Excitation of 3914 Å N_2^+ Radiation in Collisions of Heavy Ions with N_2 †

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The cross sections for production of the (0, 0) transition of N_2^+ first negative bands (3914 Å) produced in collisions of several heavy ions with N_2 have been measured. The ions used were Ba^+, Ba^{++}, Xe^+, N^+, O^+, and N_2^+ in the energy range from approximately 50 keV to 2 MeV. Absolute cross sections were determined by comparing signals produced on ion impact with those produced by an electron beam passing through the gas cell and using the known electron-impact excitation cross sections. Signals were detected using an interference filtered photomultiplier. The results are compared with those of other investigators where such other results exist.

INTRODUCTION

Collision-produced excitation of the (0, 0) transition of the first negative bands of N_2^+ has received considerable attention over the past years because of the importance of this radiation in aurora, air glows (both natural and induced), and gas discharges. Most of the experiments have studied excitation of this radiation, which occurs at 3914 Å, by electron impact on neutral N_2, [1–8] detecting the radiation with photomultipliers which had been calibrated against standard lamps. The electron-impact results were generally in good agreement as far as shape of the excitation function curve is concerned, but the absolute cross-section curves have tended to cluster about two curves, one having values about twice those of the other. The later and presumably more reliable results[4–8] cluster very well around the higher curve which displays a maximum in the cross section of about 1.5×10^{-17} cm^2 at an electron energy of about 100 eV.

Some results are also available for proton-impact excitation of this radiation[2, 9–12] with considerable disagreement again appearing in the absolute magnitudes of the cross section. Measurements for various other light ions, including N^+ and N_2^+ have also been reported, [11, 13] with energies extending up to 65 keV.

The purpose of the present experiments was to extend the range of data on ion-impact excitation of this radiation using both heavier ions and ion energies from 50 keV to 2 MeV.

The process under consideration is

$$A^{n+} + N_2 \rightarrow N_2^+(B^2\Sigma_u^+) + A^{m+} + (m-n+1)e,$$

followed by

$$N_2^+(B^2\Sigma_u^+,\ v'=0) \rightarrow N_2^+(X^2\Sigma_g^+,\ v''=0) + h\nu\ ,$$

where A^{n+} is a heavy ion with a charge of $+ne$.

Measurements were made with ion beams of Ba^+, Ba^{++}, Xe^+, N^+, O^+, and N_2^+ passing through nitrogen gas contained in a collision chamber. Photons were detected at 90° with respect to the ion beam direction using a photomultiplier preceded by an interference filter. When N_2^+ beams were used, no distinction is made between simultaneous ionization and excitation of the target molecule and excitation of the incident ion in collision with the target neutral.

EXPERIMENTAL ARRANGEMENT AND PROCEDURES

The beam of ions was produced at the terminal of the van de Graaff accelerator, mass selected by an rf quadrupole mass filter located in the terminal and then accelerated. After acceleration, a 2° deflection of the ion beam was made using a transverse electric field in order to purify the beam by removing primary ions that had changed charge and background gas ions formed through charge transfer and/or ionization along the length of the acceleration column. Some 60 cm after the deflection purification, the beam was collimated and entered the collision chamber. Since the pressure in the vacuum between the purification deflection and the collision chamber was about 10^{-6} Torr, from the capture and loss cross sections known from other experiments of this laboratory[14] it can be assured that alterations in the ion beam constituents due to collisions in the vacuum following purification would be substantially less than 1%.

The essential parts of the present experiment are shown in Figs. 1 and 2. The ion beam proceeded from the left and entered the collision chamber which had a diameter of 4.1 cm and a length of 5.5 cm. The beam entered the chamber through a circular aperture of 1 mm diam and emerged through a horizontal slit of dimensions

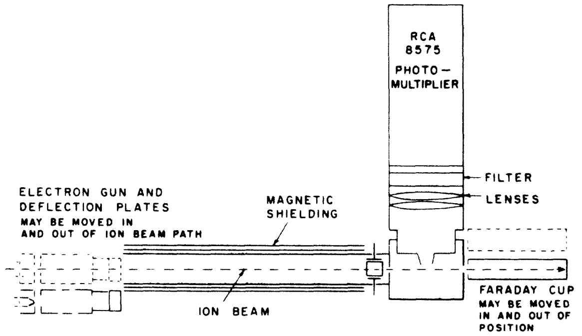

FIG. 1. Experimental arrangement for the study of excitation of 3914 Å light in collisions of ions with N_2. The removable electron gun is used alternatively with the ion beam and a comparison of the signals observed yields the ratio of the cross sections for electron-impact and ion-impact excitation.

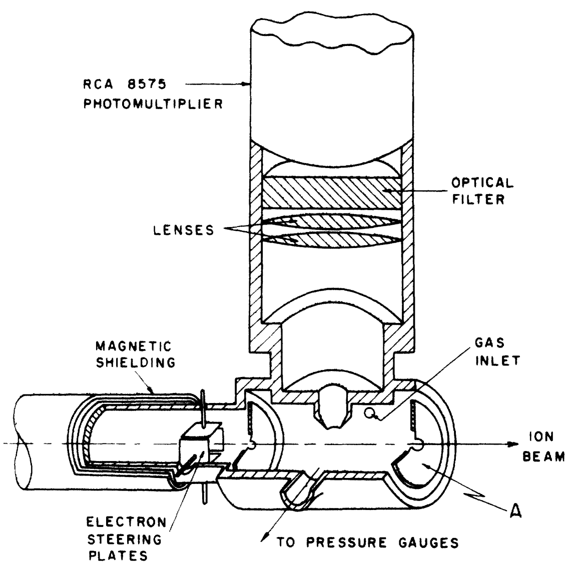

FIG. 2. Details of the collision chamber and optics used in studying excitation of 3914 Å radiation.

2×5 mm. By using a moving detector of narrow aperture behind the exit slit, measurements of the scattering of the ions were made and assurance gained that all ions entering the chamber were indeed emerging from the collision chamber and entering the deep Faraday cup used to measure the ion currents.

Further assurance of correct ion-current measurements was obtained by having the end walls of the collision chamber electrically insulated from the grounded main body of the collision chamber and by monitoring the current to the exit end plate concurrently with the Faraday cup current. With no gas in the collision chamber the end plate current was about 1% of the current measured to the Faraday cup. At the highest gas pressures (10^{-3} Torr) used, approximately 10% of the ions were typically scattered in the gas cell sufficiently to strike the end plate, with a corresponding drop in current to the Faraday cup always being noted.

Photons produced in the collision chamber were detected through a circular aperture of 6 mm diam, the plane of which was located 6 mm above the ion beam path. The light was collected by a lens system of focal length 7.5 cm which was located at this distance above the ion beam. After passing through the lens system, the parallel light beam passed through a thin film interference filter of 2 in. diam having a maximum transmittance of 25% at 3914 Å and a half-bandwidth of 25 Å. The photons were ultimately detected by an RCA 8575 photomultiplier tube operated at 1800 V.

As shown in Fig. 1, the ion beam normally passed alongside an electron gun located approximately 30 cm from the entrance to the collision chamber. This electron gun could be moved into a position such that its electron beam could be used to excite the radiation. Magnetic shielding was placed around the region of travel of the electron beam and two sets of steering plates were used to trim the electron beam until measurements of the currents to the exit end plate of the collision chamber indicated that the electron beam was following the same path through the collision chamber as the ions had. Determination of the ion excitation cross sections was made by comparing the signals using alternatively the ion beam and the electron beam, as discussed below.

The vacuum system used in the experimental region was a two-stage differentially pumped system, each stage being pumped by a liquid-nitrogen baffled NRC Type 162 oil diffusion pump. The first stage contained the deflection purifier of the ion beam and the electron gun, the collision chamber being located in the second chamber. The second chamber, which pumped back into the first chamber, had a pressure in the 10^{-6} Torr range in normal operation of the experiment.

Pressure measurements were made using a differential capacitance manometer (MKS Baratron) operating between the collision chamber and the vacuum of the second differentially pumped vacuum stage. The procedure in taking measurements was to fill a gas reservoir to a pressure slightly greater than 1 atm and let gas from the reservoir enter the collision chamber through a needle valve. The reservoir was connected through a second needle valve to an external forepump which slowly evacuated the reservoir. As the reservoir was evacuated the pressure in the chamber diminished also. The baratron signal measuring the collision chamber pressure was put on the X axis of an

X-Y recorder while the Y axis recorded the photomultiplier output signal. In this way a plot of photon signal versus pressure was obtained immediately.

The baratron was calibrated using helium gas at a pressure of 10^{-3} Torr and above against a McLeod gauge that was dry-ice trapped against the Ishii-Nakayama gauge pumping effect. Linearity of the baratron in the pressure range 10^{-4} to 10^{-3} Torr was established by comparing its pressure readings against those of an ionization gauge operating at low emission current. The pressure measurements are believed to be uncertain by no more than ±5%.

The curves of signal-versus-chamber pressure were linear up to pressures of about 5×10^{-4} Torr. The slope of the curve in this region dS_i/dp is related to the cross section $Q_i(E_i)$ of an incident ion at an energy E_i by

$$dS_i/dp = KQ_i(E_i)I_i \ , \tag{1}$$

where I_i is the ion current and K is a factor which includes experimental geometry, efficiency of photon detection, and the conversion factor between pressure and molecular number density. When the electron beam replaces the ion beam a similar expression describes the slope,

$$dS_e/dp = KQ_e(E_e)I_e \ , \tag{2}$$

where the subscript e refers to the electron and where K has the same value as in Eq. (1). Dividing the two expressions, the ratio of the ion to the electron excitation cross sections is

$$\frac{Q_i(E_i)}{Q_e(E_e)} = \frac{(dS_i/dp)I_e}{(dS_e/dp)I_i} \ , \tag{3}$$

and can be determined from the experimental data. Since the cross sections $Q_e(E_e)$ are known,[4-8] the absolute value of $Q_i(E_i)$ is readily determined. The electron energy normally used was 300 eV where the cross section was taken to have the value 1.3×10^{-17} cm^2.

The standard deviation in the measurements of $(dS_e/dp)/I_e$ was normally 3.5% or less and reached as high as 6.5% only on one occasion (at the time O^+ was used as the primary ion). The standard deviation in reading values of $(dS_i/dp)/I_i$ from the graphs of signal versus pressure was estimated to be 4% except in the case of Xe^+ where, because of low signal levels, scatter in the data led to a standard deviation of 9%. The standard deviation of the value of the ratio defined in Eq. (3) was therefore normally about 5% and reached 7.6% and 9.6% for the cases of O^+ and Xe^+, respectively.

The possibility of extraneous radiation contributing to the signal was checked by replacing the N_2 in the collision chamber by Ar, Ne, H_2 and O_2. When using primary ions other than N_2^+, the radiation signals reached no higher than 2% of the signals obtained under the same conditions but with N_2 in the collision chamber, and reached 2% only for O_2.

No corrections were made for angular distribution of the radiation. Measurements by Thomas, Bent, and Edwards[12] of the polarization of 3914 Å radiation on proton impact on N_2 show less than 6% polarization and we assume that this figure is typical of the polarization when other primary ions are used. Srivastava and Mirza[7] reported that the polarization of the radiation on electron impact is less than 1.5%. Consideration of the angular distributions appropriate to such low polarizations would require at most a 3% correction to the ratio of Eq. (3) obtained assuming isotropic radiation.

With regard to the radiation produced when N_2^+ collides with N_2 and the question of whether the excitation is produced by excitation of the ion by the neutral or by simultaneous ionization and excitation, an experiment was performed in which O_2 replaced the N_2 in the collision chamber. It was found that with O_2 in the chamber the signals were only about 5% of the signals with N_2. The similarity between N_2 and O_2 suggests that simultaneous ionization and excitation dominates in $N_2^+ + N_2$ collisions.

RESULTS

The results of the measurements are presented in Figs. 3 through 8. The heavy-ion excitation cross sections are of the same magnitude as the proton-impact cross sections reported by Carleton and Lawrence,[9] Sheridan, Oldenberg, and Carleton[2] and Philpot and Hughes,[10] and about an order of

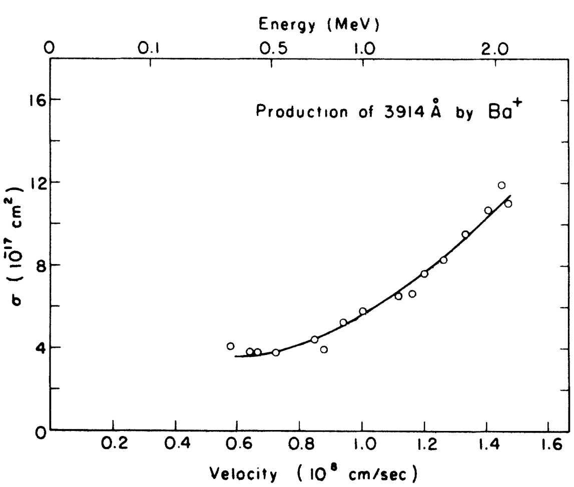

FIG. 3. Cross section for the production of 3914 Å radiation in collisions of $Ba^+ + N_2$.

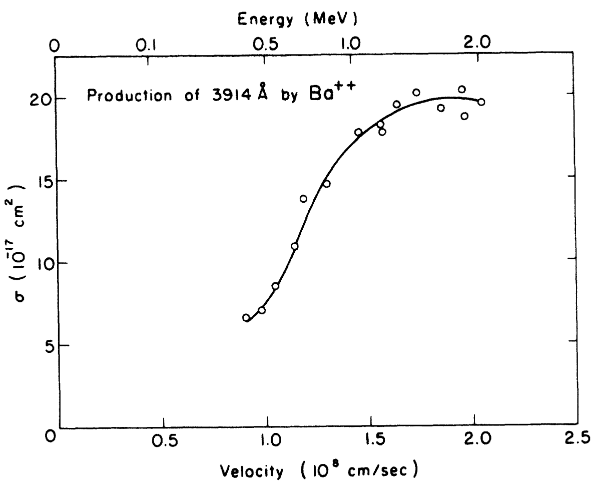

FIG. 4. Cross section for the production of 3914 Å radiation in collisions of $Ba^{++} + N_2$.

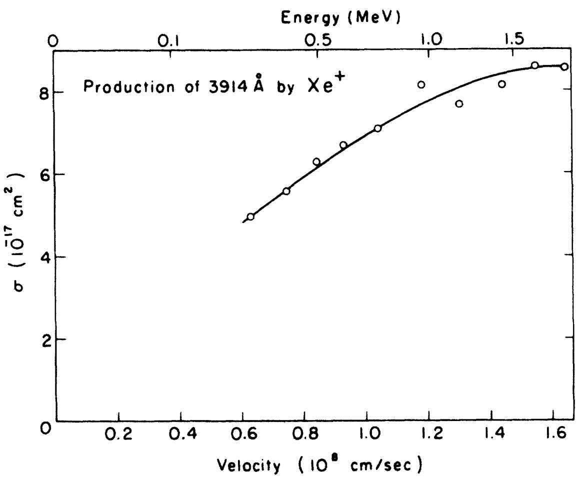

FIG. 5. Cross section for the production of 3914 Å radiation in collisions of $Xe^{+} + N_2$.

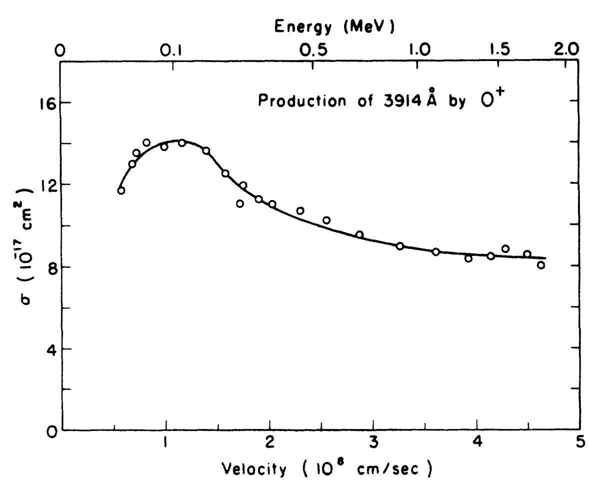

FIG. 6. Cross section for the production of 3914 Å radiation in collisions of $O^{+} + N_2$.

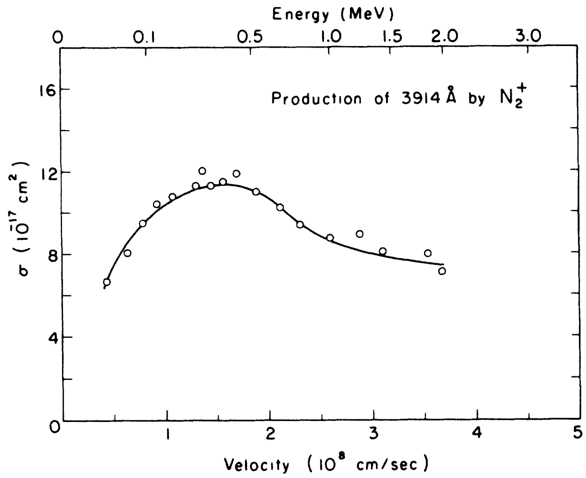

FIG. 7. Cross section for the production of 3914 Å radiation in collisions of $N_2^{+} + N_2$.

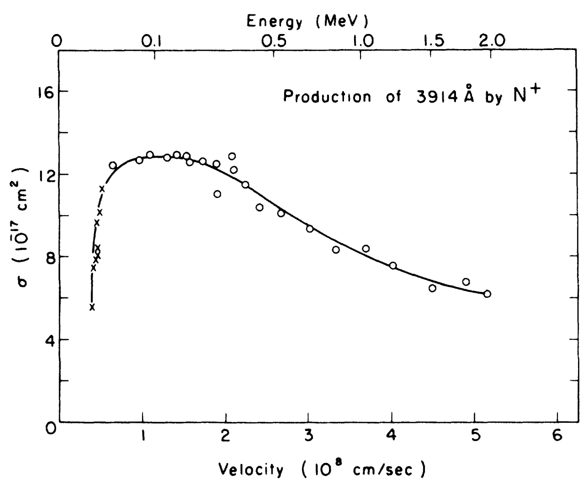

FIG. 8. Cross section for the production of 3914 Å radiation in collisions of $N^{+} + N_2$. The data of Sheridan and Clark[11] at low energies are observed to be consistent with the present measurements.

magnitude higher than electron-impact excitation cross sections for comparable velocities.

Figure 8 shows the data of Sheridan and Clark[11] as well as our own for excitation by N^{+}. Although the experimental energy ranges did not overlap, the two sets of results appear quite consistent.

The data of Fig. 7 are replotted in Fig. 9 and the results of Doering[13] at energies below 10 keV are also included in this semilog plot. Doering's results have been renormalized to reflect the more recent results for the electron impact excitation cross section,[4–8] this being used in assigning absolute values of the ion impact cross section in Doering's experiment.

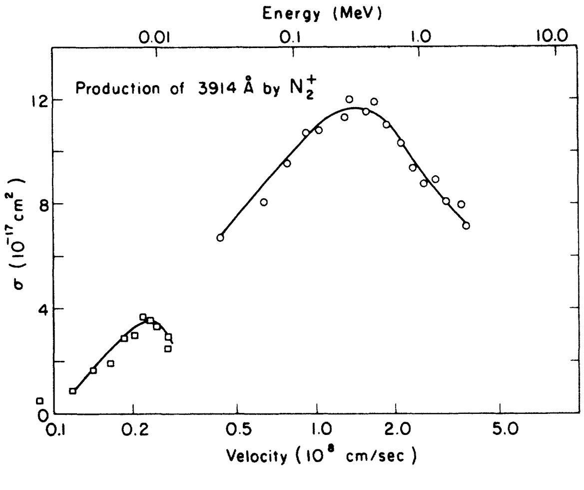

FIG. 9. Cross section for the production of 3914 Å radiation in collisions of $N_2^+ + N_2$ replotted in a logarithmic abscissa and plotting the data at low energies obtained by Doering.[13]

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