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Excitation of Meinel and the first negative band system at the collision of electrons and protons with the nitrogen molecule

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The absolute cross sections for the e-N_2 and p-N_2 collisions for the first negative $B\,^2\Sigma_u^+ - X\,^2\Sigma_g^+$ and Meinel $A\,^2\Pi_u - X\,^2\Sigma_g^+$ bands have been measured in the energy region of 400–1500 eV for electrons and 0.4–10 keV for protons, respectively. Measurements are performed in the visible spectral region of 400–800 nm by an optical spectroscopy method. The ratio of the cross sections of the Meinel band system to the cross section of the first negative band system (0,0) does not depend on the incident electron energy. The populations of vibrational levels corresponding to $A\,^2\Pi_u$ states are consistent with the Franck-Condon principle. The ratios of the cross sections of (4,1) to (3,0) bands and (5,2) to (3,0) bands exhibit slight dependence on the proton energy. A theoretical estimation within the quasimolecular approximation provides a reasonable description of the total cross section for the first negative band.

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I. INTRODUCTION

Solar matter impacting the atmosphere is ejected from the Sun primarily as a result of solar flares, solar wind, coronal mass ejections, and solar prominences. Solar flares are sporadic events and are caused by the magnetic instabilities and disturbances in the corona that happen when energy stored in twisted magnetic fields is suddenly released. The other source of electrons and protons is the low-energy solar wind which results from the high temperature of the corona. The solar wind carries an electron-proton plasma, constantly evaporated by the sun and which is hot enough to escape the Sun's gravity and to flow outward into space, continuously shedding electrons and protons. Coronal mass ejection from the Sun consists of plasma composed primarily of electrons and protons as well as small quantities of nuclei such as helium, oxygen, and iron. Solar prominences are loops of radiant gas ejected from an active region on the solar surface that move through the inner parts of the corona under the influence of the Sun's magnetic field. The ionized gas generated by these phenomena follows the solar magnetic field lines away from the Sun. Most of it subsequently cools and falls back to the photosphere. Therefore, besides the electromagnetic radiation, the basic corpuscular parts of the solar radiation heading toward the Earth that subsequently interact with the atmosphere are electrons and protons in the energy spectrum between a few tenths of eVs to hundreds of MeVs [1,2]. They are deflected by the Earth's magnetic field toward the p's and get scattered and absorbed by atmospheric atoms and molecules. The accompanying ionization of various gases in the upper atmosphere causes a beautiful display known as the a—a luminous glow of the upper atmosphere.

While there have been investigations of the main characteristics of the a and their dependence on factors such as altitude, geographic placement, solar activity, etc., there is still a lack of quantitative description of this phenomenon. Upon reaching the denser layers of the atmosphere, electrons and protons participate in various inelastic processes such as ionization, molecular excitation, and charge-exchange reactions on atmospheric gases, especially on nitrogen molecules. Spectral analysis of the a shows that the ionized nitrogen molecules can radiate in the visible, infrared, and ultraviolet regions. Usually, the appearance of this radiation is observed at an altitude of approximately 110 km.

Observations of the prominent first negative ($B\,^2\Sigma_u^+ - X\,^2\Sigma_g^+$) and Meinel ($A\,^2\Pi_u - X\,^2\Sigma_g^+$) band system in the ionized nitrogen molecule $\mathrm{N_2}^+$ indicate their presence in the a and the dayglow [3–8]. The $A\,^2\Pi_u - X\,^2\Sigma_g^+$ system of the $\mathrm{N_2}^+$ ion has been extensively studied since Meinel [9] first observed the existence of the $A\,^2\Pi_u$ excited state in auroral emissions in the near-infrared and the $A\,^2\Pi_u - X\,^2\Sigma_g^+$ system of the $\mathrm{N_2}^+$ ion became known as the Meinel system.

Because the $A\,^2\Pi_u$ state of the $\mathrm{N_2}^+$ ion is effectively created during the ionization of the N_2 molecule by electron impact or capture of an electron by a proton (hydrogen emissions are the signature of proton a), the spectrum of the a is characterized by the bright lighting of the Meinel band. These bands appear in the spectra of polar a's and carry information on the collision processes which take place between molecules and electrons in the upper atmosphere. During e-N_2 and p-N_2 collisions, vibrationally excited $\mathrm{N_2}^+$ molecules and their radiative decay are accompanied by the creation of ground electronic $X\,^2\Sigma_g^+$ states. Hence, in the a the relative vibrational population of the $X\,^2\Sigma_g^+$ state is partly governed by electron excitation and relaxation processes of the $A\,^2\Pi_u$ states.

The study of the emission spectra gives the opportunity to determine the concentration and energy distribution of particles entering the upper layer of the atmosphere. To solve this problem, it is necessary to determine the absolute cross sections of various inelastic processes, such as ionization, excitation, and charge-exchange, with high precision. Determination of the absolute cross section of the Meinel band system is especially problematic. The number of experimental works in which the Meinel band system is measured is very limited, and they are usually related to the processes of excitation of the Meinel band through electron collisions with nitrogen molecules [10–19]. In addition, in the case of electron impact, the experimentally determined cross section for a formation of the N_2^+ ions in the A state is also known within 50% because measurements of the excitation cross section are connected with various difficulties. In particular, the lifetime of the nitrogen molecule ions in the $A\,^2\Pi_u$ state is about 10^{-5} s [10,11], and during measurements the quenching of excited particles (the transfer of the excited energy to other particles) is expected to occur. There is only one study [20] of the excitation of the Meinel band (2,0) by a proton impact on the N_2 molecule in the energy range 1.5–4.5 keV.

In this article, we present the results of measurements for the electron and proton impact excitation of the N_2^+ first negative (1NG) and Meinel band system obtained with high precision. The measurements are performed in the visible (600–800 nm) spectral region using the optical spectroscopy method for electron energies of 400–1500 eV and proton energies of 0.4–10 keV. A relative population of vibrational states corresponding to the Meinel band is measured at a sufficiently low pressure (0.1–0.7 mTorr). Therefore, the quenching and excitation effects caused by collisions involving secondary electrons are minimized. We have measured the absolute value of the cross sections for the first negative nitrogen molecule ion ($B\,^2\Sigma_u^+$–$X\,^2\Sigma_g^+$) with band (0,0) and for the Meinel system ($A\,^2\Pi_u$–$X\,^2\Sigma_g^+$) with bands (3,0), (4,1), and (5,2). The discrepancies in absolute cross sections and theoretical interpretations are discussed.

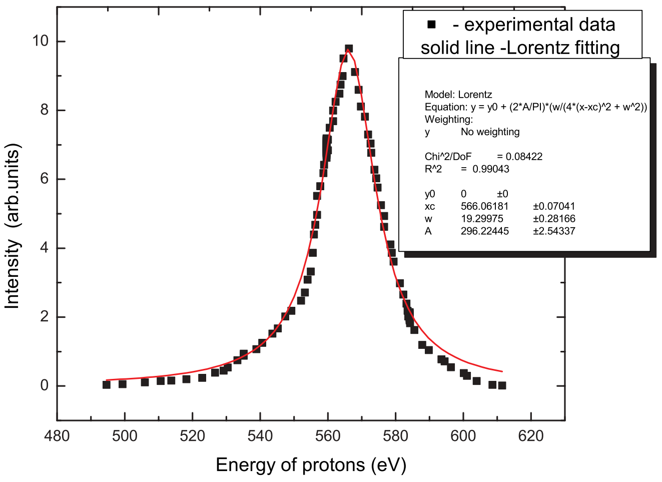
The article is organized in the following way. In Sec. II the research method is described. In Sec. III the experimental results and their discussion are presented. Finally, conclusions follow in Sec. IV.

II. RESEARCH METHOD

We have used an experimental setup and method of measurement similar to those described and used in our previous papers [21–23]. The protons extracted from the high-frequency discharge source were accelerated, collimated and focused, and mass-selected with a 60° magnetic sector field. Then the proton beam was directed into the collision chamber. In order to make the measurements for the case of electron collisions we used the electron gun placed into the mass-analyzer chamber. The electron beam was deflected at 90° and, after the collimation and additional focusing, was directed into the collision chamber. The fluorescence emitted as a result of the excitation of colliding particles was observed at 90° with respect to the beam. In the present work, measurements were performed by the optical spectroscopy method that allowed us to have the sufficiently high energy resolution of 0.001 eV, which was therefore sufficient to distinguish the excitation channels. This is one of the advantages of this method, with respect to the collisional spectroscopy method. This method also allowed us to estimate the polarization of excitation, which itself is a powerful tool for establishing the mechanism for inelastic processes. The spectroscopic analysis of the emission was performed with a monochromator incorporating a diffraction grating with a resolution of 40 nm/mm operated in the visible (400–800 nm) spectral region. A polarizer and a mica quarter-wave phase plate were placed in front of the entrance slit of the monochromator and the linear polarization of the emission was analyzed. For cancellation of the polarizing effect of the monochromator, the phase plate was placed after the polarizer and was rigidly coupled to it. The emission was recorded by a photomultiplier with a cooled cathode and operated in the current mode.

Calibration of the spectral sensitivity was performed by a tungsten filament standard lamp, which was chosen due to the lack of reliable experimental data in the infrared region (the bright Meinel system), that could be used for the calibration of the system for registration of radiation. To obtain the proton beam we used a high-frequency (20 MHz) ion source. The measurements for low-energy collisions required a precise determination of the energy of ions or electrons as well as of their energy dispersion. To avoid errors in the measurement of the energy of the incident protons and electrons, we employed the retarding potential method and used the electrostatic analyzer with a resolution of 500. Thus, the energy resolution of the electron beam was the same as that for protons, that is, 500. The energy of the proton and electron beams was calibrated by measuring their energy. To estimate the dispersion of energy provided by the high-frequency ion source and electron gun we measured the energy of impacting particles. The results of the measurements for protons accelerated by the potential of 600 V are given in Fig. 1. The measurements show that the energy deviation from 600 eV is approximately 35 eV. This is related to the specification of the high-frequency ion source and the selection of ions from plasma. From Fig. 1, we can see that the maximum is observed at 566 eV with a half-width of about 20 eV. In our experiments the energy dispersion of the protons does not exceed this value. For electrons the energy dispersion is less then 5 eV.

The proton current in the collision chamber was of the order of 1–10 μA while the electron current was 5–20 μA. The system was pumped by an oil-diffusion pump. The operating pressure of the gas under investigation did not exceed 6×10^{-4} Torr, so that multiple collisions could be ignored. The residual-gas pressure did not exceed 10^{-7} Torr. The absolute accuracy of the measurements was 30%. The accuracy of measurements is related to the following factors: the accuracy



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Model: Lorentz
Equation: y = y0 + (2*A/PI)*(w/(4*(x-xc)^2 + w^2))
Weighting:
y         No weighting

Chi^2/DoF       = 0.08422
R^2      =  0.99043

y0       0          ±0
xc       566.06181       ±0.07041
w        19.29975        ±0.28166
A        296.22445       ±2.54337
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FIG. 1. (Color online) Dispersion of the proton energy for the acceleration potential of 600 V.

of pressure measurements in the collision chamber; the precise and immediate determination of the primary beam current that produces the radiation that is collected by the optical system from the region where the collision occurs; and the accuracy of the relative and absolute calibration procedures.

The precision of the measurements of the Meinel band system strongly depends on two factors—quenching of the excited $N_2{}^+$ molecule in the $A\,^2\Pi_u$ state and overlapping of the Meinel bands with the other molecular emission [12,13]. Most of the Meinel bands are spectrally overlapped with nitrogen first positive emissions [13,24,25]. The degree of overlapping depends on pressure and the Meinel bands are less overlapped at low pressures where the excitation of the Meinel bands is stronger relative to the excitation of the first positive bands. At higher pressures the Meinel bands are quenched more efficiently. Also, the flux of secondary electrons increases with pressure and the secondary electrons excite the first positive bands more efficiently than the primary electrons do [25].

To explore electron excitation quenching effects, we investigated the spectrum of the Meinel band system in processes of excitation of the nitrogen molecule by the electron impact. The experiment was performed with various densities of the nitrogen target particles. To control the excitation quenching effect, the ratio of the excitation cross section of the Meinel band and the excitation cross section of the first negative band system (0,0) of a nitrogen molecular ion have been measured under various experimental conditions by varying the concentration of target particles. At the lowest pressures (less than about 1 mTorr), when the number of created secondary electrons was small the degree of the first positive band excitation relative to the Meinel band excitation was at most only a few percent [13]. The single collision condition was checked by a linear dependence of the intensity of spectral lines versus target gas pressure and density of the electron current. Measurements are performed in the visible (400–800 nm) excitation region. To demonstrate a reliability of the emission spectrum measurements, as an example in Fig. 2, the spectral scan is shown from 700 to 715 nm in the first order of the diffraction grating for the $N_2{}^+(A\,^2\Pi_u)$ (4,1) band for the e-N_2 collision at 400 eV. It is clear that there is no influence due to the collision quenching effect, because the lifetime of the zero vibrational level of the $B\,^2\Sigma_u^+$ state is about three orders of magnitude less than the lifetime of the vibrational level of $A\,^2\Pi_u$ states. The optimal experimental conditions were established based on these considerations.

To obtain the absolute value of the cross section, we use the cross section 8.66×10^{-17} cm^2 of the first negative system (0,0) for a p-N_2 collision at the energy of 7 keV from Ref. [26] as reference. In Ref. [26] the analysis of all experimental data of the excitation state for the (391.4 nm) (0,0) band spectrum in a wide energy interval is performed. Their analysis shows that the data obtained at a high-energy interval are more reliable (discrepancy in data at energy of protons $E > 5$ keV is about ±15%). It should be mentioned that during the experiment it was possible to measure the band spectrum for protons and electrons under the same experimental conditions. This provides an opportunity to obtain the absolute cross section for the electron collision based on the proton data. For the same experimental conditions, the radiation band for the first negative system (0,0) was measured for the proton and the electron at energies of 7 keV and of 600 eV, respectively. Comparison determined that the cross section for electrons for the 1NG (0,0) band at the given energy was 6.6×10^{-18} cm^2.

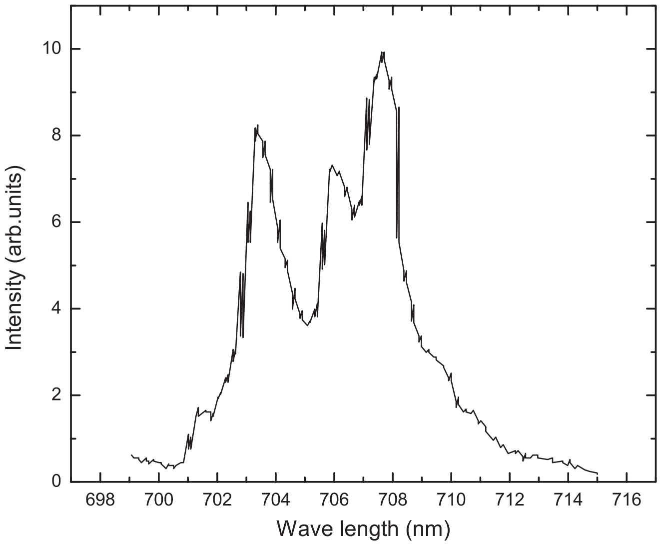

FIG. 2. Experimental spectrum of the $N_2{}^+$ Meinel (4,1) band for an electron energy of 400 eV.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Excitation cross sections of $N_2{}^+$ by electron impact

First, let us present the results for the electron impact excitation of the $N_2{}^+$ nitrogen ion for the first negative and Meinel bands. The results of the measurements of the absolute excitation cross sections for the first negative (0,0) and Meinel (3,0), (4,1), and (5,2) band systems by electron impact on N_2 in the energy region of 400–1500 eV are shown in Fig. 3. Analysis of the results shows that the aforementioned vibrational population of molecule states $N_2{}^+$ $(A\,^2\Pi_u)$ obey

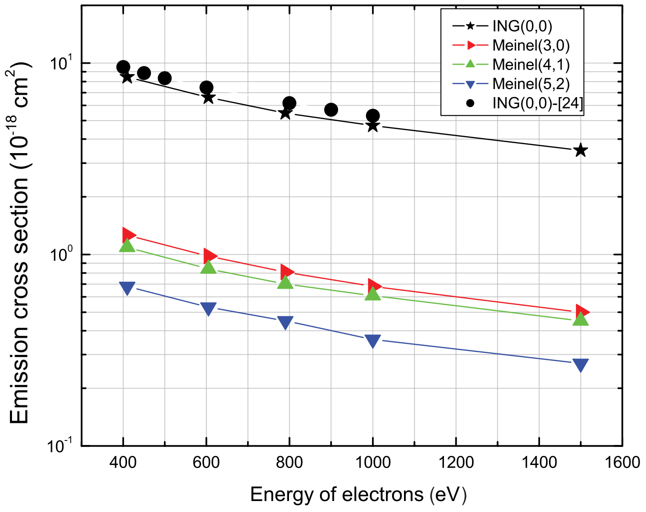

FIG. 3. (Color online) Dependence of the excitation cross sections for the first negative (0,0) and Meinel (3,0), (4,0), and (5,2) band systems on the electron energy for the e-N_2 collision.

the Franck-Condon principle [27,28]. From the comparison of the results of our measurements of the cross section for the 1NG (0,0) band system with the data from Ref. [24] shown in Fig. 3, we can conclude that their magnitude and energy dependence are in good agreement. Note that in Ref. [24] the detailed analysis of all existing data for the excitation of the (0,0) band of the first negative system by electron impact was carried out. It was emphasized that the energy dependence of the cross sections measured in Ref. [29] can be used as a representative in the wide energy interval (19–1000 eV). The recommended data from [24] was obtained by renormalizing the value of cross section from Ref. [29] to the best values determined in Ref. [30] at 100 eV. From Fig. 3, it is clearly seen that the ratio of the cross sections of the Meinel band system to that of the first negative band system (391.4 nm) (0,0) does not depend on the energy of incident particles. The same behavior has been obtained by Piper and co-authors [13]. However, the measured excitation cross sections of the Meinel band system by the electron impact differ by a factor of 2 from the existing measurements in Refs. [31] and [32].

B. Excitation cross sections of $N_2{}^+$ by proton impact

To study the excitation of the Meinel band system by proton impact on the nitrogen molecule, with the omission of the quenching effect, the impulse gained by the target particle in charge-exchange processes is taken into consideration. For the case in which the collision processes occur at a small impact parameter, a large momentum transfer to the target particle takes place. Therefore, it is expected that the target particles will have large velocity and, due to a long lifetime (10^{-5} s), the excited particles will escape from the observable excitation area without being registered by the detector. For this reason, we analyzed the results obtained in Ref. [33] for the differential cross sections of charge-exchange processes. The data analysis showed that the scattering cross section had a maximum at very small angles and then at the angle of about 1° it was reduced by three orders of magnitude [33]. For this reason for collision of 10-keV protons the measurements were taken within the scattered angle limited to 1°. Therefore the estimated maximal value of energy obtained by the target particles is determined as [34]

$$\Delta E = \frac{m_p}{m_{N_2}} E\theta^2 f(E\theta) = \frac{1}{28} 10^4 \left(\frac{1}{57.3}\right)^2 f(E\theta) < 0.11 \text{ eV} \tag{1}$$

where m_p and m_{N_2} are the masses of a proton and N_2 molecule, respectively, E and θ are the energy and scattering angle of the proton, respectively, and the function $f(E\theta)$ reaches the maximum value of 1 for the elastic limit only. According to Eq. (1) the velocity of target particles is $v = 10^5$ cm/s. The particle in the excited A states with this velocity can run 1 cm of distance. In order to register all of the radiation it is necessary that the height of the entrance slit of the monochromator be more than 1 cm and an observed object in the collision area should be away from the entrance slit at a distance that is sufficiently greater than 1 cm. In this case, the saturation of the excitation along the beam will be kept in advance. During measurements, the pressure of the target particles was kept sufficiently low in order to minimize collisional quenching effect. Results obtained for these conditions are shown in Fig. 4, where the total excitation cross sections for the excitation of the (3,0), (4,1), and (5,2) bands of the Meinel system by proton impact on N_2 are presented. Interestingly enough, the ratios of the cross sections of (4,1) to (3,0) bands and (5,2) to (3,0) bands are 0.8 and 0.55, respectively. These ratios are practically independent of the proton energy. The approximate values 0.9 and 0.54 are obtained for these ratios for the case of the e-N_2 collision. These results are also in good agreement with previously published data in Refs. [13] and [24].

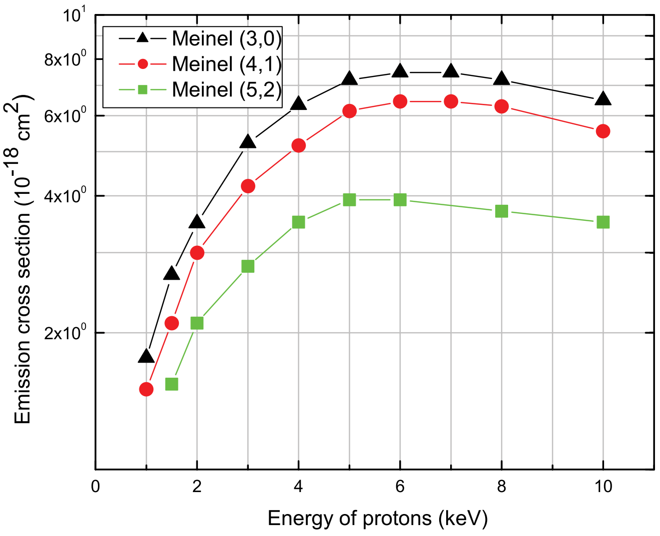

FIG. 4. (Color online) Dependence of excitation cross sections for the Meinel (3,0), (4,0), and (5,2) band systems on the proton energy for p-N_2 collisions.

The total excitation cross sections for $N_2{}^+(B\,^2\Sigma_u^+)$ and $N_2{}^+(A\,^2\Pi_u)$ by proton impact on N_2 are presented in Fig. 5. For the given states, the total cross sections are determined

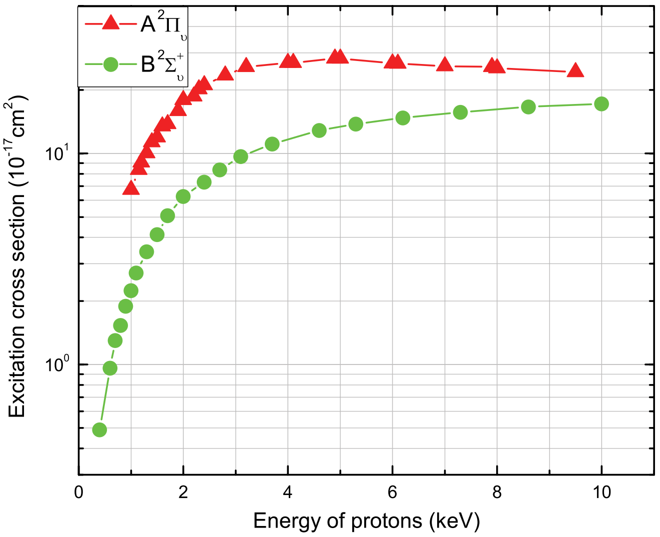

FIG. 5. (Color online) Dependence of the manifold excitation cross section for the $A\,^2\Pi_u$ and $B\,^2\Sigma_u^+$ states on the proton energy for p-N_2 collisions.

by summation of the cross sections that correspond to the population of the partial vibrational levels. The data analysis for the Meinel band system shows that the relative population of the separate level is well described by the Franck-Condon principle. Thus, for determination of the excitation cross sections of electronic states, it is sufficient to measure the excitation function for some intense excitation band.

The behavior of the excitation function for the 1NG ${N_2}^+(B\,^2\Sigma_u^+)$ ground state and the excitation of vibrational levels are different and essentially depend on the energy interval. To determine the excitation cross sections for the 1NG ${N_2}^+(B\,^2\Sigma_u^+)$ state the cross sections for the (0,0), (1,2), and (2,3) excitation bands were measured. Using the decay probabilities of the vibrational states from Ref. [35], the excitation cross sections of the states 0, 1, and 2 were determined. Using the expression

$$\sigma\big(N_2^+(B\,^2\Sigma_u^+)\big) \approx \sum_{\nu=0}^{2} \sigma(\nu), \tag{2}$$

we determine the total cross section of the excitation state of ${N_2}^+(B\,^2\Sigma_u^+)$. The total cross section obtained in this way is quite accurate because the contributions of the excited vibrational states with $\nu \geqslant 2$ are small.

To describe collision processes, we use the quasidiatomic approximation; that is, the molecule is considered as one centered atomic particle. Therefore we can use the analogy between the ion-atom and the ion-molecule particles, so that the data obtained for atoms can be extended to molecules.

For charge exchange between the H^+ and the N_2 molecule, the intermolecular potential at large distances may be written as

$$V_i(R) = V_i(\infty) - \frac{\alpha_i}{2R^4}, \tag{3}$$

where α_i is the dipole polarizability of the hydrogen atom and the nitrogen molecule and $i = 1,2$ for the reactant and product states, respectively. The transfer of charge occurs in the region of the critical distance R_c, where the coupling-matrix element $H_{12}(R)$ equals half the difference between the intermolecular potentials:

$$H_{12}(R_c) = \frac{1}{2}\Delta V_{12}(R) = \frac{1}{2}\left|\Delta E - \frac{\alpha_1}{2R_c^4} + \frac{\alpha_2}{2R_c^4}\right|, \tag{4}$$

where $\Delta E = V_2(\infty) - V_1(\infty)$ is the energy defect for the charge-exchange process. In our case $\Delta E = 0.19$, $\alpha_1 = 11.74a_0^3$, and $\alpha_2 = 4.5a_0^3$, where a_0 is the Bohr radius. Following Refs. [36,37] over the region of transfer, $R_c \pm \Delta R_c$, it is a reasonable approximation to use an exponentially decreasing coupling-matrix element in the simple form

$$H_{12}(R) = e^{-\lambda R}, \tag{5}$$

where λ is a coupling parameter and all quantities are in atomic units. The experimental results for the excitation functions for the B states are shown in Fig. 6 and are compared with the simple theoretical estimate [38]

$$\sigma = \tfrac{1}{2}\pi R_c^2 \sigma^*(\delta^{-1}). \tag{6}$$

In Eq. (6) σ^* is a tabular function of the parameter $\delta^{-1} = \hbar\lambda v_0/\pi H_{12}(R_c)$ [38], where v_0 is the collision velocity. To calculate the cross section, it is necessary to estimate the internuclear separation R_c at which the transfer occurs. To find the cross section we need to determine the coupling parameter λ and the value of the matrix element $H_{12}(R_c)$. To determine these values we use a self-consistent procedure by varying R within the interval $2.8a_0 \leqslant R \leqslant 4a_0$ and obtain an appropriate value of $H_{12}(R_c)$ from Eq. (4) and then get the corresponding value of λ from Eq. (5). This procedure was conducted in such a way that the maximum value of the cross section (6) satisfactorily coincided with the experimental maximum value in Fig. 6. As a result, we obtained $R_c \approx 3a_0$, $H_{12}(R_c) = 0.073$, and $\lambda = 0.87$.

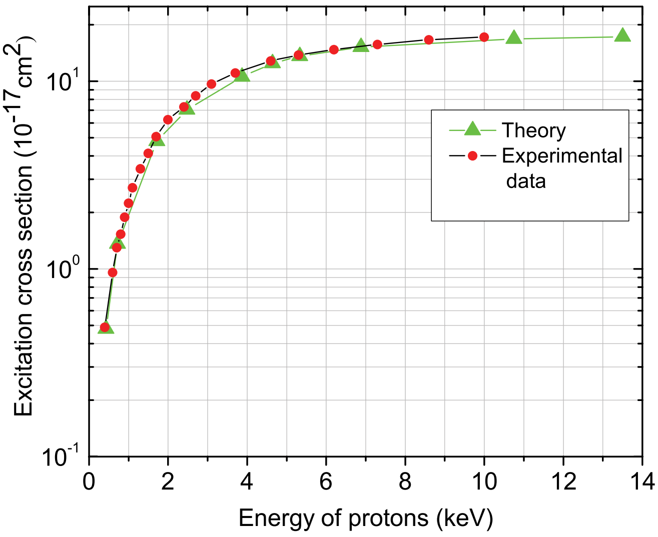

FIG. 6. (Color online) Dependence of the excitation cross section for the first negative band system on the proton energy for p-N_2 collisions.

The interatomic distance may also be estimated from the expression [38]

$$H_{12}(R) = \sqrt{I_1 I_2} R^* e^{-0.86R^*}, \tag{7}$$

where I_1 and I_2 are the ionization potential of the hydrogen atom and nitrogen molecule, respectively, and

$$R^* = \tfrac{1}{2}(\alpha + \gamma)R. \tag{8}$$

In Eq. (8), $\frac{1}{2}\alpha^2$ equals the effective ionization potential I_1 of the hydrogen atom and $\frac{1}{2}\gamma^2$ equals the effective ionization potential I_2 of the nitrogen molecule, with all quantities being in atomic units. For $R = R_c$ where the charge transfer occurs, we obtain

$$\sqrt{I_1 I_2} R^* e^{-086R^*} = \frac{1}{2}\left|\Delta E - \frac{\alpha_1}{2R_c^4} + \frac{\alpha_2}{2R_c^4}\right|. \tag{9}$$

Solving Eq. (9) for R_c, we obtain $R_c = 3.6a_0$ and $H_{12}(R_c) = 0.085$. However, this value significantly shifts the maximum of the cross section to the region of high energy. In Ref. [39] it was mentioned that the discrepancy in the estimation for R_c can be explained by the variation of the coupling parameter in the exponent in Eq. (7) from 0.5 to 2.3.

To determine the value of R_c, one can also use the table from Ref. [38]. From this table it follows that the maximum of the reduced cross section is $\sigma^* = 1.08$. By substituting this value in the equation $\sigma^* = \sigma/\frac{1}{2}\pi R_c^2$, where $\sigma = 1.9 \times 10^{-16}\,\text{cm}^2$ is the maximum value of the experimental cross section in Fig. 6, we obtain $R_c \approx 2a_0$. However, this value is less than the interatomic distance in the nitrogen molecule and, therefore, it cannot be used since the idea of a polarization interaction loses its meaning. Probably Eq. (5) for the ion-molecular collision must be corrected by taking into account Franck-Condon factors.

Based on our results, we can conclude that the population mechanism for $B\,^2\Sigma_u^+$ states in slow collisions is determined by nonadiabatic transitions between crossings of potential-energy curves, with charge transfer occurring at the curve crossing (Demkov mechanism [36,37]) for the collided particle system. The obtained value of $R_c = 1.6 \times 10^{-8}$ cm corresponds to the distance which is greater than the size of the molecule. It is obvious that the impact particle collides with randomly oriented molecular particles. Our data represent results that are averaged with respect to the orientation. According to our estimation, we can expect that the influence of the effect of molecular orientation in these collision processes is minimal. Otherwise, the maximum of the cross section will be reduced by at least one order of magnitude. We can conclude that the employed quasimolecular approximation is valid for the given pairs. All of the above may be extended to the case of excitations of A molecular states as well. The maximum of the excitation cross section for the given states is reached at relatively low collision energy and that is greater than the maximum of the cross section of the B states. This fact indicates that excitation of the A state due to nonadiabatic transition occurs at a comparatively large distance and that the value of the coupling-matrix element $H_{12}(R_c)$ is less than that in the case of the B state.

IV. CONCLUSION

We presented measurements of the absolute cross sections for the e-N_2 and p-N_2 collisions for the first negative $B\,^2\Sigma_u^+$–$X\,^2\Sigma_g^+$ and Meinel $A\,^2\Pi_u$–$X\,^2\Sigma_g^+$ bands in the energy region 400–1500 eV for electrons and 0.4–10 keV for protons, respectively. Measurements were performed in the visible spectral region 400–800 nm by an optical spectroscopy method. The experimental results were obtained under the condition that the collision quenching effect was taken into consideration and was minimized to the single-collision condition. This was verified by the linear dependence of the intensity of spectral lines on the target gas pressure and the density of the electron current.

In the case of electrons, the measurements of the excitation functions for the first negative nitrogen molecule ion ($B\,^2\Sigma_u^+$–$X\,^2\Sigma_g^+$) system with band (0,0) and for the Meinel ($A\,^2\Pi_u$–$X\,^2\Sigma_g^+$) system with bands (3,0), (4,1), and (5,2) show that the ratio of the cross section of the Meinel band system to the cross section of the first negative band system (0,0) does not depend on the energy of incident particles. The population of vibrational levels corresponding to $A\,^2\Pi_u$ states is well described by the Franck-Condon principle.

The ratios of the cross sections of (4,1) to (3,0) bands and of (5,2) to (3,0) bands are slightly dependent on the proton energy. The theoretical estimate within the quasimolecular approximation gives a reasonable description of the total cross section for the first negative band system of the nitrogen ion $N_2{}^+$ for H^+-N_2 collisions. This approach can be extended to the description of excitation of A states as well, assuming that excitations are due to the nonadiabatic transitions occurring at large distances. Moreover, it becomes possible to ignore the orientation of the target molecule for the H^+-N_2 collisions in the considered energy region of the incident proton.

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[1] R. Ya. Kezerashvili and G. L. Matloff, J. Br. Interplanet. Soc. **60**, 169 (2007).

[2] R. Ya. Kezerashvili and G. L. Matloff, Adv. Space Res. **44**, 859 (2009).

[3] L. Campbell, M. J. Brunger, P. J. Teubner, and D. C. Cartwright, J. Electron Spectrosc. Relat. Phenom. **144–147**, 119 (2005).

[4] K. J. Remick, R. K. Smith, and D. Lummerzheim, J. Atmos. Sol. Terr. Phys. **63**, 295 (2001).

[5] A. Shinsuke *et al.*, Astrophys. J. **618**, L141 (2005).

[6] P. Jenniskens, C. O. Laux, and E. L. Schalle, Astrobiology **4**, 109 (2004).

[7] D. E. Shemansky and X. Liu, J. Geophys. Res. **110**, A07307 (2005).

[8] A. W. Harrison and A. Vallance Jones, J. Atmos. Terr. Phys. **13**, 291 (1959).

[9] A. B. Meinel, Astrophys. J. **112**, 562 (1950).

[10] M. Hollstein, D. C. Lorents, J. R. Peterson, and J. R. She Ridan, Can. J. Chem. **47**, 1858 (1969).

[11] D. E. Shemansky and A. L. Broadfoot, J. Quant. Spectros. Radiat. Transfer **11**, 1385 (1971).

[12] L. G. Piper, B. D. Green, W. A. M. Blumberg, and S. J. Wolnik, J. Chem. Phys. **82**, 3139 (1985).

[13] L. G. Piper, B. D. Green, W. A. M. Blumberg, and S. J. Wolnik, J. Phys. B **19**, 3327 (1986).

[14] R. L. Gattinger and A. Vallance Jones, Can. J. Phys. **52**, 2343 (1974); **59**, 480 (1981).

[15] D. Mandelbaum and J. Feldman, J. Chem. Phys. **65**, 672 (1976).

[16] I. P. Borst and E. C. Zipf, Phys. Rev. A **1**, 834 (1970).

[17] L. Campbell, D. C. Cartwright, M. J. Brunger, and P. J. O. Teubner, J. Geophys. Res. **111**, A09317 (2006).

[18] B. Van Zyl and W. Pendleton, J. Geophys. Res. **100**, A12, 23755 (1995).

[19] D. E. Shemansky and A. L. Broadfoot, J. Quant. Spectros. Radiat. Transfer **11**, 1401 (1971).

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

[21] M. R. Gochitashvili and B. I. Kikiani, Tech. Phys. **44**, 367 (1999) [Zh. Tekh. Fiz. **69**, 20 (1999)].

[22] M. R. Gochitashvili, B. I. Kikiani, and R. A. Lomsadze, ICAMDATA 97, **926**, 245 (1997).

[23] M. R. Gochitashvili, N. R. Jaliashvili, R. V. Kvizhinadze, and B. I. Kikiani, J. Phys. B **28**, 2453 (1995).

[24] Y. Itikawa, J. Phys. Chem. **35**, 31 (2006).

[25] Y. Itikawa, M. Hyashi, A. Ishimura, K. Onda, K. Sakimoto, K. Takayanagi, M. Nakamura, H. Nishimura, and T. Takayanagi, J. Phys. Chem. Ref. Data **15**, 985 (1986).

[26] S. V. Avakyan, R. N. Il'in, V. M. Lavrov, and G. N. Ogurtsov, *Collision Processes and Excitation of UV Emission from Planetary Atmospheric Gases: A Handbook of Cross Sections* (Gordon & Breach, London, 1998).

[27] J. Franck, Trans. Faraday Soc. **21**, 536 (1926).

[28] E. Condon, Phys. Rev. **27**, 640 (1926); **28**, 1182 (1926).

[29] W. L. Borst and E. C. Zipf, Phys. Rev. A **1**, 834 (1970).

[30] J. P. Doering and J. Yang, J. Geophys. Res. **101**, 19723 (1996).

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

[32] P. N. Stanton and R. M. St. John, J. Opt. Soc. Am. **59**, 252 (1969).

[33] E. J. Quintana, V. R. Heckman, and E. Pollack, Phys. Rev. A **48**, 3670 (1993).

[34] J. O. Olsen, T. Andersen, M. Barat, C. Courbin-Gaussorgues, V. Sidis, J. Pommier, J. Agusti, N. Andersen, and A. Russek, Phys. Rev. A **19**, 1457 (1979).

[35] V. Degan, J. Quant. Spectros. Radiat. Transfer **18**, 113 (1977).

[36] Yu. N. Demkov, Sov. Phys. JETP **18**, 138 (1964).

[37] Yu. N. Demkov and L. P. Presnyakov, Sov. Phys. Usp. **21**, 881 (1978).

[38] R. E. Olson, Phys. Rev. A **6**, 1822 (1972).

[39] R. E. Olson, F. T. Smith, and E. Bauer, Appl. Opt. **10**, 1848 (1971).