Cross Section for Electron-Impact Excitation of the (0,0) First Negative Band of N_2^+ from Threshold to 3 keV*

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(Received 28 July 1969)

The cross section for the excitation of the (0, 0) first negative band of N_2^+ by electron impact has been measured, using photon-counting techniques, in the energy range from threshold to 3 keV and extrapolated to 10 keV by means of a Bethe-Oppenheimer relation. In order to avoid polarization effects, the primary measurements were made at the "magic angle" of 54° 44′; complementary measurements at 90° were also obtained for comparison purposes. The excitation cross section for the (0, 0) band reached its maximum value at an energy of about 100 eV where it was $(1.74 \pm 0.17) \times 10^{-17}$ cm^2. The ratio of the total ionization cross section to the excitation cross section was nearly constant over the energy range from 30 eV to 10 keV, and had a value of 14.1.

I. INTRODUCTION

The absolute cross section for the excitation of the (0, 0) first negative band of N_2^+ by electron impact is of considerable geophysical importance. For example, when taken together with *in situ* rocket measurements of the secondary-electron energy spectrum and the local-volume emission rate of the (0, 0) band, the excitation cross section can be used[1,2] to determine the primary N_2^+, N^+, O_2^+, and O^+ ionization rates in an aurora and to provide an independent measure of the total electron flux above 18.8 eV. By combining these results with simultaneous mass spectrometer measurements[3] of the ion and neutral particle densities, we have an effective means for studying the transient behavior of the ionosphere under auroral conditions.[4]

The present study was prompted by a series of rocket experiments which showed that the bulk of the secondary electrons in an aurora has energies well below 100 eV.[5] This is shown clearly in Fig. 1. For auroral applications an accurate knowledge of the excitation cross section over an energy range extending from threshold to approximately 100 eV, where the cross section reaches its maximum value, is essential. Recent measurements[6,7] of the excitation cross section, however, do not extend much below 100 eV and although the general agreement at energies above 300 eV is very good, the discrepancies in the shape and the absolute magnitude of the cross section in the vicinity of its maximum value are difficult to explain in view of the absolute error estimates (typically 10–15%) reported by these workers. Two measurements[8,9] cover the important range from 100 eV to threshold. Unfortunately, the results of McConkey *et al.* must be accepted with some reservations in view of the unusual threshold behavior exhibited by their data, which disagree with the low-energy results of Stanton and St. John.[9]

In the present experiment, the excitation cross section for the (0, 0) band of N_2^+ was measured from threshold to 3 keV with a probable absolute error of ±10%. In order to be completely free of polarization problems the primary measurements were made at the magic angle of 54° 44′; complementary measurements were also made at 90° for comparison purposes. The experiment was housed in a bakable ultrahigh vacuum system in order to preserve the purity of the reagent grade gas used in these measurements and to minimize the effect of residual background gases. Pulse counting techniques were used in this experiment to facilitate a statistical analysis of the data. The details are presented in the following sections.

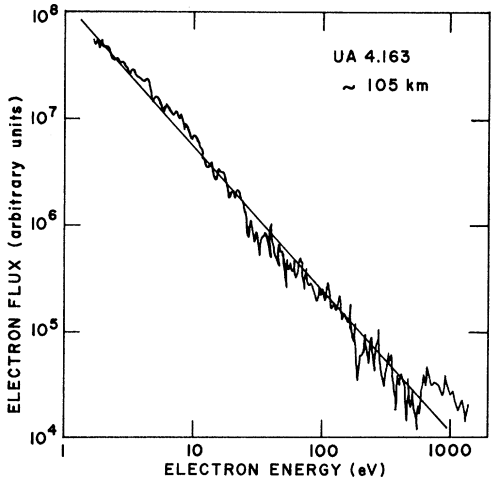

FIG. 1. Secondary-electron-energy spectrum at 105 km during auroral activity as measured by Doering (see Ref. 5).

II. EXPERIMENTAL DETAILS

The apparatus used in this work is shown schematically in Fig. 2. It consisted basically of an electron gun, a collision chamber assembly, a filtered photometer, 100-mHz pulse-counting equipment, and a related data-recording system. The electron gun and the collision chamber were housed in a 200-l multipurpose ultrahigh vacuum chamber in which vacuua of the order of 3×10^{-11} Torr could be obtained after a mild bakeout. During a measurement the entire vacuum chamber was filled with nitrogen to a pressure of about 1×10^{-4} Torr. A Granville-Phillips servo-valve and controller were used to hold the pressure constant to within 1%. Because the background pressure was normally less than 5×10^{-7} Torr, it was not necessary to bake the system for the purposes of this experiment.

The electron gun was an oscilloscope gun that was modified for use at low energies and, when necessary, at high beam currents. The details of the gun will be described elsewhere. It suffices to mention here that satisfactory gun performance was achieved from 5 to 400 eV. In this energy domain the electron gun produced a well-collimated beam with a current of several microamperes and an energy spread of about 0.5 eV. The stray electron current to the collision chamber was generally less than 1% of the current collected in the Faraday cup. It was not found necessary or desirable to collimate the electron beam further by an external magnetic field. Rather, the electron gun and the collision chamber were magnetically shielded by several layers of conetic-AA foil attached to the inside of the vacuum chamber while the residual earth's magnetic field was compensated by a Helmholtz coil outside of the vacuum chamber. A second oscilloscope gun, that was operated in a different mode, was used at energies above 400 eV.

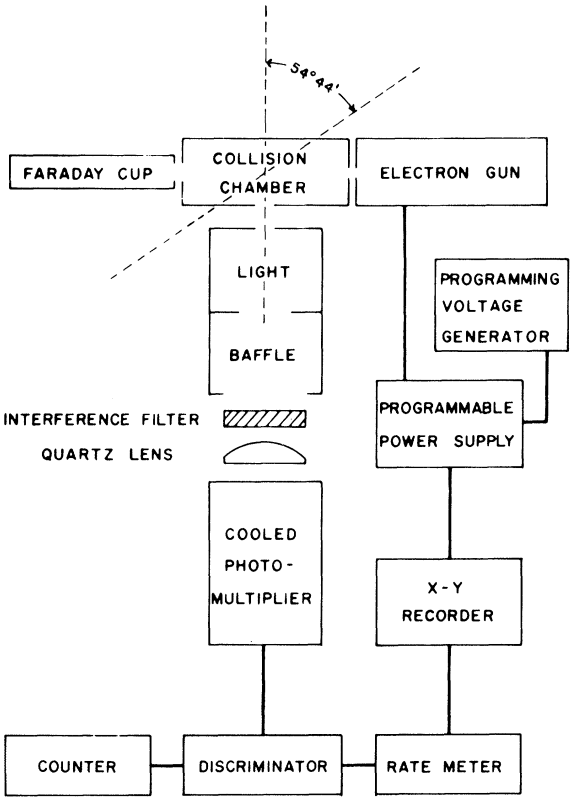

FIG. 2. Schematic diagram of apparatus. The collision chamber could be rotated into the "magic angle position" of 54° 44′ in order to avoid polarization effects. For the other details, see text.

In order to minimize the reflection of photons and electrons from the gun, the collision chamber and the Faraday cup were painted with a colloidal dispersion of graphite. The Faraday cup was biased positively with respect to the collision chamber by about +20 V and collected virtually all of the beam electrons without noticeable reflections. No change in the magnitude of the cross section was observed when the biasing voltage was varied from 10 to 100 V. The potentials for all gun electrodes were derived from one programmable power supply. The programming voltage for this power supply was obtained from an operational amplifier circuit. In this way the excitation cross section could be measured from threshold to 400 eV in about 3 min thereby minimizing any systematic errors due to slow instrumental drifts. The energy scale was obtained from the voltage difference between the center of the gun filament and the collision chamber. This resulted in the correct threshold energy to within 0.2 eV. No energy corrections were applied to the measurements.

A filtered photometer was used to detect the (0, 0) band photons emanating from the collision chamber. The components of the photometer included a blocked, narrow band interference filter (25 Å at full width half-maximum), a quartz collimating lens, and an EMR 641E side-window photomultiplier tube (S-20 photocathode). In order to minimize the effects of noise due to the residual dark current of the photomultiplier, the 641E tube was mounted in an evacuated Dewar and cooled by a dry ice-acetone mixture. Individual photoelectron pulses from the tube were amplified by a Keithley pulse preamplifier (180-mHz bandwidth) and converted by an EGG TD101 discriminator into standard logic pulses. The system had a pair pulse resolution of 10 nsec, and it was carefully adjusted to avoid pile-up effects. The background counting rate under operating conditions without N_2 admitted into the vacuum chamber was about 10 counts/sec. With nitrogen in the collision chamber, the observed signal counting rate was about 5000 counts/sec with an electron-beam energy of 100 eV and a

beam current of 1 μA.

Pressure Calibration

The absolute gas pressure was measured with nude Varian Millitorr and low-pressure ionization gauges, which were mounted in the 200-l vacuum chamber. These gauges were calibrated absolutely over the range of pressures used in the scattering experiment (0.01 – 1 μ) by carefully comparing their nominal pressure readings with a McLeod gauge. In order to eliminate any uncertainties concerning the effects of the dry-ice trap located between the McLeod gauge and the ionization gauges, the calibration of the McLeod gauge was simultaneously checked by using a precision absolute oil manometer. In the construction of the manometer, precision bore tubing with a large inside diameter (0.75 in.) was used in order to minimize wall effects and to provide a flat, well-defined meniscus. The glass tubes were epoxied into stainless-steel wells that were mounted on a rigid frame.

The density of the oil was measured to four significant figures with a hydrometer; standard mass-volumetric techniques were also used to independently verify this result. The height of the oil column was measured with a Gaertner cathetometer with an uncertainty of ± 0.001 cm. The McLeod gauge, manometer, and ionization gauges were cross compared in a stainless-steel ultrahigh vacuum gas-handling system in order to effectively eliminate any undesirable problems caused by outgassing. Both McLeod gauge and oil manometer gave identical readings to better than ± 1 % over the pressure range (100 to 5 μ) covered in the cross-calibration experiments. The ionization gauges were then cross calibrated with the McLeod gauge. The comparison experiment involved a check of both the absolute value of the pressure and the linearity of the ionization gauge over the entire pressure range used in the scattering experiment; the precision of the over-all calibration of the ionization gauges was about ± 2 %. Comparison measurements were made with the McLeod gauge both cooled and uncooled. No systematic differences due to the Ishii effect were observed.

The pressure in the 200-l vacuum chamber, which housed the entire gun-collision chamber assembly and the ionization gauges, was uniform. This was achieved by the proper choice of large conductances between vacuum chamber and collision chamber and by relatively small pumping speeds (~100 l/sec) at the vacuum chamber. The mean residence time of molecules in the vacuum chamber was of the order of 1 sec.

The electron-gun mount was thermally isolated from the collision chamber. Only small areas of the gun, which were far away from the collision chamber, ionization gauges as well as any surrounding walls warmed up during operation. This minimized any small pressure gradients between collision chamber and ionization gauges. We adopt ± 5 % as a conservative estimate of the maximum possible error in the pressure determination in the collision chamber.

Optical Calibration

The filtered photometer was calibrated absolutely with a General Electric Type 30A/T24/13 standard lamp and a freshly prepared MgO screen in an experiment shown schematically in Fig. 3. Both the geometry and the signal levels encountered in the actual scattering experiment were accurately preserved during these measurements. The standard lamp, which was fitted with a 1.25-in.-diam quartz window and an SR8A tungsten ribbon filament, was calibrated by the National Bureau of Standards; their data gives the brightness temperature of the filament as a function of the dc current when the filament is viewed normally through the quartz window at a wavelength of 0.653 μ. In our apparatus the required current was supplied to the lamp by a Kepco KS8-50M dc power supply (regulation of ± 0.05 %). A Leeds and Northrup Model 4361 precision 100-A resistor (0.01 Ω ± 0.04 %) was wired in series with the filament, and the current was determined by measuring the potential difference across the resistor (10 mV/A) with a Fluke Model 885AB Differential Voltmeter (absolute accuracy ± 0.0025 %). During a calibration measurement the filament current was held constant to better than ± 0.01 A.

In order to make sure that the original NBS lamp data still applied at the time of our calibration experiments, the brightness temperature of the lamp was monitored periodically with a Leeds and Northrup Model 8632-C optical pyrometer. Under the conditions of the calibration experiment, the pyrometer can measure the brightness temperature with an absolute accuracy of ± ½ % and therefore provides a sensitive test of the soundness of the calibration apparatus.

The actual temperature of the filament T is related to the brightness temperature T_B by the following expression:

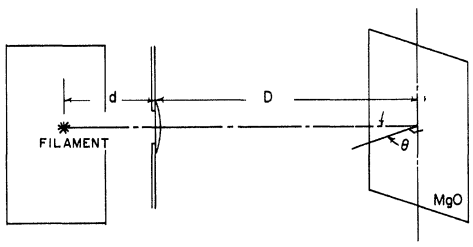

FIG. 3. Geometry of the optical calibration experiment using a standard lamp and a MgO screen.

$$\ln[\tau_Q(\lambda)\epsilon(\lambda, T)] = \frac{C_2}{\lambda}\left(\frac{1}{T} - \frac{1}{T_B}\right), \quad (1)$$

where $\tau_Q(\lambda)$ is the transmission of the quartz window, $\epsilon(\lambda, T)$ is the emissivity of tungsten, and $C_2 = 1.4388$ cm °K. The surface brightness (photons cm^{-2} $Å^{-1}$ sec^{-1} sr^{-1}) of the tungsten ribbon is given by

$$B(\lambda, T) = \frac{\tau_Q(\lambda)\epsilon(\lambda, T)C_1}{\pi hc\lambda^4(e^{C_2/\lambda T} - 1)}, \quad (2)$$

where $C_1/hc = 1.8836 \times 10^3$ cm^2 $Å^{-1}$ sec^{-1}. In this experiment, the emissivity values measured by Larrabee[10] (with a probable error of 2%) were used. When the small uncertainty in the temperature of the filament is taken into account, the surface brightness obtained from Eq. (2) will have a probable error of less than ±5%.

In order to reduce this uncertainty further, we compared our standard lamp with a similar General Electric tungsten lamp whose absolute spectral radiance had been measured by the NBS. The calibration data gives the absolute surface brightness as a function of wavelength with four-figure precision and a quoted absolute accuracy of ± ½%. No measurable difference (< 1%) could be detected between the output of the lamps, indicating that the actual surface brightness of our lamp was known with a probable error of less than 1%.

Only a small portion of the filament is calibrated and it is essential in a precision calibration experiment to use only this area. This is readily accomplished by using a magnesium oxide screen. The standard lamp is placed in a light-tight housing and a quartz lens is used to focus an image of the filament on a fresh MgO screen (Fig. 3). If the screen is viewed *normally*, it has a surface brightness of

$$B_S(\lambda, T) = \frac{B(\lambda, T)}{\pi D^2} A\tau_Q(\lambda)R(\lambda)\cos\theta, \quad (3)$$

where $R(\lambda)$ is the reflectivity of fresh MgO, $\tau_Q(\lambda)$ is the transmission of the quartz lens, and A is the area of the aperture of the quartz lens. By adjusting the ratio A/D^2, the surface brightness of the screen can be set to a value comparable to that encountered in the scattering experiment. The focal length of the lens can be chosen so that the magnified image of the calibrated section of the filament is viewed by the photometer. This arrangement also makes it a simple matter to check the linearity of the detection system by systematically changing the area of the lens aperture.

In order to duplicate the experimental conditions, an aperture of area A' was placed in front of the screen. The aperture diameter was the same as the effective scattering length (~1 cm) in the collision chamber. The number of photons per Å and per sec that was perpendicularly reflected from the screen into a solid angle $d\omega$ was then $B_S(\lambda, T)d\omega A'/\cos\theta$. The solid angle $d\omega$ was given by the photometer entrance aperture and its distance from the screen, which was the same as in the beam experiment.

During the course of the calibration measurements and throughout the actual experiment the gain and the pulse-height spectrum of the photomultiplier tube were frequently measured to make sure that the integrated counting efficiency of our apparatus did not change. The transmission function of the interference filter was measured with a 0.5-m Elbert monochromator; a standard tungsten lamp provided the necessary illumination. In order to obtain the effective filter transmission with respect to the (0, 0) first negative band, the position and line strengths of the rotational lines in this band were calculated. This band structure was then convoluted with the measured transmission function. We feel that the total error in the

TABLE I. Emission cross section of the 3914 Å band of N_2^+ in units of 10^{-18} cm^2. The values above 200 eV were calculated from a Bethe-Oppenheimer relation fitted to the present data over the energy range 200 to 3000 eV. (See also Fig. 3 and text.)

Energy (eV)	Cross section	Energy (eV)	Cross section
		200	15.2
19.0	0.121	250	14.1
19.2	0.241	300	13.1
19.6	0.479	330	12.4
20.0	0.714	400	11.2
21	1.35	450	10.4
22	1.98	500	9.79
23	2.61	600	8.75
24	3.25	700	7.92
25	3.89	800	7.25
26	4.54	900	6.70
27	5.18	1000	6.23
30	7.17	1200	5.48
35	10.1	1400	4.90
40	12.1	1600	4.45
45	13.6	1800	4.09
50	14.7	2000	3.78
55	15.4	2200	3.52
60	16.0	2400	3.29
70	16.7	2600	3.10
80	17.1	3000	2.77
90	17.3	4000	2.22
100	17.4	5000	1.86
110	17.4	6000	1.60
120	17.3	7000	1.42
140	16.8	8000	1.28
160	16.3	9000	1.16
180	15.8	10000	1.06

optical calibration described above does not exceed ±5%.

Excitation functions were automatically recorded on an X-Y recorder as a function of the incident electron energy. An Ortec 441 ratemaker was used to provide the required digital to analog conversion. Absolute cross sections were reproducible to within a few percent over a period of several weeks. The *maximum* absolute error in the cross-section values listed in Table I is believed to be ±15%. The probable error is less than ±10%.

III. RESULTS AND DISCUSSION

The experimental results are shown in Fig. 4 and listed in Table I. The cross section rises approximately linearly from threshold up to about 30 eV, attains a maximum value of 1.74×10^{-17} cm^2 around 100 eV and falls off according to the Bethe-Oppenheimer relation $Q=AE^{-1}\ln(BE)$ at higher energies. The constants A and B were determined by a least-squares fit to the data points between 200 to 3000 eV, and we find that $A=1.91\times10^{-15}$ cm^2 eV and $B=2.60\times10^{-2}$ eV^{-1}. The data points are well represented by the Bethe-Oppenheimer approximation for energies above 70 eV. Owing to the accuracy of the fit, the cross section was extrapolated to 10 keV (solid curve in Fig. 4).

A comparison of the most recent cross-section measurements is shown in Fig. 5 and Table II. The agreement at high energies (300 eV) is very good. However, there are remarkably large discrepancies (as much as 40%) in the maximum value of the cross section. This disagreement may be due in part to limitations in the electron guns in those cases where the measurements were not extended to energies much below the maximum and where collimating magnetic fields were employed. The cross section of McConkey *et al.* does not drop off properly near threshold. In fact, it remains finite with a rather large value at threshold. The reason for this was not discussed by these authors.

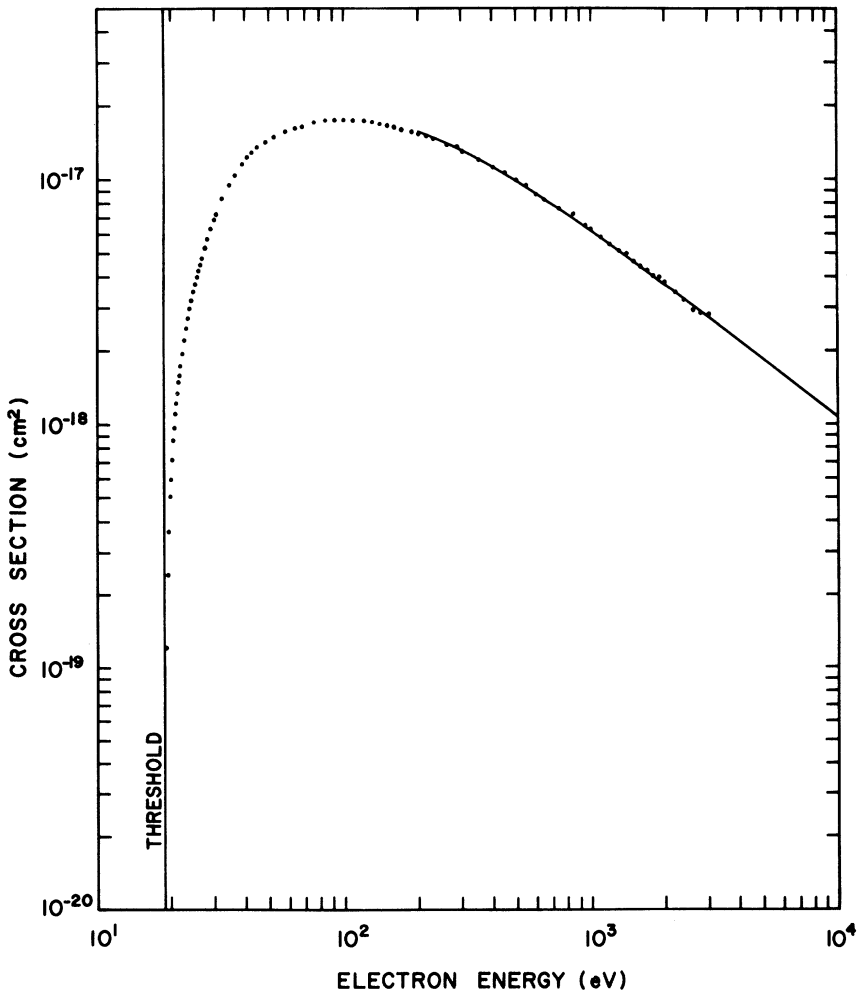

FIG. 4. Emission cross section for the electron-impact excitation of the 3914 Å (0, 0) $B^2\Sigma_u^+ - X^2\Sigma_g^+$ band of N_2^+. The solid line represents a Bethe-Oppenheimer relation $Q=AE^{-1}\ln(BE)$ obtained from a least-squares fit to the data points between 200 and 3000 eV. The experimental points up to 400 eV are only a representative sample taken from a continuous cross-section measurement.

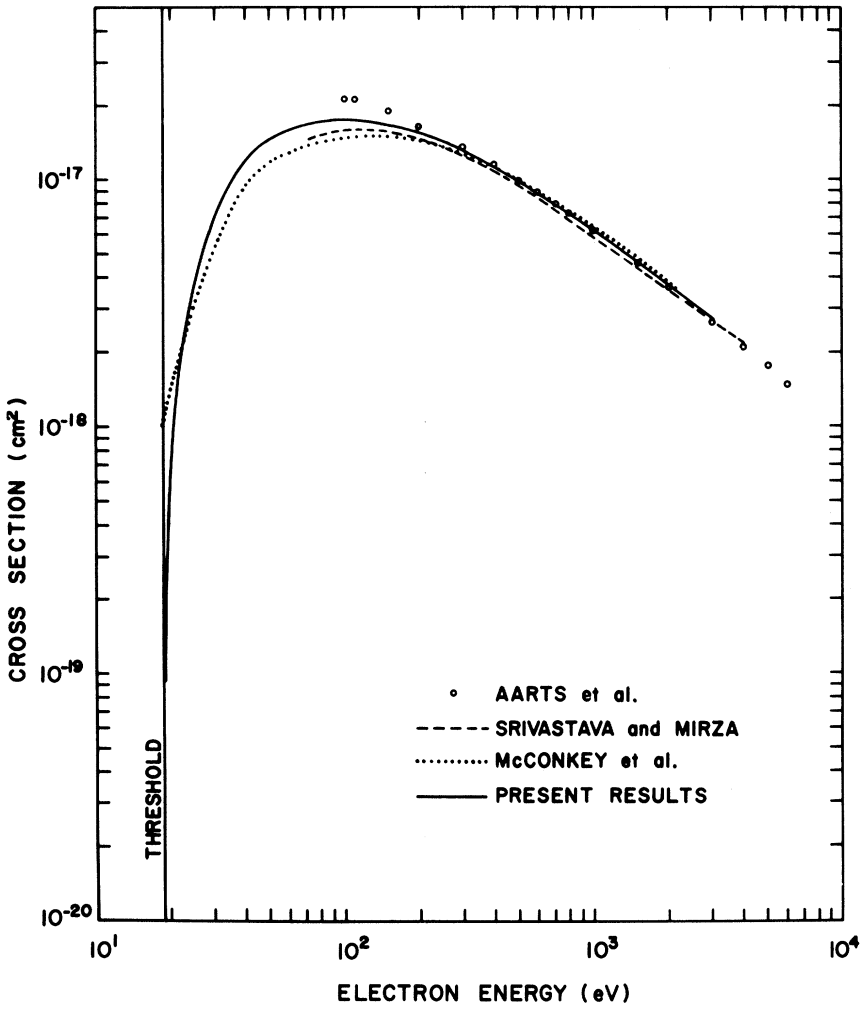

FIG. 5. Comparison of most recent emission cross section for the 3914 Å band of N_2^+.

From threshold to 100 eV our results are in satisfactory agreement with the cross-sectional shape observed by Stanton and St. John.[9] At higher energies, however, their cross section which was measured only up to 450 eV, appears to fall off more slowly than the present results.

The ratio of the present cross section to the total ionization cross section is shown in Fig. 6.

TABLE II. Comparison of maximum excitation cross sections of the (0, 0) first negative band of N_2^+.

Cross section in units of 10^{-18} cm^2	Author
21.2	Aarts, de Heer, and Vroom
17.4	This work
16.8	Srivastava and Mirza[a]
15.6	Stanton and St. John
15.2	McConkey, Woolsey, and Burns

[a]B. N. Srivastava and I. M. Mirza, Phys. Rev. 168, 86 (1968).

In obtaining this ratio, the total ionization cross section of Rapp and Golden[11] was used below 700 eV. At higher energies the total ionization cross section of Schram *et al.*[12] was normalized to that of Rapp and Golden at 700 eV. It can be seen from the figure that this ratio is nearly constant from 30 eV to 10 keV. In this energy range, the average value of the ratio for the production of an ion pair to that for the emission of a 3914-A photon is 14.1. This is in good agreement with a value of 13 obtained by McConkey, Woolsey, and Burns.[8] The agreement with a value of 17 given by Dalgarno, Latimer, and McConkey[13] is rather poor. The reason for the discrepancy between the last two values is not clear.

In the present experiment, the polarization of the emitted light was less than 5% over the entire energy range. This was found by rotating the collision chamber and gun assembly from the "magic angle" of 54° 44′ into the 90° position (see Fig. 2) and comparing the results. The cross section did not differ significantly in the above two positions. Polarizations of 6%, less than 3%, and

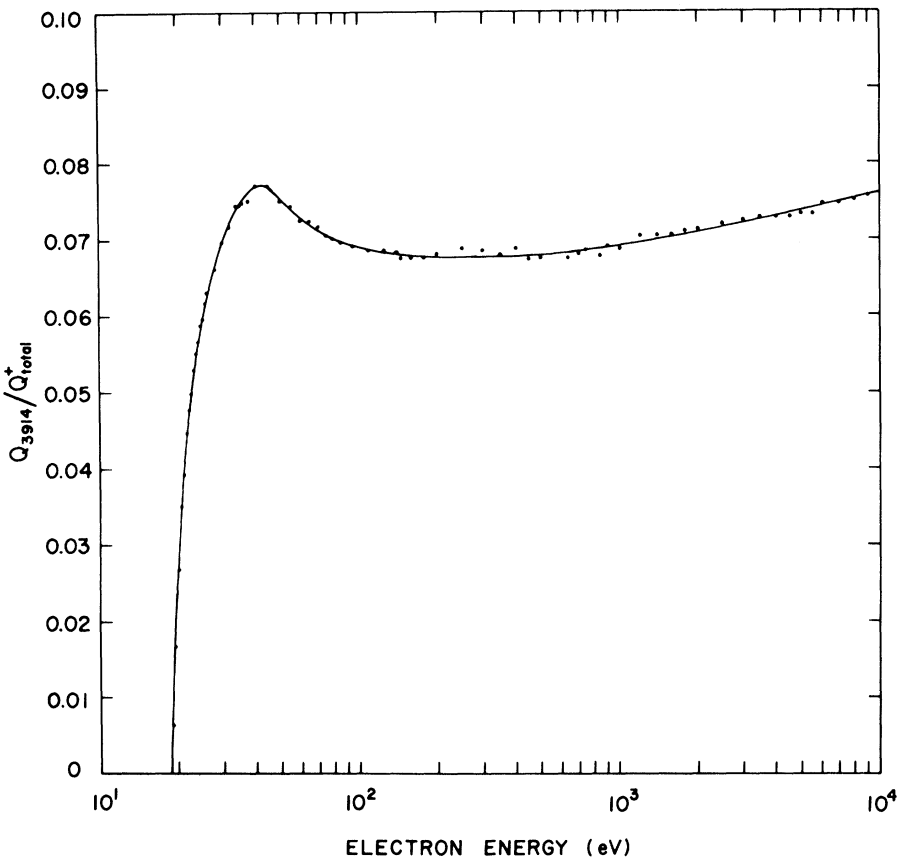

FIG. 6. Ratio of present emission cross section for the 3914 Å band to the total ionization cross section in N_2.

less than 2% at 100 eV have been found by McConkey *et al.*,[8] Aarts *et al.*,[6] and Srivastava and Mirza,[7] respectively.

IV. ACKNOWLEDGMENTS

We wish to thank Miss G. L. Unger and G. E. Mechler for their assistance.

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*Research reported in this paper supported in part by the National Aeronautics and Space Administration (NGL 39-011-030) and by the Advanced Research Projects Agency (DA-31-124-ARO-D-440).

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