of Hg), capillaries 0.535 mm in diameter, and a gauge constant of 1.02×10^{-6}. The McLeod gauge was connected to the liquid nitrogen-cooled cold trap by a uniform bore of tubing. Problems arising with such a system have been reviewed by Carr.[7]

The conventional way of operating the gauge may produce wrong pressure readings if the surface characteristic of the open and closed capillaries are different. In the method used the open capillary was ignored, and the level of the mercury in the large, open side arm was used for reference. The capillary depression was measured at low pressure as a function of the mercury level in the closed capillary. In each pressure measurement the compression was varied to produce several pressure readings, as in the method of Podgurski and Davis.[8] The readings at each pressure usually agreed within 2–3% for measurements up to 1×10^{-4} Torr.

At the lower end of the range, appreciable error can be caused by the diffusion of mercury from gauge to cold trap. To avoid this source of error, the mercury reservoir can be cooled. However, this technique for reducing the error is cumbersome for the large quantity of mercury (75 lbs). Moreover a difference in temperature between the bulb of the McLeod and the gauge system under calibration can introduce pressure differences due to thermal transpiration effects. A bakable needle valve was used at the mouth of the cold trap to change the effective radius of the tubulation from the McLeod gauge to the trap, as suggested by Meinke and Reich[9] to overcome these effects. Also the cold trap's outer wall's i.d. was kept nearly equal to the sum of i.d. and o.d. of the inner tube (cf. Rusch and Bunge[10]) to further reduce the error due to the presence of the cold trap between the McLeod gauge and the system. The maximum estimated error in the pressure measurements may be about 5–6% after taking all necessary precautions as outlined by Carr.[7]

4. RESULTS

Figure 2 shows experimental cross sections for emission of the (0, 0) (0, 1) and (0, 2) bands of the N_2^+ first negative system and also compares these with the recent measurements of McConkey and Latimer.[6] Measurements of Holland[11] at 907-eV electron energy have also been shown on the graph. The results of Stewart[5] and recently measured cross sections of Nishimura[12] are not in agreement with our results. Our cross sections are a factor of 2.5 higher than those of Refs. 5 and 12 and have been omitted in the graph for the sake of clarity. The disagreement between our results and those of Stewart[5] and Nishimura[12] can not be evaluated because of the absence of details of photometric and pressure calibrations in their papers. The absolute values of the cross sections of this work are in reasonably good agreement within the quoted experimental errors over a narrow range of overlap with those of McConkey and Latimer[6] (see Fig. 2). The McConkey and Latimer photometric calibration was indirect and that may be one of the reasons for only fair agreement with our results. The measurements of Holland at 907 eV are also in very good agreement with ours.

During the course of our measurements, the photometer and pressure calibrations were checked periodically. Immediately after the final measurements (results plotted in Fig. 2) of each band, photometric and pressure calibrations were performed to avoid any significant change in the characteristics and sensitivity of both the photomultiplier tube and the ionization gauge. The emission

TABLE I. Relative intensities of the $v'=0$ progression in the N_2^+ First Negative System.

Investigators	λ3914 Å (0, 0)	λ4278 Å (0, 1)	λ4709 Å (0, 2)	Method
Wallace and Nicholls[a]	1.0	0.32	0.063	Measured in N_2 negative glow
Stewart[5]	1.0	0.39	0.10	Using electron impact excitation
Philpot and Hughes[b]	1.0[h]	0.32	0.067	Proton impact excitation
Pillow[c]	1.0	0.31	0.099	Calculated
Herzberg[d]	1.0	0.34	0.048	Measured in N_2 discharge
Bates[e]	1.0	0.31	0.072	Calculated
Hayakawa *et al.*[f]	1.0	0.39	0.07	Using electron impact excitation
McConkey and Latimer[6]	1.0[h]	0.32	0.075	Using electron impact excitation
Sheridan and Clark[g]	1.0	0.49	0.105	Using ion impact excitation
Holland[11]	1.0	0.33	0.075	Using electron impact excitation at 907 eV
Nishimura[12]	1.0	0.3	0.05	Electron excitation
Present work	1.0[h]	0.34	0.065	Using electron impact excitation

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[g] J. R. Sheridan and K. C. Clark, Phys. Rev. 140, A1033 (1965).
[h] The table gives the relative emission probabilities in these cases.

cross sections are uncorrected for the polarization, which is less than 2% at 100-eV electron energy in all cases. No variation in output intensity with magnetic field was observed in the range 100–250 G indicating that magnetic field had no undesirable effects on the emission. The accuracy of our absolute measurements is estimated to be about 15%, mainly because of systematic errors in the photometer calibration and the gas pressure measurements. The day-to-day reproduction of the cross sections was better than ±3%. The relative band intensities of the (0, 0), (0, 1), and (0, 2) bands are compared with the other experimental and theoretical values in Table I. The maximum cross section for the population of the $v'=0$ vibrational level of the $B\ ^2\Sigma_u^+$ state of N_2^+ is 2.38×10^{-17} cm^2 in our measurements.

The excitation cross section of the $v'=0$ vibrational level of the $B\ ^2\Sigma_u^+$ state is compared with the ionization cross sections of N_2 by electron impact[13–15] in Fig. 3. The excitation of the $v'=0$ vibrational level is of the order of 0.1 of the total ionization cross section of N_2 by electron impact. This ratio is in excellent agreement with the observation of Dahlberg, Anderson and Dayton[16] for proton bombardment at higher energies.

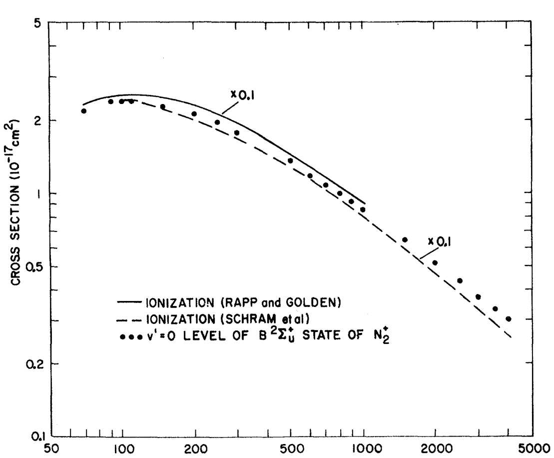

FIG. 3. Excitation cross section of the $v'=0$ vibrational level of the $B\ ^2\Sigma_u^+$ state of N_2^+ and ionization cross section of N_2 by electron impact.

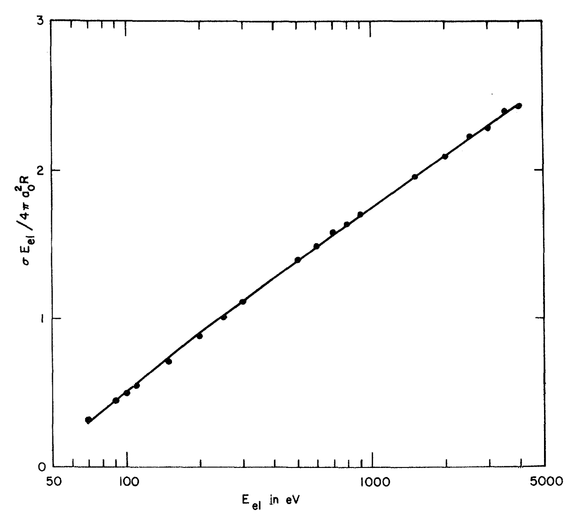

FIG. 4. Emission cross section for the $v'=0$ vibrational level of the $B\ ^2\Sigma_u^+$ state of N_2^+ by electron impact plotted as $\sigma E_{el}/4\pi a_0^2 R$ versus $\log E_{el}$.

5. COMPARISON WITH THEORY

The excitation of the N_2^+ first negative system is mainly by simultaneous ionization and excitation of N_2 molecules leaving N_2^+ ion in the $B\ ^2\Sigma_u^+$ excited state. The experimental measurements of the N_2^+ first negative cross sections indicate that the $B\ ^2\Sigma_u^+$ excited state is a constant fraction of the total ionization of N_2. This means the excitation cross section can be represented similar to the Bethe-Born approximation equation for ionization (cf. Schram *et al.*[14]),

$$\sigma_e = (4\pi a_0^2 R/E_{\mathrm{el}}) M_e^2 \ln(c_1 E_{\mathrm{el}}), \qquad (1)$$

where σ_e is the excitation cross section in cm^2, a_0 is the first Bohr radius, R is the Rydberg energy, E_{el} is the electron energy corrected for the relativistic effects, c_1 is a constant and M_e^2 is the effective dipole matrix element squared for excitation.

From Eq. 1 it can be seen that a plot of $\sigma_e E_{\mathrm{el}}/4\pi a_0^2 R$ versus $\ln E_{\mathrm{el}}$ will allow a determination of the value of M_e^2. Such a plot is given in Fig. 4 for the $v' = 0$ [sum of the (0, 0), (0, 1), and (0, 2) cross sections] vibrational level of $B\ ^2\Sigma_u^+$ state. The value of M_e^2 for the $v' = 0$ level of the $B\ ^2\Sigma_u^+$ state obtained from the graph is 0.51. The measured cross sections very nicely display $E^{-1} \ln E$ variation above 300-eV electron energy.

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