Measurements of excitation cross sections in collisions of $1 – 10$ keV $O^+(4S,2D,2P)$ with $N_2$ molecules

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We report measurements of excitation functions for the $O^+–N_2$ process with the incident beam of $1–10$ keV $O^+$ in the ground $O^+(4S)$ and metastable $O^+(2D)$ and $O^+(2P)$ states. The measurements are performed with the sufficiently high energy resolution of 0.001 eV, which allows to distinguish the excitation channels. The excitation cross section induced by incident ions in the metastable state $O^+(2P)$ is much larger than that for the ground $O^+(4S)$. The excitation cross section of $N_2^+$ ion for $(0,0)$, $(0,1)$ and $(1,2)$ bands system is measured and the ratio of intensities for these bands is established as $10 : 3 : 1$. It is shown that the cross sections for the $N^+$ ions excitations in the dissociative charge exchange processes increase with the increase of the incident ion energy. The energy dependence of the excitation cross section of the band $(0,0) = 391.4$ nm of the first negative system of the $N_2^+$ and degree of polarization of radiation in $O^+–N_2$ collision are measured for the first time. An influence of an admixture of the ion metastable state on a degree of polarization is revealed. It is demonstrated that for $O^+–N_2$ collision system the degree of polarization by metastable $O^+(2P)$ ions is less compared to those that are in the ground $O^+(4S)$ state and the sign of polarization degree of excited molecular ions does not change.

I. INTRODUCTION

The oxygen and nitrogen molecules are two of the most common elements in the atmosphere and the ionosphere of the Earth. There has been considerable research in the past 20 years on both the production and loss of vibrationally excited $O_2$ and $N_2$ in the thermosphere and their role in ionospheric processes. Excitation and deexcitation of $O_2$ and $N_2$ molecules can occur through direct electron impact, during impact of various atomic ions, cascade from excited states, and chemical reactions. For example, electron impact excitation of $O_2$ and $N_2$ molecules can occur through direct electron impact, eventually resulting in radiative cascade from the $A$ state into vibrational levels of the $N_2$ ground state, is considered a major source of $N_2$ vibrational quanta in the ionosphere and could be the dominant mechanism for producing vibrationally excited $N_2$ in the aurora [1]. Different constituents of the atmosphere have their characteristic airglow emissions. The atomic oxygen is a very important constituent of the upper atmosphere. It plays a crucial role in the atmospheric chemistry at the mesosphere and thermosphere altitudes. On the other hand, oxygen is also one of the typical impurities in almost all laboratory plasmas. Among many interactions involving oxygen, the excitation, dissociation and charge transfer between singly charged $O^+$ ions and various atmospheric molecules are relevant to the low–temperature edge plasma region of current thermonuclear fusion devices [2].

The importance of excitation and dissociation processes of $O^+–N_2$ and $e$–$O_2$ has been established from the fundamental atomic physics point of view. One important motivation to study the collision of $O^+–N_2$ pair is the fact that the cross section is strongly dependent on the initial electronic state of the $O^+$ ions $^{[3]}$ and, in particular, two low-lying excited metastable states $^2D$ and $^2P$ of $O^+$ have approximate lifetimes of 3.6 h and 5 s, respectively $^{[4]}$. As a result of these long lifetime metastable $O^+(2D)$ and $O^+(2P)$ states, $O^+$ ions are available for electron – and ion – molecule reactions. Various experimental investigations are performed for $O^+$ collisions with $H_2$, $N_2$, CO, CO$_2$, CS$_2$ molecules and these studies are mostly related to charge transfer processes $^{[5][21]}$. However, cross section measurement in charge transfer processes of $O^+$ ions colliding with carbon-containing molecules are scarce $^{[22][23]}$, though there are some experimental data for $H_2$, $N_2$ and $O_2$ molecules. The charge transfer processes induced by $O^+$ collision with $N_2$ and $O_2$ are important in the field of aeronomy $^{[24]}$ since the $O^+$ is the dominant ion in the F region of the atmosphere and both metastable species of $O^+(2D)$ and $O^+(2P)$ have
been detected here too. While the reactions of \( O^+ \) ions with \( N_2 \) have received a considerable amount of attention and several experimental studies (see e.g. [26, 27]) have been conducted, there still exists a large amount of doubt to the magnitude of the total cross sections of charge transfer and transfer with excitation processes. Since inelastic processes at low energy are known to be strongly dependent upon the internal electronic energy of colliding particles, the presence of metastable excited ions in the primary ion beam may sometimes significantly influence the observed cross sections. For example, the study of charge transfers cross sections for \( N^+ \) and \( O^+ \) ions in collisions with \( H_2 \) molecules and He atoms, have found that metastable state ions indeed enhance the cross sections, sometimes by an order of magnitude [28].

The influence of the excited \( O^+(^2D) \) state is monitored by a charge transfer reaction between \( O^+ \) and Ar collision system in Ref. [22]. The large cross section for reactions involving \( O^+(^2P) \) incident ions and small cross section for reactions of \( O^+(^4S) \) ground state ions is explained by energy difference between the \( O^+(^4S) \) recombination energy and Ar ionization potential for forming \( Ar^+(^2P_{1/2}) \). Collisions of \( O^+(^2D) \) metastable ions with \( O_2 \) leading to formation of the \( O_2^+ \) ion either in the \( A^2\Pi_u \) or \( a^2\Pi_g \) state involves only a small energy defect, and as expected, the cross sections for such processes are found to be quite large. Similar considerations also apply to the collision of \( O^+(^2P) \). As to the data related to the collision with \( N_2 \) molecules, the \( O^+(^2D) \) metastable state is also in resonance with the \( N_2(A^2\Pi_u) \) state and the cross section is expected to be large, while there is 2 eV between the \( O^+(^4S) \) and the nearest \( N_2^+ (X^3\Sigma^+_g) \) state, resulting in smaller cross section. The charge transfer performed with \( O^+(^2P) \) to \( N_2^+ (B, \nu = 0) \) level is a near-resonance (energy defect is 0.1 eV) that causes about a two order of magnitude difference of cross sections between the metastable \( O^+(^2P) \) state and the ground \( O^+(^4S) \) state [7]. In Ref. [3] it is stated that abundance of the metastable ions is strongly dependent upon the operating conditions. In particular, the abundance depends on the gas pressure in the ion source and on the energy of impacting electrons producing ions. Translational spectroscopy experiments have indicated that the long lifetime \( ^2D \) and \( ^2P \) metastable states comprise a significant fraction of ions in an \( O^+ \) beam, and determined the \( O^+(^4S) \), \( O^+(^2D) \) and \( O^+(^2P) \) relative abundance to be 0.55, 0.25 and 0.20 respectively for 100 eV electron impact ionization of \( O_2 \) [24]. There are many options that allow the control of metastable states and perform measurements with known species [8–16, 19]. The ratio of the metastable electronic states to the ground state can be varied by a careful control of the energy of the ionizing electrons in the primary ion source. For example, when electron energy is below the threshold for formation of the excited states, no excited states can be formed and the resultant beam will be composed entirely of ground state ions. As the ionizing electron energy increases and goes above the threshold the metastable ions will appear in the beam. For example, ionization of \( O_2 (X^3\Sigma^-_g, \nu = 0) \) molecules by 18.9 eV electrons results in the formation of the ground state \( O^+(^4S) \) which is 6.84 eV above the 12.06 eV ionization potential of \( O_2(X^3\Sigma^-_g, \nu = 0) \). The energy difference between the ground \( O^+(^4S) \) and first excited \( O^+(^2D) \) state is 3.32 eV [30]. Thus, the minimum electron energy required to produce excited \( O^+(^2D) \) ions from \( O_2 (X^3\Sigma^-_g, \nu = 0) \) is 22.2 eV. It is well known (see e.g. [31] and [32]) that the use of high pressure ion sources can lead to a significant loss of metastable ions due to collisional quenching mechanisms. In Ref. [32] observed loss of \( O^+(^2D) \) and \( O^+(^2P) \) state ions in the reaction \( O^+(^2D,^2P) + CO \) with a rate constant of \( 1.3 \times 10^{-9} \text{ cm}^3\text{s}^{-1} \), which is four orders of magnitude larger than the corresponding ground state of the \( O^+(^4S) + CO \) reaction. The relatively low \( O^+(^2D,^2P) \) metastable ion abundance is observed in Ref. [33], when the CO pressure, of the order of 10^{-1} Torr is applied in an ion source. The beam attenuation method, to determine the fractional abundance of different states in an \( O^+ \) ion beam formed by the ionization of \( O_2 \) is considered in an early study [34]. In particular, when the ionization electron energy is 100 eV, this result indicated that 70% of \( O^+ \) ions are in the ground \( ^4S \) state and 30% are in the \( ^2D \) state.

The measurements [34] showed that the \( O^+ \) excited state component could be nicely evaluated in the 10^{-3} to 10^{-2} Torr pressure range. In Ref. [35] an appropriate range of an ion source pressure (0.02–0.1 mTorr) is found for the \( O^+ – N_2 \) collision system and reported that the excited metastable species exhausted by about 3.5 times. As stated by authors of [35] at a pressure higher 2 mTorr the beam can contain either ground state \( O^+ \) ions or a mix of the ground state and excited-state ions. At a low pressure 0.1 mTorr the ion beam is composed of the mix of ground and excited state ions. The quenching rate of \( O^+(^2P) \) by \( O \) and \( N_2 \) have evaluated in Ref. [36]. Their founding for \( O \) agrees well with the measurements reported in [37] and a factor of 8 lower than that obtained in Ref. [35]. Selected ion-flow-tube measurements [39] of \( O^+ \), from ionization of CO, have indicated that less than 10% of the \( O^+ \) ions occupy the \( ^2D \) and \( ^2P \) excited states. Two-component types of attenuation for \( O^+ \) beams in
N₂ gas are also reported in Ref. [40]. The authors ascribed this to considerable (30%) admixtures of metastable O⁺ ion in the beam, which could be varied by using different ionizing electron energies in the source. The composition of the ion beam with the abundance about 65% of the ground state and about 35% that of the metastable species ²D are obtained in [27]. Production of the O⁺ ions in [41] expected to be a mix of ground state and metastable species but again at some unknown ratio. In paper [42] the O⁺ metastable fraction is estimated to be approximately 0.19 from an ion beam attenuation technique. This brief survey shows that much of difficulty in the laboratory investigation of inelastic processes is due to the fact that incident ions are typically present in both the ground ⁴S state and in the long-lived excited metastable ²D and ²P states. It should be noted that metastable species are attenuated differently and that the composition of the total metastable fraction is different. It seems also, that the data related to the abundance for different targets is contradictory. This difference is also observed for the same target case. The source of this large discrepancy between an abundance of metastable state can be attributed to a different operating condition of an ion sources. We can conclude that magnitudes of cross section for inelastic processes are largely dependent on the composition of the beam. To control the metastable species in the ion beam are crucial both the precise exploration of pressure condition in the ion source and the evaluation of electrons energy used in the ion source for ionization.

In this paper we study the excitation processes in reactions of the ground O⁺(⁴S) and long lifetime metastable O⁺(²D) and O⁺(²P) state ions with N₂ molecule in the ion energy range 1–10 keV. The paper is organized in the following way. In Sec. II an experimental apparatus which allows one to perform measurements by means of electron and optical spectroscopy methods is presented. Here we introduce our approach and procedure for cross section measurements and its determination. We report measurements of the excitation function for O⁺−N₂ processes with the incident beam of O⁺ in the ground and metastable states and discuss results of measurements in Sec. III. Finally, in Sec. IV we summarize our investigations and present conclusions.

II. EXPERIMENTAL APPARATUS, METHOD AND PROCEDURE OF MEASUREMENTS

The experimental study of excitation processes in reactions of the oxygen ions in the ground and metastable state with nitrogen molecules is performed in three steps. First, to investigate the formation of charged ions we use electron impact to produce charged ions by using electron spectroscopy. To calibrate and check the mass transmission we measure the electron induced ionization of CH₄ molecules and Ar atoms. Second, we study the ion production in e+O₂ collision as a function of the incident electron energy for different pressure conditions of the molecular oxygen in the ion source. These investigations allow us to find conditions for reliable beams of the ground O⁺(⁴S) and metastable O⁺(²D) and O⁺(²P) ions to study the excitation processes induced by these ions in collisions with N₂ molecules. The latter measurement we perform using optical spectroscopy.

In our study we used two different types of ion sources: a source of radio frequency (RF) discharge and an electron impact source. Let us focus on the advantages of the RF discharge source and an electron impact ion source. The RF source is used for the investigation of the excitation function in collisions of oxygen ions with nitrogen molecules. Optical spectroscopy, used to study the excitation function, is characterized by a high energy resolution, but low luminosity, since radiation is observed only at a certain angle and for a certain spectral line. Therefore, it is necessary to study the process for a relatively large current of O⁺ ions. The radio frequency source allows to obtain much higher ion currents (∼ µA) than the electron impact source. However, the use of an electron impact source makes it possible to study the formation of ions inside the source. Our experiments showed that, depending on the condition (pressure, power, gas mixture) of ion beam formation, the proportion of O⁺ ions in different electronic states (ions in ⁴S and metastable ²D, ²P states) significantly changes, which significantly affects the dependence of the excitation cross section on the ion impact energy. Establishing the formation mechanism of the ion beam in the RF source, one faces challenges. When the pressure inside the source changes, due to various inelastic processes (charge exchange process, excitation quenching, recombination), the ion filtration process takes place. In this case, the degree of filtration and neutralization of ions depends on the internal electronic state of the ion. An increase in pressure decreases the free path of electrons, which participate in the formation of ions in various electronic states via in the process of dissociative ionization. Consequently, the probability of formation of ions in different states changes. Neutralization of ions occurs not only in the discharge region, but also in the ion extraction probe, where the gas pressure...
is much higher than in the discharge region. Inside the discharge, the reaction rate (the rate of formation and disappearance of ions) substantially depends on the internal electronic state of the ions. It is very difficult to analyze all the processes occurring in the area of the discharge and ion probe. In order to determine the mechanism of the formation of O\(^{+}\) ions, we investigated the dependence of the dissociative ionization cross section on the electron energy inside the ion source for various pressures of the working gas. For this, we used the electron impact source to produce charged ions.

A. Electron Spectroscopy

Measurements carried out with the electron impact source are performed by mass-spectrometric (MS) device, a schematic view of which is shown in Fig. 1. The main MS assembly consists of (in sequential order): an electron impact ionization ion source (1); extracting and focusing lenses (2) and (3), respectively; a quadruple filter (4); deflector plates (5); an electron multiplier (6); a data acquisition system (7). The apparatus is partitioned into three chambers which are separately evacuated by two mechanical and two diffusion pumps.

The pressures are measured by two separate MKS Baratron gauges and are kept at about \(10^{-7}\) Torr. Basically, the target gas ions are generated in the ionization region by low energy (15-120 eV) electron impact. The electron beam is produced by thermionic emission from a filament. The electrons are than accelerated by the potential applied between the filament and the ionization chamber. This potential defines the energy of the ionizing electrons. The absolute energy of the electron beam has been checked by measuring ionization potentials of rare gas atoms and diatomic molecules. The electron energy is monitored during each experiment by a measurement of the \(O_2\) ionization potential and \(O^{+}\) appearance potential as well. The electron current is of order 0.2 mA with the energy inhomogeneity (full with half maximum) \(E = 50\) meV. The produced \(O^{+}\) ions are extracted from the source and focused by appropriate ion optics. The potential of the ionization chamber is adjustable and determines the energy of the ions entering the quadrupole filter. A quadrupole filter shown in insert in Fig. 1 consists of an assembly of four parallel electrodes with a hyperbolic cross section. Each pair of opposite electrodes is electronically connected. The following potential is applied to one pair of electrodes

\[
F(t) = U + V \cos 2ft, \tag{1}
\]

where \(U\) is the DC potential, while \(V\) and \(f\) are the amplitude value and frequency of an AC potential, respectively. An opposite potential \(F(t)\) is applied to the other pair of electrodes. Both DC and AC

![FIG. 1: (Color online) Schematic diagram of the experimental setup: 1 - collision chamber, 2 - extracting lens, 3 - focusing lens, 4 - quadruple filter, 5 - deflector, 6 - electron multiplier, 7 - acquisition system. The insert at the upper right panel shows the device for a quadruple filter.](image)
electrical fields are directed perpendicular to the \( z \) axis and produce lateral oscillations of any ion entering the device parallel to the \( z \) axis.

The motion of the \( \text{O}^+ \) ion in the filter is described by a set of differential equations, known as the Mathieu equations, which can be resolved into two types of movement – stable or unstable – according to the value of parameters \( U, V, f, r_0 \) and \( m/q \). Here \( 2r_0 \) is the distance between two opposite electrodes, and \( m \) and \( q \) are, respectively, the mass and charge of the incoming ion. In practice, ion selection is achieved by variations of the \( U \) and \( V \) potentials. For an appropriate value of these two parameters, the ions injected into the quadruple filter are separated, and only the ions with a value of \( m/q \) ratio in a certain bandwidth will be transmitted by the filter. All the other ions have unstable trajectories and are captured on the electrodes. For a mass spectrometer the capacity to separate particles of similar mass known as “a resolving power” is defined as the ratio \( R = \frac{m}{q U V} \), where \( d(m/q) \) is the bandwidth of the mass to charge \( m/q \) ratios for which ions achieve stable trajectories. The theoretical resolution of a quadruple filter depends on the value of the ratio \( V/U \): a decrease of this ratio increases sensitivity. An amplitude scans between zero and maximum value if the DC and radio frequency voltages applied to the electrodes yields a transmission by the filter of ions of increasing \( m/q \), with the constant resolution. The whole of the source assembly is heated to prevent cold areas which would act as condensation traps for the analyzed compounds. A cross section profile of the bars is hyperbolic, as it is shown in the insert in Fig. 1. A careful choice of design parameters such as the relation between the distance and the diameter of the bars gives a good approximation of an ideal quadruple field in the vicinity of the \( z \) axis of the filter. The whole assembly is bakeable for degassing. Ions selection is achieved by a manual or automatic scanning of the DC and RF voltages. The RF frequency is fixed and equal to 1.2 MHz for automatic scanning. The amplitudes of the \( U \) and \( V \) potentials are modulated by a saw tooth signal and the whole spectrum (from mass 2 to mass 1000) can be explored in one second. The detector of the ions, produced by electron impact, is an electron multiplier consisting of a chain of 21 copper-beryllium dynodes. Ions selected by the quadruple filter, using the deflector plates (5), bombard the first dynode and extract secondary electrons. These secondary electrons are then accelerated, hit the next dynode where they produce the secondary electrons resulting in an amplification of the electron current. The overall gain is of the order of \( 10^6 \) and it is controlled by a 3 keV regulated power supply fed to the dynodes through a chain of resistors. The electron multiplier is mounted off-axis to reduce the noise produced by photons emitted from the source filament and by the soft X rays generated by electrons bombardment of the rods of the quadruple filter. The output signal of the electron multiplier is fed either into an analogy measurement signal or into a digital data acquisition system for a further treatment by computer. In practice, ion selection is achieved by variations of the particles. For an appropriate value of parameters, the ions injected into the quadruple filter are separated, and only the ions with a value of \( m/q \) ratio in a certain bandwidth are transmitted by the filter. All the other ions have unstable trajectories and will be captured by the electrodes.

B. Optical Spectroscopy

Cross sections for the excitation processes were measured by optical spectroscopy. We have used an experimental setup and method of measurements similar to those described and used previously[43].

To obtain the oxygen beam we use a 20 MHz RF ion source. The oxygen ions extracted from the RF ion source, are accelerated, collimated and focused, and mass-selected with a 60º magnetic sector field. Then the ion beam is directed into the collision chamber. The fluorescence emitted as a result of the excitation of colliding particles was observed at 90º with respect to the beam. In the present work, measurements are performed with sufficiently high energy resolution of 0.001 eV, which allows to distinguish the excitation channels. This method also allowed us to estimate the polarization of excitation, that itself is a powerful tool for establishing the mechanism for inelastic processes. The spectroscopic analysis of the emission is performed with a monochromator incorporating a diffraction grating with a resolution of 40 nm/mm operated in the 400 – 800 nm spectral region. A polarizer and a mica quarter-wave phase plate are placed in front of the entrance slit of the monochromator and the linear polarization of the emission is analyzed. For cancellation of the polarizing effect of the monochromator, the phase plate is placed after the polarizer and is rigidly coupled to it. The emission is recorded by a photomultiplier with a cooled cathode and operated in current mode. The spectral sensitivity calibration is performed by a tungsten filament standard lamp, which is 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 [44]. The measurements for low energy collisions required a precise determination of energy of ions as well as their energy dispersion. To avoid errors in the measurements of the incident ions energy we employ the retarding potential method and use the electrostatic analyzer with a resolving power of 500. In our experiments the energy dispersion of the ions does not exceed 20 eV. For electrons the energy dispersion is less than 5 eV. The ion current in the collision chamber was of the order 1−10 µA, while the electron current was 5 − 20 µA. The residual gas pressure did not exceed 10^{-7} Torr. The single collision condition is checked by a linear dependence of the intensity of spectral lines versus target gas pressure and density of the ion current. Measurements are performed in the 400 − 800 nm excitation region. The absolute accuracy of the measurements is 25%. The accuracy of measurements is related to the following factors: i. the accuracy of pressure measurements in the collision chamber; ii. the precise and immediate determination of the primary beam current that produce the radiation, which is collected by optical system from the region where the collision occurs; iii. the accuracies of the relative and absolute calibration procedures. The uncertainty of relative measurements is about 5%.

C. Cross section measurements and determination

1. Electron spectroscopy measurements

We use the electron impact source to produce charged ions. When performing measurements for electron impact it is important to control the energy of electrons and detect all positively charged ions with equal efficiency, regardless of their mass, charge or initial kinetic energy. Let us first present investigation of the electron induced ionization, dissociative ionization and ionic fragmentation of hydrocarbon CH4 molecules and Ar atoms in the energy range from the ionization threshold up to 120 eV. In particular, we are conducting studies for the following reactions:

\[ e + CH_4 \rightarrow CH_4^+ + 2e \]  \hspace{1cm} (2)
\[ \rightarrow CH_3^+ + 2e + ... \]  \hspace{1cm} (3)
\[ \rightarrow CH_2^+ + 2e + ... \]  \hspace{1cm} (4)
\[ \rightarrow CH^+ + 2e + ... \]  \hspace{1cm} (5)

![FIG. 2: (Color online) A typical ion fragment’s mass spectrum of methane for an incident electron energy of 115 eV. Species detected are as labeled on the figure.](image-url)

\[ e + Ar \rightarrow Ar^+ + 2e \]  
\[ \rightarrow Ar^{++} + 3e \]  
(6)  

\[ e + O_2 \rightarrow O_2^+ + 2e \]  
\[ \rightarrow O_2^{++} + 2e + ... \]  
\[ \rightarrow O^+ + 2e + ... \]  
(7)  

The motivation of these studies is to check and calibrate the mass transmission of the quadrupole spectrometer and to provide data of the appearance energy (AE) and the partial ionization (PI) cross section which may serve as the input parameters for the optical spectroscopy measurements of excitation processes with the beam of oxygen ions. The measurements were performed using a quadruple mass spectrometer at a precisely selected electron energy. The mass dependence of transmission of the quadrupole spectrometer is performed by measuring the mass spectra of CH\(_4\) molecule for reactions (2) – (5) and compared these results with the cross sections for CH\(_4^+_i\) \((i = 1, 2, 3, 4)\) fragment ions [45]. Our measurement of the typical ion fragment’s mass spectrum for methane molecules is shown in Fig. 2 which is in good agreement with previous results [45]. A number of well-resolved mass peaks are detected in the mass range 10 – 20 amu and are assigned to the corresponding ionic fragments. As can be seen, our mass resolution is somewhat limited, so that fragments differing only by one mass unit are not fully resolved. It is found that the transmission is constant in the mass region from 12 (C\(^+\)/CH\(_4\)) to 16 (CH\(_4^+_i\)/CH\(_4\)), which is the region where the majority of the relative efficiencies of the oxygen cation fragments O\(^{++}\), (O\(^+\)–O\(_2^{++}\)) and O\(_2^+\) appear. In determining the relative cation efficiencies of the oxygen ions it is assumed that the ion fragmentation does not change appreciably for masses outside of this region and that the transmission for masses of 8, 16 and 32 amu is equal to that of 12 – 16 amu region. Significant efforts are also put into the determination of appearance energies of ionic fragments. For this reason the electron energy was calibrated against the known AE of Ar\(^+\) (15.7 eV) to within ± 0.25 eV. As a result, the ionic fragment cross section curves obtained in 50 – 120 eV range are used to confirm the correctness of this approach. We check this approach by performing measurements of the ionization cross sections for the processes (6) – (7). The results of the ratio for (Ar\(^{++}\)/Ar\(^+\)) double to single ionization cross section of the Ar atom as a function of impacting electron energy are presented in Fig. 3. On the same figure the theoretical

![Fig. 3](image-url)  
**FIG. 3:** (Color online) Dependence of the ratio of double to single ionization cross sections of Ar atom in the \(e+Ar\) collision on the electron energy. Curves: 1 - present data; 2 - theoretical prediction [46].
FIG. 4: (Color online) Dependence of cross sections for production of \( \text{O}_2^+ \) and \((\text{O}^+ + \text{O}_2^+)\) ions on the electron energy in \(e+\text{O}_2\) collision. Curves: 1 - present data for \( \text{O}_2^+ \) ions; 2 - data for \( \text{O}_2^+ \) from Ref. [47]; 3 - data for \( \text{O}_2^+ \) ions from Ref. [48]. Curves: 4 - present data for \((\text{O}^+ + \text{O}_2^+)\) ions; 5 - data for \((\text{O}^+ + \text{O}_2^+)\) ions from Ref. [47].

results are presented for comparison. The experimental errors for these data, including the accuracy of the present normalizing procedure, have been estimated at about 10%. As can be seen from Fig. 4, our cross section data show a general agreement with the calculations from Ref. [46] within 7%. The close agreement between these data sets demonstrate the expected efficient collection of ion fragments in our apparatus.

The results for molecular oxygen ionization (\(\text{O}_2^+\)), production of fragment ions (\(\text{O}^+ - \text{O}_2^+\)) and \(\text{O}^2+\) by electron impact are investigated in Ref. [47]. It is shown, that all processes have threshold character, with broad maxima in the 100 – 200 eV energy range. Theoretical calculations for \(\text{O}_2^+\) molecule ions are presented in Ref. [48]. A compression of these sets of results show a similar behavior of energy dependence. It should be noticed that in both of these papers [47, 48], there is no information at all about the existence of metastable particles in the beam. The data for the excitation function of total \(\text{O}^+\) ions and metastable \(\text{O}^+\) ions produced in \(e+\text{O}_2\) collisions, from threshold to 450 eV energy interval, is presented in Ref. [49]. The authors observed interesting but surprising results: the cross section for the ion production in the ground and metastable states falls off more slowly compared to metastable ions as the electron energy is increased to energies higher than 150 eV. Although production of metastable \(\text{O}^+\) ions was confirmed, no information regarding the influence of the pressure condition in the ion source on the formation of metastable \(\text{O}^+\) was presented in Refs. [47–49]. We address this situation by performing measurements with a variable electron energy and pressure condition in the ion source using the electron spectroscopy method (Fig. 1). Our results for the energy dependence for electron impact ionization of molecular oxygen, \(\text{O}_2^+\), as well as for production of fragment ions, \(\text{O}^+ - \text{O}_2^+\), obtained in arbitrary units are normalized to the results from [47]. These data, along with the results for \(\text{O}_2^+\) ions obtained in [48] are presented in Fig. 4.

It should be noted that the individual cross section for \(\text{O}^+\) and \(\text{O}_2^+\) cannot be separately determined because each set of ions has the same mass-to-charge ratio in the mass spectrometer. As to \(\text{O}_2^+\) fragment ions, formed also in dissociative processes, its value is by two orders of magnitude less compare to other fragment ions and are not presented in Fig. 4. As it is seen from Fig. 4, the agreement between our results for \(\text{O}_2^+\) (curve 1) for \(\text{O}^+ + \text{O}_2^+\) (curves 4) and the results of [47] (curve 2) and (curve 5), respectively, is excellent. A similarity of the energy dependence of the cross section for \(\text{O}_2^+\) is observed also with the theoretical results (curve 3) obtained in [48] but it is not consistent with absolute value of our results and with the results obtained in [47]. For convenience if we normalize the results of relative cross section from [48] to our and to the results of [47] (not shown in Fig. 4), it will show excellent agreement. All presented data are obtained under single collision conditions (3 \(\times\) 10\(^{-6}\) Torr). As it is well known (see e.g. 31),
FIG. 5: (Color online) The cross section of O\(^+\)+O\(_2\)^{2+} ions production in e+O\(_2\) collision as a function of the electron energy for two different pressure conditions. Curves: 1 - data at the pressure \(P = 1 \times 10^{-4}\) Torr; 2 - data at the pressure \(P = 5 \times 10^{-4}\) Torr.

at a such pressure condition the production of metastable particles take place, which can significantly affect the value of the cross section. For this reason, for the e−O\(_2\) collision system, we carried out the measurements for production of ions (O\(^+\)+O\(_2\)^{2+}) in the 55−120 eV electron energy interval and for two different pressure condition: \(1 \times 10^{-4}\) and \(5 \times 10^{-4}\) Torr. The results, normalized with respect to each other, are given in arbitrary units in Fig. 5. As it follows from Ref. [31] the increase of working pressure in the ion source is strongly related to an increase of a quenching effect. Hence, the difference observed between the curves indicates the presence of metastable particles in the ion beam. It means that a more sophisticated exploration is needed by using an intense ion beam to control the influence of metastable particles on the cross section. This issue can be addressed by using the RF ion source.

2. Optical spectroscopy measurements

One advantage of the RF source used in this experiment is that, depending on its operating mode, a certain fraction of the ions can be found in metastable states and easily identified. As it was mentioned in the introduction the probability of quenching is significantly related to the increase of the target pressure in the ion source. Hence, it is important to explore the working condition of a source by changing the pressure in it. Therefore we considered the following reaction

\[
\text{O}^+ + \text{Ar} \rightarrow \text{O}^+ + \text{Ar}^*(6s).
\]

(11)

The typical excitation spectra for the intense spectral line of Ar atom (\(\lambda = 731.1\) nm) in O\(^+\)−Ar collision for the process (11) at the different pressure in the ion source are presented in Fig. 6. It was found that by increasing the O\(_2\) gas pressure in the ion source about 6 times (from \(1.5 \times 10^{-2}\) to \(1.0 \times 10^{-1}\) Torr) the intensity of this lines decreases by a factor of 1.4. This result indicates the fact that the presence of metastable ions plays definite a role in excitation of the Ar(6s) state (excitation energy = 14.85 eV) and hence, this process is effectively realized due to the transfer of internal energy. In order to check the influence of the ion source operating parameters and to evaluate the role of metastable ions in excitation processes we have extended this research to nitrogen molecules and to its dissociative products. For the latter we chose energy and pressure values with which the observation of a metastable state could be possible at high energy and for a single collision condition.

The test experiment is performed on the excitation cross section of the (0,0), (0,1) and (1,2) bands of molecule ions N\(_2^+\) in collision of the O\(^+\) ion with nitrogen N\(_2\) molecules. A typical spectrum at a fixed
energy $E = 5$ keV of the primary beam and pressure $P = 7 \times 10^{-3}$ Torr in the ion source is shown in Fig. 7. As it is seen from Fig. 7, the relation between the intensities of these bands is $10 : 3 : 1$, respectively. As the relative intensity has been established, we chose an intensive band $(0,0) \text{N}_2^+$ ion $(\lambda = 391.4 \text{ nm})$ and performed a study with variable pressure. Such procedure allowed us to separate the ground and metastable state ions in the primary beam and to perform a systematic measurement. Let us mentioned that on the same Fig. 7, the excitation of the satellite dissociative product for the relatively intense nitrogen ionic line $(\lambda = 424.2 \text{ nm})$ is also presented, while in Fig. 7, the less intensive band $(0,3)$ of the N$_2^+$ ion $(\lambda = 552.8 \text{ nm})$ is shown.

The main objective of our research is the study of the excitation processes in reactions of the ground O$^+$($^4S$) and metastable O$^+$($^2D$) and O$^+$($^2P$) state ions with N$_2$ molecule in the wide energy range of incident ions. In particular, in collisions of O$^+$ ions with nitrogen molecules the studies are carried out for

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**FIG. 6:** (Color online) The typical spectra of Ar atomic line $(\lambda = 731.1 \text{ nm})$ for O$^+$–Ar collision system at fixed $(E = 2.5 \text{ keV})$ energy of O$^+$ colliding ions and for two different pressure in high-frequency ion source. Curves: 1 - for the pressure $P = 1.5 \times 10^{-2}$ Torr; 2 - for the pressure $P = 1 \times 10^{-1}$ Torr.

**FIG. 7:** (Color online) Relative excitation cross section of the bands of N$_2^+$ ion and dissociative product of N$^+$ ionic lines in O$^+$–N$_2$ collision at the energy $E = 5$ keV and pressure in the ion source $P = 7 \times 10^{-3}$ Torr. Observed wavelengths are as labeled on the figure. (a) $(0,0)$, $(0,1)$, and $(1,2)$ bands of the N$_2^+$ ion and NII 424.2 nm line of the N$^+$ ion. (b) $(0,3)$ band of the N$_2^+$ ion and NII 500.5 nm, NII 504.0 nm, NII 552.8 nm, NII 567.9 nm, NII 571.1 nm and NII 574.7 nm lines of the N$^+$. 
the following inelastic channels with formation of the excited state $B^2\Sigma_u^+$ of the molecular ion of nitrogen and the dissociation products of $N^+$

\[
\begin{align*}
O^+(4S) + N_2(X^2\Sigma_g^+) &\rightarrow N_2^+(B^2\Sigma_u^+) + \ldots \quad (12) \\
O^+(2D + P) + N_2(X^2\Sigma_g^+) &\rightarrow N_2^+(B^2\Sigma_u^+) + \ldots \quad (13) \\
O^+(4S) + N_2(X^2\Sigma_g^+) &\rightarrow N^+ + N + O(3P) \quad (14) \\
\downarrow &\rightarrow N^+(3d\;^3F^0) + N + O(3P) \quad (15) \\
&\rightarrow N^+(3p\;^3D) + N + O(3P) \quad (16) \\
&\rightarrow N^+(4f\;^3F) + N + O(3P) \quad (17) \\
O^+(2D + 2P) + N_2(X^2\Sigma_g^+) &\rightarrow N^+ + N + O(3P) \quad (18) \\
\downarrow &\rightarrow N^+(3d\;^3F^0) + N + O(3P) \quad (19) \\
&\rightarrow N^+(3p\;^3D) + N + O(3P) \quad (20) \\
&\rightarrow N^+(4f\;^3F) + N + O(3P) \quad (21)
\end{align*}
\]

In the reactions (14) and (16) the dissociative product $N^{+\ast}$ can be in different excited states. In our study we focus on the particular dissociation channels (15) – (17) and (19) – (21).

### III. RESULTS OF MEASUREMENTS AND DISCUSSION

In collisions of $O^+$ ions with $N_2$, we studied the excitation of the band $(0,0)$ of the first negative system of the $N_2^+$ which corresponds to the transition $B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+$. The study is carried out with $O^+$ in the ground state $4S$ and metastable states $(2D, 2P)$. The presence of ions in metastable states is monitored by measuring the excitation function of the $(0,0) \lambda = 391.4$ nm bands of the first negative system of $N_2^+$ ion for different operating conditions of the RF source. The energy dependences of the efficiency of excitation of the given band system by oxygen ions in the metastable states for the energy of the incident ion in $O^+$, we studied the excitation of the band $(0,0)$ of the $N_2$ ground state proceeds with a significantly lower efficiency than excitation by ions in the metastable $2D$ and $2P$ states. The ratio of the corresponding cross sections is $1 : 9 : 300$ [7]. As can be seen from Fig. 8 these curves differ not only by their shape, but also by the magnitude of excitation cross section. At a fixed energy, as the pressure in the RF source increases the excitation efficiency decreases. The excitation cross section for oxygen ions in the $4S$ ground state and the metastable $2D$ and $2P$ states for the energy of the incident beam $E = 1$ keV and the oxygen pressure in the RF source $P_1 = 2.4 \times 10^{-2}$ Torr obtained in Ref. 7 are $\sigma = 0.73 \times 10^{-18}$ cm$^2$, $\sigma = 6.6 \times 10^{-18}$ cm$^2$, $\sigma = 2.20 \times 10^{-16}$ cm$^2$, respectively. The comparison of these results with the excitation efficiency $\sigma = 1.7 \times 10^{-17}$(cm$^2$) that we measured at the same energy and pressure shows that our result is greater than the values of the excitation cross sections obtained in 7 for the oxygen ions in the $4S$ ground and metastable $2D$ states and significantly less than for the ions in the metastable $2P$ state. Consequently, one can suppose that the value of the excitation efficiency we obtained is determined to a significant extent by oxygen ions in the metastable $2P$ state. Our results in the energy interval $E = 0.25 - 10$ keV and for the same oxygen pressure in the RF source $P_1 = 2.4 \times 10^{-2}$ Torr as in Ref. 7 are presented in Fig. 8 by curve 1.

Relate to the investigation of the presence of the metastable $2D$ state in the oxygen ions beam we examined excitation of the Meinel bands $(3,0) \lambda = 687.4$ nm and $(4,1) \lambda = 703.7$ nm, which correspond to the transition $A^2\Pi_u - X^2\Sigma_g^+$ of the $N_2^+$ ion in $O^+ - N_2$ collisions. The experiments showed that, despite
the quasiresonant character of this process (energy defect $\Delta E = 0.06 \text{ eV}$) the Meinel bands are hardly excited, which is probably due to the absence of the oxygen ions in metastable $^2D$ state in the primary particle beam. The small fraction of these ions in the primary particle beam in comparison with $O^+(^2P)$ ions is due to a peculiarity of the mechanism of formation of these ions during the dissociative ionization in collisions of electrons with oxygen molecules in the RF ion source. An analysis of the energy terms of the oxygen molecule and the oxygen molecular ion shows that the most efficient mechanism of formation of dissociation products in various states is a decay of highly excited states of the $O_2^+$ ion in the region of internuclear distances corresponding to the Franck–Condon transitions. Using the data of Ref. 7, we can estimate from our results the fraction of oxygen ions in the metastable $^2P$ state in the primary particle beam for different values of the pressure of the working gas in the RF source. Simple calculations show that the fraction of $O^+(^2P)$ ions in the primary particle beam for the pressures of $2.4 \times 10^{-2}$ Torr, $8 \times 10^{-2}$ Torr and $2 \times 10^{-1}$ Torr in the RF source is 7%, 3%, and 1%, respectively. As we mentioned our measurements show that the $O^+(^2P)$ ions make a substantial contribution to the excitation efficiency. Therefore, the decrease in the excitation efficiency resulting by the increase of the pressure inside the RF source is entirely due to the decrease of the fraction of these ions in the primary beam. The contribution of the metastable ions to the excitation efficiency also depends substantially on their energy — it decreases as their energy increases. After determining the fraction of metastable ions in the primary beam, it is easy to reconstruct the dependence of the cross section of excitation of the $(0,0) \lambda = 391.4 \text{ nm}$ band by $O^+$ ions in the $^4S$ ground state and in the metastable $^2P$ state from the energy dependence of the excitation efficiency by solving some simple algebraic equations. The results of this reconstruction are shown in Fig. 8. It can be seen that the cross section for excitation of the given band by $O^+(^2P)$ and $O^+(^4S)$ ions behave differently. The excitation cross section for the incident $O^+$ ion in $^2P$ state slightly increases in the energy range $1-5 \text{ keV}$ and is almost constant in the energy range $5-10 \text{ keV}$. The excitation cross section for the ground state incident $O^+$ ion $^4S$, sharply increases in the entire energy range of the incident beam, and at higher ion energies the contribution of the ions found in the $^4S$ ground state to the excitation becomes decisive. However, the magnitude of this cross section is still more than one order of magnitude smaller than one for $O^+(^2P)$ ions at the energy $10 \text{ keV}$.

In order to check the influence of the ion source operating parameters and evaluate the role of metastable ions in excitation processes we have made measurements for first negative band system of the $N_2^+$ ion in different pressure condition. The dependence of the excitation cross section for the band $(0,0) \lambda = 391.4 \text{ nm}$ of $N_2^+$ on the pressure in the ion source are presented on Fig. 11. An analysis of Fig. 11 shows that

![Figure 8](image-url)

FIG. 8: (Color online) Energy dependence of the efficiency of excitation for the band $(0,0) \lambda = 391.4 \text{ nm}$ of the first negative system of $N_2^+$ ion in $O^+\text{--}N_2$ collision for different pressure in the RF ion source. Curves: 1 - $P = 2.4 \times 10^{-2}$; 2 - $P = 8 \times 10^{-2}$; 3 - $P = 2 \times 10^{-1}$ Torr.
FIG. 9: (Color online) Energy dependence of the excitation cross section for the (0,0) \( \lambda = 391.4 \) nm band of the first negative system of \( N^+ \) ion in \( O^+ - N_2 \) collision. Curves: 1 - measurements for \( O^+ \) ion in \( ^2P \) metastable state; 2 - measurements for \( O^+ \) ion in \( ^4S \) ground state.

FIG. 10: (Color online) Dependence of the relative excitation cross section for the (0,0) \( \lambda = 391.4 \) nm band of the first negative system of \( N^+ \) ion in \( O^+ - N_2 \) collision on the pressure in the RF ion source at the incident ions energy \( E = 2.5 \) keV.

the intensity of the radiation from the decays of the excited (0,0) state (\( \lambda = 391.4 \) nm) band sharply decreases with the increase of the pressure in the RF ion source and reaches saturation at \( P > 10^{-1} \) Torr. In this region the percentage ratio of the metastable and ground states ions does not change. The abrupt decrease of intensity indicates a decrease of the relative portion of metastable ions in the ion source. Therefore, in collisions mainly ions of \( O^+ \) in the ground \( ^4S \) state participate.

To confirm this fact let us consider the dependence of the excitation cross section of the band (0,0) \( \lambda = 391.4 \) nm on the inverted velocity of the incident ion. This dependence is presented in Fig. [11]

The observed linear dependence of the cross section on a semilogarithmic scale (linear decrease with increase of \( 1/v \)) is nicely described by the relation \( \sigma = A e^{-a/v} \), where \( A \) and \( a \) are constants. As it is well known such a dependence is a peculiar characteristic of inelastic processes realized in an adiabatic
area. From this dependence one can make the conclusion that the excitation process takes place in one inelastic channel and definite portion in it is related solely to the ground state \( O^+ (4S) \) ions. Thus, we can conclude that it is possible to vary the \( O^+ \) ion beam content with the different internal electronic states (metastable and ground) by changing the working condition in the ion source.

In our study of \( O^+ - N_2 \) collisions, in addition to molecular bands, we also observed lines related to the \( N^+ \) ions excitations, which are formed in the process of dissociative charge exchange processes (14) and (18). The most clearly identified lines for the dissociative product \( N^+ \), which have the sufficient intensity in the considered energy interval are \( \lambda = 424.2 \) nm, \( \lambda = 500.5 \) nm, and \( \lambda = 567.9 \) nm and
are presented in Fig. 13. The dissociation of the N$_2$(X$^2\Sigma^+$) molecule in O$^+-$N$_2$ collisions leads to the production of N$^+$ ions in different excited states. The results of measurements of the dependence of the excitation cross section on the energy of O$^+$ ions for the excitation wavelength $\lambda = 500.5$ nm, $\lambda = 567.9$ nm and $\lambda = 424.2$ nm are presented in Fig. 12. The excitation cross sections for the dissociative product N$^+$ increase with increases the incident ion energy and show almost a linear dependence on the energy. The cross sections are measured at a pressure of 2.4 $\times$ 10$^{-2}$ Torr in the ion source. With increasing of pressure inside the source, the ion current at the outlet from the source drops sharply and, therefore, decreases also in the collision chamber. As a result the measurement error increases and therefore the sensitivity of the measurement of the excitation cross section significantly reduces. In particular, with a change in pressure inside the source by an order of magnitude from 1 to 2.5 keV does not exceed 30% and at the high energy range of 5 to 10 keV 10 to 15%, and the latter one is within the accuracy of experimental measurements. The analyses of the cross sections for the 3$^d$F$^0 \rightarrow$3p $^3$D (the line, NII 500.5 nm) and 3$^p$ $^3$D $\rightarrow$ 3s $^3$P (the line NII 567.9 nm) transitions shows that while the cross sections are the same order of magnitude, the increment of the cross section for the 3$^d$F$^0 \rightarrow$3p $^3$D transition is slightly larger than one for the 3$^p$ $^3$D $\rightarrow$ 3s $^3$P transition. Moreover, these cross sections are significantly ($\sim$ 15 times) greater than the excitation cross section for the 4$^f$F $\rightarrow$3d $^3$D (the line NII 424.2 nm) transition. The proximity of the cross sections for NII 500.5 nm and NII 567.9 nm is probably due to the cascade population of the 3$^p$ $^3$D state by the 3$^d$ $^3$F$^0 \rightarrow$3p $^3$D transition.

As the strong effect of the different electronic states of ions O$^+$ on the magnitude of cross section for O$^+-$N$_2$ collision, one can conduct the study of molecular orientation by measuring the polarization degree for the emission of exited molecular ions and explore the mechanism of inelastic processes during the collision of O$^+$(3$^S$) and O$^+$(2$^P$) ions with nitrogen molecules.

The energy dependence of the degree of polarization for the emission of bands of the first negative system of the N$_2^+$ ion in collision of O$^+$ ions with N$_2$ molecules is presented in Fig. 13. For seeking of comparison in Fig. 13 the results of polarization for the He$^+-$N$_2$ collision system are presented. The comparison of the curves 1 and 2 in Fig. 13 shows that degree of polarization obtained by the 7% of metastable O$^+$(2$^P$) ions’ admixture is less compared to those for the 1% admixture. In spite of the fact, that the portion of the metastable 2$^P$ state in the total beam does not exceed 7% (curve 2), their input into the cross section is determinative. This is true because it is known that the process of charge

![FIG. 13: (Color online) Energy dependence of the degree of polarization for the O$^+-$N$_2$ and He$^+-$N$_2$ collision systems. The data for the O$^+-$N$_2$ collision system are obtained with different admixture (ground + metastable) of O$^+$ ions. Curves: 1 - the incident beam contains about 1% of metastable 2$^P$ states; 2 - the incident beam contains about 7% of metastable 2$^P$ states; 3 - data obtained for He$^+$ reactant ions.](image-url)
exchange (our case) by oxygen ions in the $^2P$ metastable states proceeds with a significantly higher (about two order) efficiency than by ions in the $^4S$ ground state. This means, that the process of charge exchange take place at a relatively large internuclear distance and an influence of the ion electric field on an electron cloud of the molecule is less pronounced. A relatively small as well is an electron cloud orientation in space and hence the degree of polarization.

It should be noted that the sign of the degree of polarization of the excited molecular ions does not change in the case of the $O^+−N_2$ collision system (curves 1 and 2), while in the case of the He$^+−N_2$ collision system (curve 3) the polarization changes its sign at $E = 2.0$ keV energy. From the energy dependence of the degree of polarization, we can conclude, that in the case of $O^+−N_2$ collision the symmetry of three-particle (ion-molecule) system does not change, but in the case of the He$^+−N_2$ collision system the change of molecular axis orientation takes place with respect to the direction of incident beam.

**IV. CONCLUSIONS**

Electron and optical spectroscopy methods, with two independent ion sources were used to perform excitation function measurements for the $O^+−N_2$ collision system. Precisely controlled electron energy with an inhomogeneity of $50$ meV was used to measure the production of incident $O^+$ ions in the ground $^4S$ and metastable $^2P$ and $^2D$ states. The absolute energy of the electron beam has been monitored by measurement of the ionization and appearance potentials for well known atomic and molecular targets reported in the literature. It should be especially noted that we used the ion source as the collision chamber. The latter allowed us to investigate collisions inside the ion source. This significantly raised the luminosity, and simplified and accelerated the measurement procedure. A comparison of our results with other experimental and theoretical data shows good agreement and proves the validity of our approach.

The optical spectroscopy device, incorporated with the intense RF ion source was applied to explore the pressure condition in the ion source and to perform excitation measurements for molecular $N_2^+$ and atomic $N^+$ ions in collisions of $O^+ (^4S, ^2P, ^2D)$ with $N_2$ molecules. The excitation cross section of $N_2^+$ ion for the $(0,0)$, (0,1) and (1,2) bands system in collision of mixed states of $O^+$ ions beam with nitrogen molecules have been measured. The ratio of intensities for these bands is established as $10 : 3 : 1$.

The exact edge of the pressure condition in the RF source was revealed which enabled us to distinguish ground state and metastable states ions in the primary beam. The presence of ions in the metastable states of $^2P$ and $^2D$ was monitored by measurement of the excitation function of the first negative band system $(0, 0)$ and $(1, 1)$ for $N_2^+$ and $O^+$ states in $N_2$ molecules. The excitation cross section of $N_2^+$ ion for different pressure condition in the RF source. An influence of the pressure condition in the RF source on the formation of certain $O^+(^2P)$ states was established. Its percentage value for a pressure in the RF source of $P = 2.4 \times 10^{-2}$, $8 \times 10^{-2}$ and $2 \times 10^{-1}$ Torr was determined to be $7\%$, $3\%$ and $1\%$, respectively. A small fraction of metastable $^2D$ ions in the ion source compare to $^2P$ and $^4S$ states was proven by measurements of the Meinel band system $(3,0)$ $\lambda = 687.4$ nm and $(4,1)$ $\lambda = 703.7$ nm.

The absolute excitation function for $(0,0) \lambda = 391.4$ nm band of the first negative system of the $N_2^+$ by O$^+$ ions in the ground $^4S$ and metastable $^2P$ state was obtained in a wide $(1 − 10$ keV) energy interval. The influence of ions, having different electronic states (ground and metastable) on the magnitude of the cross section was established. It was found that metastable $^2P$ state ions indeed enhance the excitation cross section compared to those measured for the ground $O^+(^4S)$ state ions. While the excitation cross section obtained for the $O^+(^4S)$ state ions sharply increases in all energy interval, the excitation cross section for the incident $O^+$ ions in $^2P$ state is large than by two orders of magnitude at $1$ keV and $10$ time larger at $10$ keV than that one for the $O^+(^4S)$ incident ions.

In the case of collisions of $O^+$ with nitrogen molecules to assess the role of the metastable state $O^+(^2D, ^2P)$ in the incident beam in excitation processes, we used a filtration chamber, as in the earlier works. However, the originality of our work lies in the fact that ion filtration occurs in the RF ion source. The latter allows us to change the pressure and the mixture of gases inside the source, the power deposited inside the discharge, and other conditions which have an influence on formation of the incident beam.

The cross sections for the $N^+$ ions excitations in the dissociative charge exchange processes increase with increasing of the incident ion energy and show almost a linear dependence on the energy. The cross sections for the $3d^3F^0 \rightarrow 3p^3D$ and $3p^3D \rightarrow 3s^3P$ transitions are of same order of magnitude but significantly greater than the excitation cross section for the $4fF \rightarrow 3d^3D$ transition. The proximity of the cross sections for the $3d^3F^0 \rightarrow 3p^3D$ and $3p^3D \rightarrow 3s^3P$ transitions is probably due to the cascade...
population of the $3p\,{}^{3}D$ state by the $3d\,{}^{3}F\rightarrow{}^{3}D$ transition.

The mechanism of the processes realized during collisions of ground and metastable oxygen ions on molecular nitrogen have been estimated by the study of molecular orientation effect and measurement the degree polarization for emission of excited molecular ions. It was demonstrated that for the $O^{+}-N_{2}$ collision system the degree of polarization by the metastable $O^{+}(2P)$ ions is less compared to those that are in the ground $O^{+}(4S)$ state and the sign of polarization degree of excited molecular ions does not change.

This is the first measurements of the energy dependence of the excitation cross section of the band $(0,0) = 391.4$ nm of the first negative system of the $N_{2}^{+}$ in a wide energy range of $1-10$ keV of the incident $O^{+}(4S)$ and $O^{+}(2P)$ ions, as well as the degree of polarization of radiation was measured for the first time.

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