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MEASUREMENT OF EFFECTIVE CROSS SECTIONS AND EXCITATION FUNCTIONS OF THE BANDS OF THE FIRST NEGATIVE SYSTEM OF THE MOLECULAR ION N_2^+ *IN EXCITATION OF NITROGEN BY FAST ELECTRONS*

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The effective cross sections of the bands (0–0), (0–1), (0–2), (0–3), (1–2), (1–3), and (1–4) of the first negative system of the N_2^+ ion and of the lines of the multiplet λ = 5001–5005 Å of the N II spectrum were measured in the energy interval 0.5–20 keV. The nitrogen was excited with electrons of energy 0.5–20 keV. In the region of overlapping energies, the measured effective cross sections are in good agreement with the data of[1-5]. The course of the excitation functions of the investigated bands and lines is well described by formula (2) in the energy interval 0.8–20 keV.

INTRODUCTION

In a brief communication[1] we presented the results of measurements of the effective cross sections for the excitation of the (0–0) band of the first negative system of the N_2^+ ion (1 NS N_2^+). In the present paper we present the results of measurements of the effective cross sections of the bands 1 NS N_2^+ and of the lines of the multiplet λ = 5001–5005 Å of the N II spectrum.

The energies of the exciting electrons were in the interval 0.5–20 keV. The effective cross sections for the excitation of the bands 1 NS N_2^+, as well as of other emissions of nitrogen, were never measured before in such a wide energy interval. In recently reported investigations of the excitation of nitrogen by electrons, the excitation functions were measured up to energies no higher than 6 keV[2-7]. It should also be noted that there are considerable discrepancies between the results of the latest investigations[1-5], which are in good agreement with one another, and the results of earlier measurements[6,7].

As is correctly noted in the majority of the latest papers, the stimulus for the measurement of the effective excitation cross sections of different nitrogen emissions at high electron energies was the demands of geophysics, particularly the observation of fast electrons in the auroral zones.

EXPERIMENTAL SETUP AND MEASUREMENT PROCEDURE

A cross section and a block diagram of the experimental setup are shown in Fig. 1. The setup consists of the following main units: electron gun, intermediate chamber or corrector chamber, vacuum system, and recording apparatus. To cover the entire energy interval, electron guns of two designs were used. The first operated in the energy interval 0.4–6 keV, and the second at 4–20 keV. The source of electrons in both guns was a tungsten wire 0.15 mm in diameter, coiled into a helix of 1–1.5 mm diameter (1). The shaping and acceleration of the electron beam were effected in a gap between the filament and the first electrode 2 of the gun and between the first and second electrodes 3. The design of the electrodes has made it possible to produce Pierce optics in the region of beam shaping. An additional cylindrical electrode 4 was placed in the electron gun used for the energy interval 4–20 keV. In the gap between the second and third electrodes of this gun there was additional acceleration and focusing of the electrons. The electron beam was additionally focused at the output of the electron gun by means of a magnetic field produced by coil 5. In the intermediate vacuum chamber there were installed beam correctors 6, comprising two crossed flat capacitors. a Faraday cylinder 7 with magnetic control for the measurement of the beam current ahead of the entrance to the collision chamber, and a block of manometric tubes. Connected to the same chamber was a system for evacuating the apparatus, comprising a diffusion oil pump with a capacity of 500 liters/sec, a nitrogen trap, and a rotary forevacuum pump.

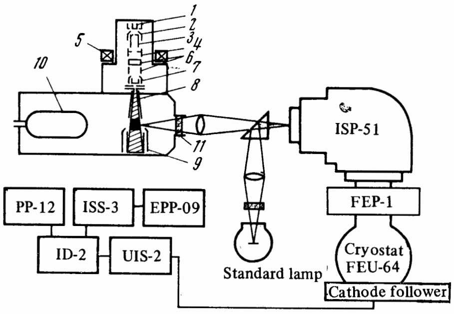

FIG. 1. Cross section and block diagram of experimental setup.

From the intermediate chamber the beam of electrons passed through conical input channel 8 and entered the collision chamber. Located in the collision chamber were a receiver for the primary-beam current 9, a metal trap 10 cooled with liquid nitrogen, and a Knudsen manometer (not shown in the sectional drawing).

The radiation from the excited gas particles emerged through a quartz window 11. The Knudsen manometer was calibrated against a McLeod manometer.[1)]

The electron receiver in the chamber was a Faraday cylinder in which the secondary electrons were suppressed by a transverse magnetic field. The input of gas into the chamber was regulated with needle valves which made it possible to vary the pressure in the chamber very smoothly.

The recording apparatus was an ISP-51 spectrograph with an FÉP-1 photoelectric attachment reconstructed to include an FÉU-64 photomultiplier, the photocathode of which was cooled to −70°C. To this end, the entire photomultiplier was placed in a special cryostat with a carbon sorption pump[9]. The cooling of the photocathode greatly decreased the dark current of the photomultiplier. The signal from the output of the photomultiplier was fed through a cathode follower to a pulsed amplifier UIS-2, and then through an integral discriminator ID-2 either to a scaling unit PP-12, or to a pulsed counter ISS-2, the output of which was connected to an automatic recorder EPP-0.9, which made it possible to plot the spectrum. The entire recording apparatus operated in the individual pulse counting mode.

Two lamps were used as the standard radiation source, SI-8-200, for which the color and brightness temperature were known, and SI-10-300, which was calibrated against an absolutely black body directly in energy units of the radiation flux. The conditions for the transmission of the radiation from the lamp were fully identical with the conditions for the transmission of the radiation from the glowing region of the gas. In particular, identical lenses and quartz glasses were used. The only exception was the rotating prism, the absorption in which was taken into account in the calculation of the effective cross sections by introducing the coefficient 0.9. The output slit of the spectrograph was reconstructed to permit variation of its dimensions from 0 to 4 mm. It was necessary to increase the slit dimension in order to transmit the entire measured band through it.

The effective cross sections were determined either by measuring the intensity of the edge of the band, in which case the cross section was doubled, or by measuring the integral intensity of the entire band. Calculation of the effective cross sections was in accordance with the formula

$$\sigma_{ik} = 0.9344 \cdot 10^{-29} b_\lambda \varepsilon_\lambda \frac{d\lambda}{dl} dl \frac{A}{IP}, \qquad (1)$$

where b_λ is the spectral brightness of an absolutely black body, ϵ_λ the emissivity of tungsten, $d\lambda/dl$ the linear dispersion of the instrument in Å/mm, dl the width of the output slit of the spectrograph in mm, A the ratio of the signal from the beam to the signal from the lamp, I the beam current in uA, and P the pressure of the gas in the collision chamber in mm Hg.

The measurements were made in the single-collision region. To this end, a study was made of the dependence of the signal on the gas pressure and on the electron current at different electron energies. These dependences were investigated up to a pressure $P = 2.5 \times 10^{-3}$ mm Hg and a beam current I = 600 μA. Up to these values of P and A, the signal varied linearly with the gas pressure and with the electron-beam current, meaning that the excited gas particles were produced by single collisions of the electrons with the gas molecules. The measurement error, calculated from the reproducibility of the results, was 10–15% for strong emissions and increased to 20% for weak ones.

RESULTS AND DISCUSSION

Figures 2a and b show the excitation functions of the bands 1 NS N_2^+ and the lines of the multiplet λ = 5001–5005 Å of the N II spectrum. As seen from Fig. 2, the excitation function exhibits the same behavior for all the 1 NS N_2^+ bands, and for energies above 0.8 keV it is well described by the formula

$$\sigma = \sigma_0 \ln cE / E, \qquad (2)$$

where E is the electron energy, σ_0 = const, and $c = 4/(E_e - E_g)$ (E_e and E_g are the energies of the excited and ground states of the N_2^+ ion). This is precisely the energy dependence obtained for the effective cross section when calculated in the first Born approximation. The decrease of the effective cross sections for the excitation of the N II lines with λ = 5001–5005 Å with increasing electron energy is much more rapid than in the case of the 1 NS N_2^+ bands. This discrepancy is apparently due to the difference between the processes of excitation of molecular and atomic emissions. Figure 3 shows a comparison of the excitation function of the band (0–0) 1 NS N_2^+, obtained in the present paper, with the data by others. We see that our

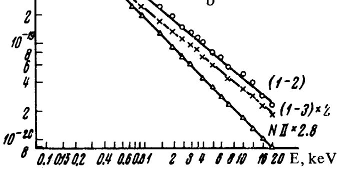

FIG. 2

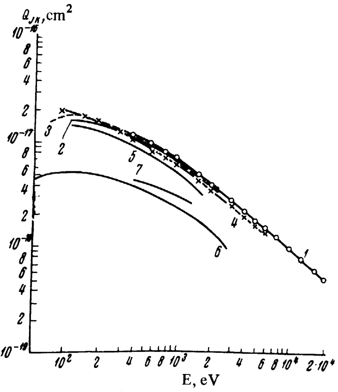

FIG. 3

FIG. 2. Excitation functions of the band 1 NS N_2^+ and of the N II lines.

FIG. 3. Comparison of the excitation cross sections of the band (0–0) 1 NS N_2^+ with λ = 3914Å measured in the present investigation with the data of [2–7]: 1–our data, 2–[2], 3–[3], 4–[4], 5–[5], 6–[6], 7–[7].

[1)] It turned out later that an error was made in the determination of the parameters of the McLeod manometer; this led to a systematic error in the determination of the pressure. The magnitude of this error was determined by comparing the effective cross sections of the hydrogen Balmer-series lines measured with our apparatus with the data of [8], where these cross sections were determined with high accuracy. The measured cross sections were then suitably corrected.

data agree well with the latest most reliable measurements[2-5]. The data of[6,7] are apparently too low.

The ratio of the effective cross sections of any definite system of bands can be calculated from the formula

$$\frac{\sigma_{ij}}{\sigma_{kl}}=\frac{N_i P_{ij}}{N_k P_{kl}}\frac{\lambda_{kl}^3}{\lambda_{ij}^3}, \qquad (3)$$

where P_{ij} and P_{kl} are the probabilities of the corresponding transitions, N_i and N_k are the populations of the i-th and k-th levels, and λ_{ij} and λ_{kl} are the wavelengths of these bands.

The transition probability is given by the formula

$$P_{v'v''}=R_e^2(\bar{r}_{v'v''})\,q_{v'v''},$$

where R_e is the moment of the electronic transition, $\bar{r}_{v'v''}$ is the average internuclear distance, and $q_{v'v''}$ is the Franck-Condon factor.

If for the given system the moment of the electronic transition R_e is not strongly dependent on the internuclear distance $\bar{r}_{v'v''}$, then the probability of the transition is proportional to the Franck-Condon factors:

$$P_{v'v''}\propto q_{v'v''}.$$

This condition is satisfied for transitions that occur with small changes of the internuclear distance. As follows from the form of the potential curves of the excited ($B^2\Sigma$) and ground ($X^2\Sigma$) states of the N_2^+ ion, the transitions that lead to the appearance of the bands 1 NS N_2^+ are accompanied by small changes of the internuclear distance. Therefore we can use the Franck-Condon factors in formula (3) in lieu of the transition probabilities.

The table shows a comparison of the effective cross sections of the bands 1 NS N_2^+ measured by us at an energy E = 4 keV with those calculated by formula (3), using the values of the Franck-Condon factors from[10] and using the data of[4]. The cross sections measured in[4] and calculated with the Franck-Condon factors are normalized to the cross sections of the band (0—0) 1 NS N_2^+. As seen from the table, good agreement is observed between the effective cross sections measured in the present investigation and those determined in[4], and also with those calculated from the Franck-Condon factors.

$v'-v''$	σ, cm²*	σ, rel. un.*	σ, rel. un.**	σ, rel. un.***
0—0	$23.6\cdot 10^{-19}$	1.0	1.0	1.0
0—1	$6.8\cdot 10^{-19}$	0.29	0.30	0.32
0—2	$1.3\cdot 10^{-19}$	0.055	0.062	0.60
0—3	$2.8\cdot 10^{-20}$	0.012	0.01	0.01
1—2	$1.07\cdot 10^{-19}$	0.045	0.042	0 044
1—3	$3.6\cdot 10^{-20}$	0.015	0.0145	0.0140
1—4	$1{,}01\cdot 10^{-20}$	0.0043	0.0035	—

*Present measurements.

**Calculation with Franck-Condon factors.

***Data taken from [4].

CONCLUSION

We have determined the excitation functions for the bands 1 NS N_2^+ in a wide energy interval. At energies above 0.8 keV, this dependence is well described by a formula obtained by calculation in the first Born approximation. The ratio of the cross sections agrees well with the calculation in which the Franck-Condon factors are used, thus indicating that no noticeable change in the moment of the electronic transition takes place in the transitions $B^2\Sigma \rightarrow X^2\Sigma$. In the region of overlapping energies, the cross sections measured in the present investigation are in good agreement with the data obtained by others.

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