Special features of the charge-exchange cross section of fast nitrogen ions with a *K* vacancy

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The cross sections $\sigma_{i,i-m}$ for the capture of one, two, and three electrons by N^{i+} ions with charges $i=3-7$ during their passage through helium, nitrogen, neon, and argon with a velocity $v=3.65$ au have been measured. Calculations of the electron-capture cross sections $\sigma_{i,i-1}$ in the same media have been performed in the Oppenheimer–Brinkman–Kramers approximation. It has been established that postcollisional autoionization results in a significant decrease in the values of $\sigma_{54}(1s2s)$ for the capture of one electron by metastable helium-like N^{5+} ions in all the media investigated and the cross sections $\sigma_{i,i-2}$ for the capture of two electrons by nitrogen ions with a vacancy in the K shell only in helium and neon. The degree of reduction of the cross sections for double charge exchange has made it possible to estimate the probability of radiative de-excitation of nitrogen ions. It has been shown that the dependence of the total charge-exchange cross sections $\sigma_i=\Sigma_m m\sigma_{i,i-m}$ on i in all the media investigated is nearly cubic. © *1995 American Institute of Physics.*

1. INTRODUCTION

The present work is a continuation of a series of experimental studies of the charge-exchange processes of fast ions of light elements.[1–4] The criterion for the predominant capture of electrons in the ground or excited states of a fast ion was established experimentally in Ref. 1. It was demonstrated experimentally and theoretically in the ensuing investigations[2,3] that the dependence of the charge-exchange cross sections on the charge of the nuclei comprising the target Z_t is oscillatory. It was discovered in Ref. 4 that postcollisional autoionization results in significant alteration of the measured cross sections for electron capture by metastable helium-like ions.

The investigation of the influence of postcollisional autoionization on the charge-exchange cross sections of fast ions was continued in the present work. For this purpose the cross sections for the capture of one ($\sigma_{i,i-1}$), two ($\sigma_{i,i-2}$), and three ($\sigma_{i,i-3}$) electrons by nitrogen ions with different numbers of electrons in the K shell as they pass with a velocity $v=3.65$ au through helium, nitrogen, neon, and argon were determined experimentally. The values of the cross sections σ_{54} and σ_{53} for the capture of one and two electrons by helium-like N^{5+} ions were obtained for ions in the ground $(1s^2)^0S$ and metastable $(1s2s)^{1,3}S$ states. Calculations of the charge-exchange cross sections were also performed in the Oppenheimer–Brinkman–Kramers (OBK) approximation for nitrogen atoms with charges $i=4-7$ in the same media.

The results made it possible to estimate the ratio between the autoionization and radiative channels for de-excitation of a multiply charged ion, as well as to ascertain the dependence of the total charge-exchange cross sections on the ion charge i.

The capture of two electrons in excited states of ions of light elements, followed by autoionization, was previously investigated in Ref. 5 for F^{7+} ions passing through helium and neon targets with a velocity $v=3.4$ au and for carbon, nitrogen, oxygen, and neon ions with charges $i=Z$, $Z-1$, and $Z-2$ (Z is the charge of the nucleus of the ion) passing through hydrogen and helium targets with velocities $v=0.3-0.4$ au. in Refs. 6–11. It was shown in those papers on the basis of studies of the spectra of the electrons pro-

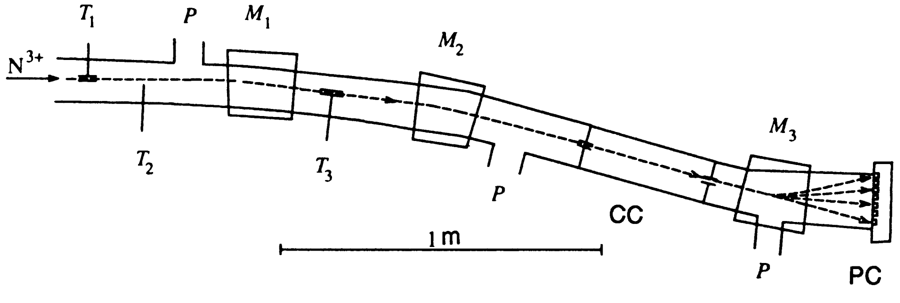

FIG. 1. Experimental layout: M_1, M_2, and M_3 are analyzing magnets, T_1 and T_3 are flow-through gas targets, T_2 is a solid target, P is a pump, CC is a collision chamber, and PC is a proportional counter. The trajectory of the ions is indicated by the dashed line.

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TABLE I. Scheme for obtaining nitrogen ions with various charges i.

i	T_1	T_2	$i(M_1)$	T_3	$i(M_2)$
3	–	–	3	–	3
4	+	–	4	–	4
4	–	+	4	–	4
5	+	–	4	+	5
5	–	+	5	–	5
5	–	+	6	+	5
6	–	+	6	–	6
7	–	+	7	–	7

Note. The charges i of the N^{i+} ions derived successively by the analyzers M_1 and M_2 following charge exchange from an initial ion charge $i=3$ to a final charge $i=3-7$ are shown. The plus and minus signs indicate the presence or absence of the solid target T_2 and the presence or absence of gas in the targets T_1 and T_3 along the path of the ion beam.

duced upon the decay of doubly excited states of the ions that when the velocity of the ions is $v=3.4$ au, electrons are captured with the highest probability in excited states of ions with a principal quantum number $n=2$ (Ref. 5). When the velocity of the ions decreases to $v=0.5$ au, the value of n increases to $n\simeq 3-4$ (Ref. 11).

2. EXPERIMENTAL METHOD

The charge-exchange cross sections were measured with an apparatus described elsewhere.[12,13] Beams of N^{3+} ions extracted from a 72-cm cyclotron with energy $E=0.34\pm 0.01$ MeV/nucleon, i.e., with a velocity $v=3.65$ au, were directed into a charge-exchange system consisting of two analyzing magnets M_1 and M_2, a thin celluloid film T_2 with a thickness of 2–3 $\mu g/cm^2$ ($\sim 10^{17}$ atoms/cm^2), and two flow-through nitrogen targets T_1 and T_3 with a thickness equal to $\sim 10^{15}$ atom/cm^2 (the gas targets also served as collimators in the cases in which no gas passed through them) (Fig. 1). The main method for obtaining ions with different charges was charge exchange in the solid target T_2. However, other production methods, which are listed in Table I, were employed for helium and the lithium-like N^{5+} and N^{4+} ions, whose beams always contain a more or less significant number of metastable particles in the $(1s2s)^{1,3}S$ and $(1s2s2p)^4P_{5/2}$ states, respectively.[14,15]

Beams of nitrogen atoms with charges $i=3-7$ produced in different ways were directed by the magnetic analyzer M_2 into a collision chamber in the form of a cylinder with a length of 40 cm having channels with a height of 0.5 cm, a width of 0.2 cm, and a length of 2.5 cm at its entrance and exit. The thickness of the gas layer in the collision chamber at which the condition of single collisions was satisfied ranged from $\sim 10^{14}$ atoms/cm^2 (the residual pressure) to $\sim 3.3\times 10^{15}$ atoms/cm^2 for helium, $\sim 1.5\times 10^{15}$ atoms/cm^2 for nitrogen and neon, and $\sim 0.6\times 10^{15}$ atoms/cm^2 for argon and was determined to within 5% by LM-2 manometric sensors, which were calibrated with respect to the absolute readings of an oil compression manometer (a McLeod manometer). The charge distribution of the ions after passage through the collision chamber was determined at two or three values of the pressure of the injected gas by a system consisting of the magnetic analyzer M_3 and eight proportional counters. The set of measurements of the charge distributions for ions with different initial charges were used to determine the electron-capture and loss cross sections $\sigma_{i,i\pm m}$, where m is the number of electrons captured (–) or lost (+) by the ions as a result of a single collision, by the method described in 12.

The measured mean electron-loss and capture cross sections $\bar{\sigma}$ for N^{5+} were found to be highly dependent on the method used to produce them, and were related to the relative number α of metastable particles in the ion beam by the straightforward expression

$$\bar{\sigma}=(1-\alpha)\sigma^0+\alpha\sigma^m, \tag{1}$$

where σ^0 and σ^m are the cross sections of the corresponding processes for unexcited and metastable ions. The values of σ^0 and σ^m for the loss of an electron by helium-like N^{5+} ions, i.e., the values of $\sigma_{56}(1s^2)$ and $\sigma_{56}(1s2s)$, were determined in Ref. 15, where it was shown that in the range of velocities $v \geqslant \frac{1}{2}(I_{nl}/I_0)^{1/2}$ (I_{nl} is the binding energy of the electron in the ion, and $I_0=13.6$ eV) the cross sections for the loss of individual $1s$ and $2s$ electrons are determined in practice only by the values of I_{nl} and, to within 10–15%, do not depend on other parameters characterizing the initial state of the ion. In addition, both the experimental and theoretical cross sections, including the cross sections for excited particles, fall on single plots of the dependence of $\sigma(1s)$ and $\sigma(2s)$ on I_{nl}. The values of $\sigma_{56}(1s^2)$ and $\sigma_{56}(1s2s)$ thus found for N^{5+} ions passing through helium and nitrogen are presented in Table II. The values of $\sigma_{56}(1s^2)$ for electron loss by unexcited $N^{5+}(1s^2)$ ions are approximately half the cross sections for the production of these ions as a result of electron loss by lithium-like N^{4+} ions, and the values of $\sigma_{56}(1s2s)$ for electron loss by metastable $N^{5+}(1s2s)$ ions are ≈ 1.6 times the corresponding cross sections for the production of N^{5+} ions as a result of electron capture by hydrogen-like N^{6+} ions.

The values of α were found from expression (2), which follows from (1),

$$\alpha=\frac{\bar{\sigma}_{56}/\sigma_{56}(1s^2)-1}{\sigma_{56}(1s2s)/\sigma_{56}(1s^2)-1}, \tag{2}$$

TABLE II. Values of σ_{56} for electron loss by N^{5+} ions in the ground $(1s^2)$ and metastable $(1s2s)$ states passing through helium and nitrogen with a velocity $v=3.65$ au (in units of 10^{-17} cm^2/atom).

State of ion nl	I_{nl}, eV	σ_{nl}(He)	$\sigma_{nl}(N_2)$
$1s^2$	551.9	0.028 ± 0.010	0.074 ± 0.010
$1s2s$	132.2	0.80 ± 0.12	2.2 ± 0.2

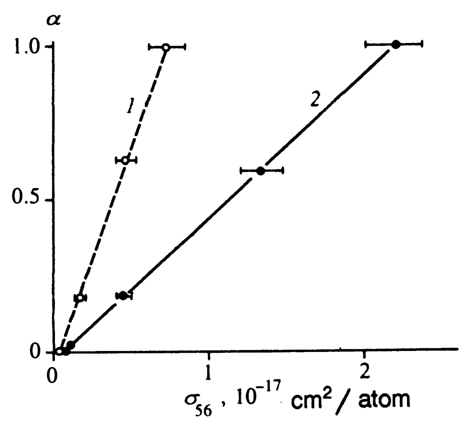

FIG. 2. Dependence of α on σ_{56} in helium (*1*) and nitrogen (*2*). The cross sections for $\alpha=0$ and $\alpha=1$ were taken from Table II.

and varied from $\alpha=0.03\pm0.01$ to $\alpha=0.6\pm0.1$ for beams of nitrogen ions formed as a result of electron loss and capture in a thin nitrogen target. The intermediate value $\alpha=0.18\pm0.03$ was obtained for a beam of nitrogen ions which passed through a thin celluloid film (Fig. 2).

The values of σ_{54} and σ_{53} for the capture of one and two electrons by N^{5+} ions, as well as the values of σ_{56} for the loss of an electron, vary linearly as α increases (Fig. 3). Extrapolation of these cross sections to $\alpha=0$ and $\alpha=1$ made it possible to evaluate the corresponding electron-capture cross sections for unexcited [$\sigma_{54}(1s^2)$ and $\sigma_{53}(1s^2)$] and metastable [$\sigma_{54}(1s2s)$ and $\sigma_{53}(1s2s)$] ions (see Table III).

For N^{4+} ions, whose beams contain no more than 3% metastable particles,[16] the values of the electron-capture cross section σ_{43} measured for two production methods were identical to within 10%.

The cross sections $\sigma_{i,i-1}$ for the capture of one electron were measured with an accuracy of $\pm10\%$, the cross sections $\sigma_{i,i-2}$ for the capture of two electrons were measured with an accuracy of $\pm20\%$, and the cross sections $\sigma_{i,i-3}$ were measured with an accuracy of $\pm30-40\%$. The accuracy of the measurements of $\sigma_{54}(1s^2)$ and $\sigma_{53}(1s^2)$ is close to the accuracy of the measurements of $\sigma_{i,i-1}$ and $\sigma_{i,i-2}$ for other unexcited ions, and the accuracy of the values of $\sigma_{54}(1s2s)$ and $\sigma_{53}(1s2s)$ obtained by extrapolation to a large distance from the experimental values is 1.5–2 times that for $\sigma_{i,i-1}$ and $\sigma_{i,i-2}$. Only estimates of an upper bound were obtained for $\sigma_{54}(1s2s)$ and $\sigma_{53}(1s2s)$ in helium and for $\sigma_{53}(1s2s)$ in neon.

Many of the cross sections measured in the present work were obtained for the first time. They include the values of σ_{76} and σ_{75} for the charge exchange of N^{7+} nuclei and the values of $\sigma_{5,5-m}(1s^2)$ and $\sigma_{5,5-2}(1s2s)$ for N^{5+} ions in the ground $(1s^2)$ and metastable $(1s2s)$ states. In most cases the remaining values of the cross sections coincide to within the range indicated with the results of our earlier studies.[1,4] Table III presents averaged values of $\sigma_{i,i-m}$ for nitrogen ions with the charges $i=2-7$ based on the results of the present work and Refs. 1 and 4.

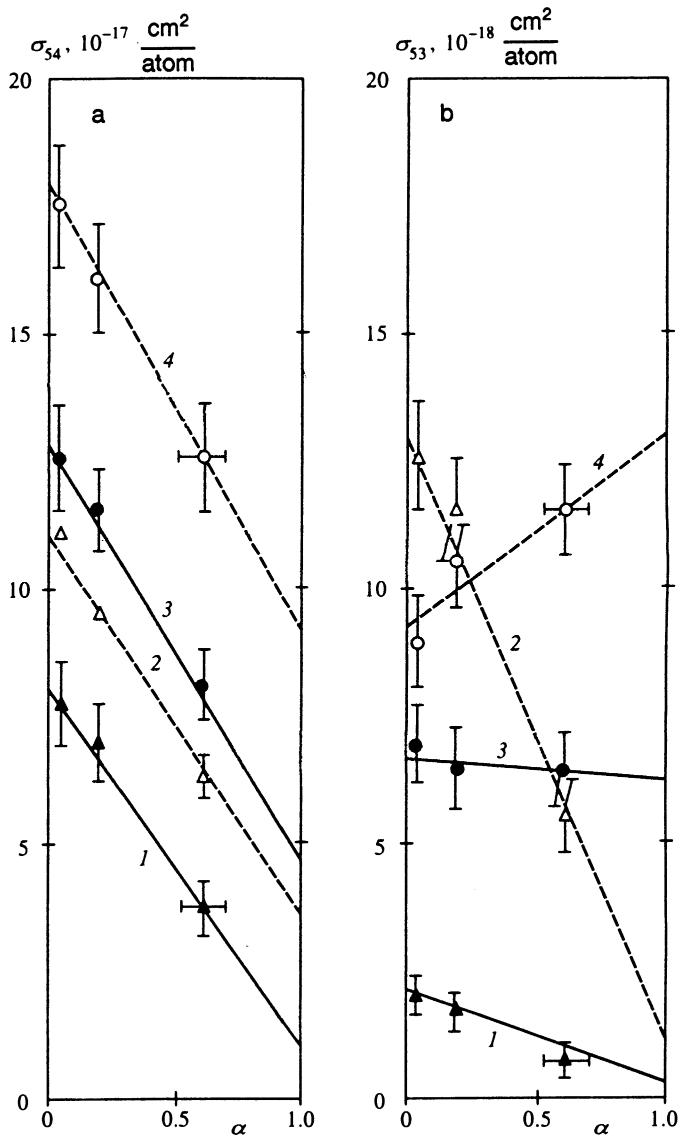

FIG. 3. Dependence of σ_{54} (a) and σ_{53} (b) on α in helium (*1*), neon (*2* reduced by a factor of 2), nitrogen (*3*), and argon (*4*).

3. METHOD FOR CALCULATING CHARGE-EXCHANGE CROSS SECTIONS

The electron-capture cross sections $\sigma_{i,i-1}$ were calculated in the quantum-mechanical OBK approximation.[17,18] It is widely known[18] that the cross sections obtained in this approximation (σ^{OBK}) are significantly greater than the experimental values; however, the dependence of the calculated cross sections on V and Z_t is in qualitative agreement with experiment. The OBK approximation has been used repeatedly to calculate the charge-exchange cross sections of ions heavier than hydrogen. For example, we established an oscillatory dependence of the charge-exchange cross sections on Z_t for the first time in the case of helium ions in Ref. 2. The cross sections for single and double charge exchange by boron, oxygen, and silicon ions were calculated in Ref. 19, and calculations of both the total and partial charge-exchange cross sections of fluorine ions in He and Ne were performed in Ref. 5. In some cases the normalized cross sections

TABLE III. Averaged values of the cross sections $\sigma_{i,i-m}$ for the capture of one ($m=1$), two ($m=2$), and three ($m=3$) electrons by nitrogen ions in helium, nitrogen, neon, and argon based on the results of the present work and Refs. 1 and 4 (in units of 10^{-17} cm^2/atom).

	$\sigma_{i,i-m}$			
$i,i-m$	He	N_2	Ne	Ar
21	0.9 ± 0.1	0.7 ± 0.1	1.9 ± 0.2	1.1 ± 0.1
32	2.4 ± 0.2	2.4 ± 0.2	5.3 ± 0.5	3.5 ± 0.4
31	0.01 ± 0.01	0.04 ± 0.01	0.14 ± 0.04	0.06 ± 0.02
43	5.1 ± 0.01	5.5 ± 0.5	12 ± 1	8.1 ± 1
42	0.04 ± 0.02	0.25 ± 0.05	0.9 ± 0.2	0.24 ± 0.05
$54(1s^2)$	8.0 ± 1.2	12.8 ± 1.2	22 ± 2	18 ± 1.8
$53(1s^2)$	0.02 ± 0.02	0.65 ± 0.10	2.6 ± 0.3	0.9 ± 0.15
52	–	0.05 ± 0.02	0.08 ± 0.04	0.10 ± 0.04
$54(1s2s)$	0.8 ± 0.8	4.5 ± 0.5	7 ± 1	9 ± 1
$53(1s2s)$	0.20 ± 0.05	0.60 ± 0.10	0.2 ± 0.2	1.3 ± 0.3
65	12 ± 1	18 ± 1.8	28 ± 3	28 ± 3
64	0.15 ± 0.06	1.7 ± 0.4	1.7 ± 0.4	2.3 ± 0.6
63	–	0.25 ± 0.07	0.17 ± 0.05	0.45 ± 0.15
76	17.5 ± 1.8	25 ± 2.5	36 ± 4	40 ± 4
75	0.7 ± 0.2	4.3 ± 1.0	5.2 ± 1.0	5.5 ± 1.4
74	–	0.6 ± 0.2	0.4 ± 0.16	0.8 ± 0.3

$\sigma^{\rm OBK}$ calculated in the papers just cited produce a more correct dependence of the cross sections on Z_t than do more complicated approximations that do not require normalization. Thus, the OBK model has frequently been used in recent years to calculate charge-exchange cross sections for ions that are both lighter and heavier than the ions studied in our work.

The expression used to calculate the partial cross section $\sigma(n_t\rightarrow n)$ for capture to unoccupied states with the principal quantum number n in a fast ion from bound states with the quantum number n_t in a target atom has the form

$$\sigma(n_t\rightarrow n)=2\pi v^{-1}F(n_t,n,Z_t^*,Z^*,\varepsilon_t,\varepsilon), \tag{3}$$

where v is the velocity of the ion, Z_t^* and Z^* are the effective charges of the nuclei of the target atom and the fast ion determined according to Slater's rules, ε_t is the binding energy of the electron in the target atom, and ε is the binding energy of the unoccupied state in the n shell of the fast ion. The values of ε for $n=1$ and 2 were taken from Ref. 19, and the values for $n\geqslant3$ were assumed to be hydrogen-like. The analytic expression for the function F was given in Ref. 2. The active electron was described by a hydrogen-like function.

The total charge-exchange cross sections were obtained by summing the partial cross sections $\sigma(n_t\rightarrow n)$

$$\sigma_{i,i-1}=\sum_{n_t}\sum_{n} N_t\theta\sigma(n_t\rightarrow n), \tag{4}$$

where N_t is the number of electrons in the n_t shell of the target atom and θ is the relative number of unoccupied states in the n shell of the fast ion. The summation with respect to n was performed up to $n=10$. The contribution of the partial cross sections with $n>10$ to the total charge-exchange cross section did not exceed 1%.

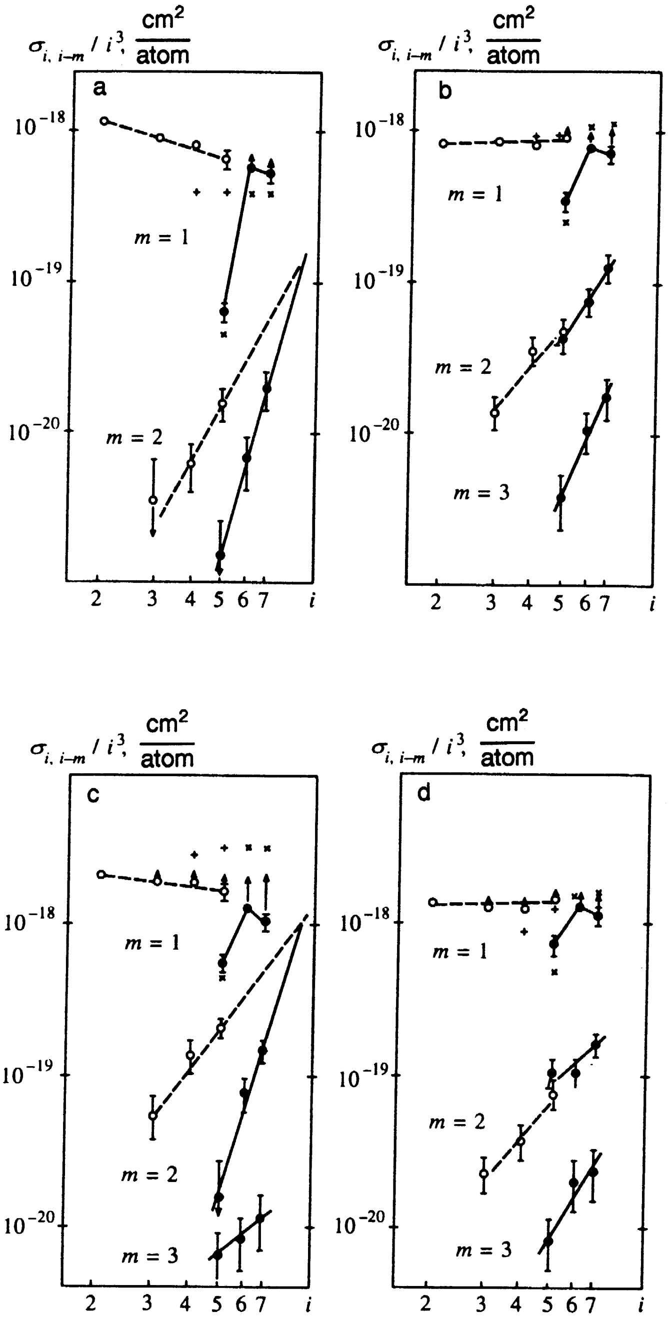

FIG. 4. Dependence of $\sigma_{i,i-m}/i^3$ on the ion charge $i=2$–7 in helium (a), nitrogen (b), neon (c), and argon (d). Experiment: ○ – for ions with a filled K shell; ● – for ions with a vacancy in the K shell. The values of the total charge-exchange cross sections σ_i are indicated by an arrow. Calculation: + – for ions with a filled K shell; × for ions with a vacancy in the K shell.

Such calculations were performed to determine the cross sections for the capture of one electron by unexcited nitrogen ions with charges $i=4$–7, as well as by metastable $N^{5+}(1s2s)$ ions, in helium, nitrogen, neon, and argon. Since the OBK approximation gives overestimated values for charge-exchange cross sections, the calculated values of $\sigma_{i,i-1}^{\rm OBK}$ were normalized to the experimental values of $\sigma_{54}(1s^2)$ for unexcited $N^{5+}(1s^2)$ ions in nitrogen. As a result of this adjustment, all the calculated values of $\sigma_{i,i-1}^{\rm OBK}$ were reduced by a factor of 9 (Fig. 4).

The values of $\sigma_{54}^{\rm OBK}(1s2s)$ for electron capture by metastable $N^{5+}(1s2s)$ ions were calculated with consideration of the influence of postcollisional autoionization, which results in an appreciable decrease in the experimentally measured cross sections. The capture of an electron by $N^{5+}(1s2s)$ ions in states with principal quantum number $n>2$ produces excited lithium-like $N^{4+}(1s2snl)$ ions in doublet and quartet states. All the doublet states make transitions by means of ordinary autoionization to the ground state of $N^{5+}(1s^2)$ ions after a time $\tau\sim10^{-13}$–10^{-15} s (i.e., at a distance of 10^{-5}–10^{-7} cm from the charge-exchange target T_2), and the quartet states with $n>3$ decay after a time equal to 10^{-7}–10^{-8} s by means of radiative transitions to one of the low-lying metastable $(1s2s2p)^4P_j$ states. The lifetime of the longest-lived state with $j=5/2$ is $(6.8\pm1.6)\times10^{-8}$ s. The lifetimes of the short-lived states with $j=1/2$ and 3/2 are approximately an order of magnitude smaller.[14] It follows from statistical arguments that when an electron is captured by helium-like ions in the $(1s2s)$ state, the relative number of lithium-like particles formed in quartet states with $j=5/2$, 3/2, and 1/2 is equal to $(2j+1)/24$. Hence it follows that the experimentally measured cross section for electron capture by metastable helium-like ions can be written in the form[4]

$$\sigma_{54}(1s2s)=\sigma(1s)+A\left[\sigma_{2p}+\sum_{n\geqslant3}\sigma(nl)\right], \tag{5}$$

where

$$A=v(24L)^{-1}\sum_j\left\{(2j+1)\tau_j\exp\left(-\frac{R}{\tau_jv}\right)\right.$$
$$\left.\times\left[1-\exp\left(\frac{-L}{\tau_jv}\right)\right]\right\},$$

τ_j is the lifetime of the lithium-like particles with total angular momentum j, $L=40$ cm is the length of the collision chamber, and $R=20$ cm is the distance from the exit channel of the collision chamber to the center of the last analyzing magnet M_3 (see Fig. 1). For N^{5+} nitrogen ions, $A=0.12$.

The mechanism for de-excitation as a result of the Stark mixing of states in the electric field appearing when a fast charged particle passes by a target atom has been discussed in the literature in recent years. Such fields with strengths up to 10^9 V/cm have been observed in plasma sources.[20] Indirect evidence of the occurrence of the Stark splitting of excited states of ions in a solid has also been obtained in experiments on the dissociation of molecular ions[21] and on the splitting of excited states in a solid.[22] It was shown in Refs. 23 and 24 that the relative intensities of the Lyman lines of Kr^{35+} ions passing through gaseous media, as well as their polarization, agree with the theoretical estimates. However, in experiments with solid-state targets, an appreciable decrease in the measured values in comparison with gases was discovered. This phenomenon was attributed to the more prolonged Stark mixing of the states.

The electric fields appearing as a charged particle passes by a target atom exist for a very short time, $t_1\sim10^{-17}$ s (Refs. 25 and 26), during which the electron cloud of the atom has no time to deform, and therefore the effect of the field is diminished significantly.

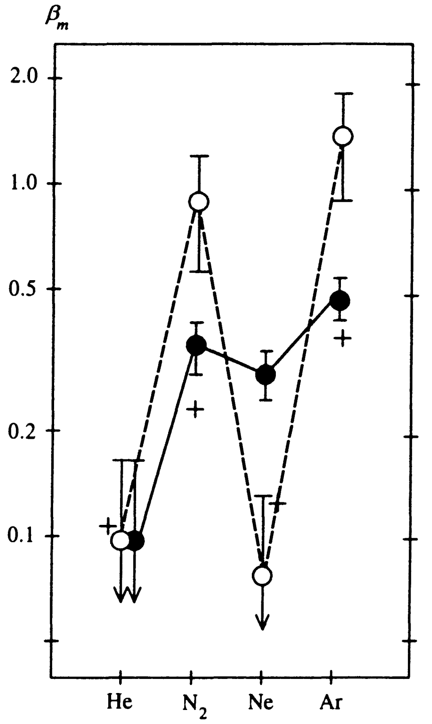

FIG. 5. Values of the ratio $\beta_m=\sigma_{5,5-m}(1s2s)/\sigma_{5,5-m}(1s^2)$ in helium, nitrogen, neon, and argon. Experiment: ● – for $m=1$; ○ – for $m=2$. Calculation: + – for $m=1$.

In a rarefied gas target, the time between successive collisions $t_2^g\sim10^{-6}$ s. At the same time, in a solid target, where the density of the medium is increased $\sim10^{11}$ fold, the time between collisions $t_2^s\sim10^{-17}$ s, i.e., it is comparable to the lifetime t_1 of the field in a single collision. This suggests that the lifetime of such a field in a solid target is determined by the transit time of the charged particle within the target $t_3\sim(10^2t_1-10^3)t_1$.

Therefore, we assume that the Stark mixing of excited states of ions is possible only when they move in solid targets.

4. RESULTS

The experimental cross sections $\sigma_{i,i-1}$ for the capture of one electron by ground-state nitrogen ions increase monotonically with increasing ion charge i approximately as i^{k_1} in all media (Fig. 4). In helium we have $k_1=2.4$ over the entire range of i from 2 to 7. In heavier media, i.e., in nitrogen, neon, and argon, $k_1\approx3$ for ions with $i=2$–5, and the value decreases to $k_1=1.5$–2 in the range $i=4$–7. At the same time, the calculated cross sections do not exhibit any weakening of the dependence of $\sigma_{i,i-1}^{\rm OBK}$ on i in the range of large charges $i=5$–7: a value $k_1^{\rm OBK}\approx3.0$–3.3 is observed over the entire range of i from 4 to 7 in all media (Fig. 4).

The values of $\sigma_{54}(1s2s)$ for electron capture by metastable $N^{5+}(1s2s)$ ions are significantly smaller than the values of $\sigma_{54}(1s^2)$ for unexcited $N^{5+}(1s^2)$ ions due to postcollisional autoionization: the ratio $\beta_1=\sigma_{54}(1s2s)/\sigma_{54}(1s^2)$ amounts to $\beta_1\approx0.1$, ≈0.55, ≈0.32, and ≈0.48 in helium, nitrogen, neon, and argon, respectively (Fig. 5). The calculated values of $\sigma_{54}^{\text{OBK}}(1s2s)$ in all four media are 30% less than the corresponding experimental values of $\sigma_{54}(1s2s)$, and the ratio $\beta_1^{\text{OBK}}=\sigma_{54}^{\text{OBK}}(1s2s)/\sigma_{54}^{\text{OBK}}(1s^2)$ between the cross sections for electron capture by metastable and unexcited N^{5+} ions has the values $\beta_1^{\text{OBK}}=0.11$, 0.24, 0.13, and 0.39 in helium, nitrogen, neon, and argon (Fig. 5), i.e., values which are 1.5 ± 0.5 smaller than the experimentally determined values of β_1.

The dependence of the cross sections $\sigma_{i,i-2}$ for the capture of two electrons on i is different in different media, but in all cases the cross sections $\sigma_{i,i-2}$ increase with increasing i more strongly than do the cross sections $\sigma_{i,i-1}$ for single charge exchange. In helium and neon the cross sections $\sigma_{i,i-2}$ for ions with $i=3-5$ (i.e., for unexcited nitrogen ions with a filled K shell) increase with increasing i as i^{k_2}, where $k_2=5-6\approx 2k_1$. When i increases further (i.e., upon the transition to nitrogen ions with a K vacancy), the cross sections $\sigma_{i,i-2}$ exhibit a sharp jump, which reaches an order of magnitude, and the exponent k_2 in the power dependence of $\sigma_{i,i-2}$ on i increases to $k_2\approx 10$. In nitrogen and argon, where the values of $\sigma_{53}(1s^2)$ and $\sigma_{53}(1s2s)$ for unexcited and metastable ions are essentially identical, the value of k_2 over the entire range of i from 3 to 7 is close to $k_2\approx 5-6\approx 2k_1$.

The value of the ratio $\beta_2=\sigma_{53}(1s2s)/\sigma_{53}(1s^2)$ between the cross sections for the capture of two electrons by metastable and unexcited N^{5+} ions varies upon passage from one medium to another from $\beta_2=0.1\pm0.1$ in helium and neon to $\beta_2=0.9\pm0.3$ in nitrogen and $\beta_2=1.4\pm0.6$ in argon, i.e., considerably more strongly than the corresponding ratio $\beta_1=\sigma_{54}(1s2s)/\sigma_{54}(1s^2)$ for the single charge exchange of N^{5+} ions (Fig. 5).

The cross sections $\sigma_{i,i-3}$ for the capture of three electrons obtained in nitrogen, neon, and argon for $i\geqslant 4$ are approximately two orders of magnitude smaller than the cross sections $\sigma_{i,i-1}$ for single charge exchange. In nitrogen and argon the dependence of $\sigma_{i,i-3}$ on i is stronger than the dependence for $\sigma_{i,i-2}$, and the corresponding values of the exponent in the power dependence on the ion charge is $k_3\approx 8-9\approx 3k_1$. In addition, the values of $\sigma_{i,1-2}/\sigma_{i,i-3}$ are close to the values of $\sigma_{i,i-1}/\sigma_{i,i-2}$ and decrease from ~ 20 for $i=5$ to ~ 7 for $i=7$. In neon the cross sections $\sigma_{i,i-3}$ depend on i less strongly than do the cross sections $\sigma_{i,i-2}$ for double charge exchange, and the corresponding exponent is $k_3\approx 4-5$.

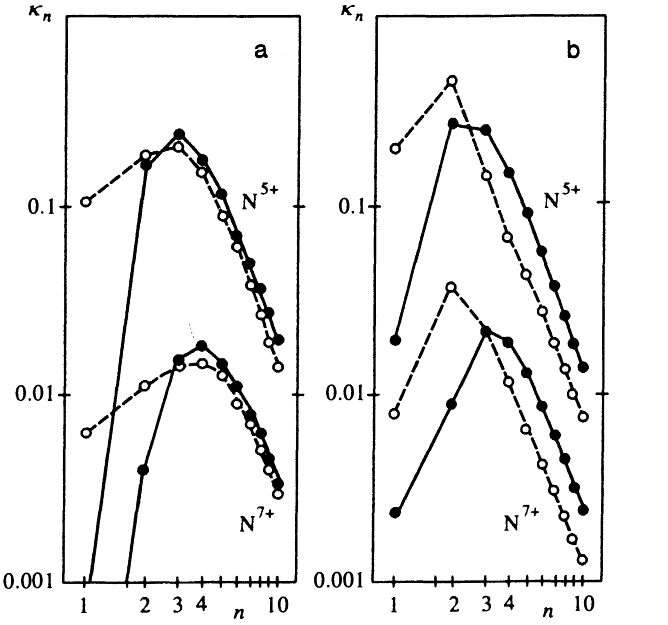

FIG. 6. Values of the populations κ_n of excited states of $N^{5+}(1s2s)$ and N^{7+} (reduced by a factor of 10): a) in helium (●) and nitrogen (○); b) in neon (●) and argon (○).

5. DISCUSSION OF RESULTS

5.1. Single charge exchange

To account for the different degrees of reduction of the ratios $\sigma_{54}(1s2s)/\sigma_{54}(1s^2)$ for metastable and unexcited N^{5+} ions in different media (from $\beta_1\approx 0.1$ in helium to $\beta_1\approx 0.5$ in argon), we utilize the conclusions in Ref. 1, which assert that electron capture by a fast ion is most likely to occur from shells of target atoms with energies of the atomic electrons $I_t=I_v/3$ where $I_v=m_e v^2/2$ is the kinetic energy of the electron), these electrons being captured predominantly in unoccupied states of the fast ions with $I_n\sim I_t$. Thus, electron capture by an N^{5+} ion is most probable in states with $n\geqslant 2$ (the binding energy of an electron in the L shell is $I_L=103$ eV). In this case capture occurs from the helium K shell, from the L shells of nitrogen and neon atoms, and from the M shell of argon atoms. The binding energy of the captured electrons is $I_t\sim 15-50$ eV. Electron capture occurs with a smaller probability in the unoccupied state of the K shell of $N^{5+}(1s^2)$ ions with $I_K=490$ eV. In this case electron capture is likely to occur from the K shell of nitrogen atoms ($I_t\approx 400$ eV) and from the L shell of argon atoms ($I_t\approx 300$ eV). In neon, in which the binding energy of the K electrons is $I_t\approx 870$ eV, the probability of electron capture in the $1s$ state is reduced significantly, and it nearly vanishes when ions pass through helium.

These qualitative arguments are supported by calculations of the populations of the states of nitrogen ions $\kappa_n=\sigma_n/\Sigma\sigma_n$ with the principal quantum number n (Fig. 6). According to the calculations for N^{4+} ions, the values of κ_n achieve a maximum at $n\approx 2$ in all four media. As the ion charge i increases from 4 to 7, the position of the maximum κ_n shifts to $n\approx 4$ in helium and nitrogen and to $n\approx 3$ in neon. In argon the position of the maximum remains virtually unchanged and close to $n\approx 2$ over the entire range of i from 4 to 7. Here the population of the $1s$ state for $N^{5+}(1s2s)$ ions is lowest in helium $[\kappa_1(\text{He})\approx 3\times10^{-4}]$ and in neon $[\kappa_1(\text{Ne})\approx 2\times10^{-2}]$. In nitrogen and argon the population of the $1s$ state is considerably higher: $\kappa_1(N_2)\approx 0.1$ and $\kappa_1(\text{Ar})\approx 0.2$. These values are only half the population at the maximum of the distribution of κ_n as a function of n (Fig. 6). It can be concluded on the basis of a comparison of the experimental and calculated values of $\beta_1=\sigma_{54}(1s2s)/\sigma_{54}(1s^2)$ (Fig. 5) that the real population of the $1s$ state should be higher than the value following from the calculations in the OBK approximation. A similar conclusion was drawn in Ref. 5, where it was shown that the experimental distribution of κ_n as a function of n for F^{7+} fluorine ions with a velocity $v \approx 3.4$ au has a maximum at $n \simeq 2$, while the calculations in the OBK approximation give $n \simeq 4$.

5.2. Multiple charge exchange

Like single charge exchange, autoionization should have a significant influence on the cross section for the capture of two electrons by $N^{5+}(1s2s)$ ions. If both electrons are captured in a state of the fast ion with $n \geqslant 2$, the $N^{3+}(1s2snln'l')$ ions formed autoionize almost immediately within a distance $L<5$ cm from the site of their formation, and the experimentally measured value of the mean cross section $\sigma_{53}(1s2s)$ is diminished appreciably. In the capture of at least one electron in an unoccupied state in the K shell, the $N^{3+}(1s^2 2sn'l')$ ions obtained are not autoionizing, and the measured value of $\sigma_{53}(1s2s)$ does not decrease.

In fact, in helium and neon, in which the probability of electron capture to the $1s$ state is lowered appreciably, the measured value of $\sigma_{53}(1s2s)$ is smaller than $\sigma_{53}(1s^2)$ by at least an order of magnitude. On the other hand, in nitrogen and argon, where the probability of electron capture to the $1s$ state is markedly higher, the measured values of $\sigma_{53}(1s2s)$ are not diminished, and they agree to within the experimental error with the values of $\sigma_{\kappa 53}(1s^2)$ (Fig. 5). While the reduction of $\sigma_{53}(1s2s)$ relative to $\sigma_{53}(1s^2)$ in helium and neon is obvious, it is difficult to explain the total absence of such a reduction in nitrogen and argon. In media with a binding energy of the orbital electrons close to the binding energy of the unoccupied state of the $N^{5+}(1s2s)$ ion, this phenomenon may well result from the fact that the simultaneous capture of two electrons requires a longer interaction time than does single charge exchange and therefore closer approach of the ion and the target atom.

In analogy to $N^{5+}(1s2s)$ ions, it can be assumed for N^{6+} and N^{7+} ions that the capture of two electrons in helium and neon also leads to the formation of autoionizing states of N^{4+} and N^{5+} ions and, as result, to reduction of the experimental cross sections σ_{64} and σ_{75} by factors of 5 and 3, respectively, relative to the values of these cross sections extrapolated from the range $i \leqslant 5$, which are indicated by the dashed line in Fig. 5. In nitrogen and argon, in which the probability of electron capture in the K shell is high, the total undiminished values of the cross sections $\sigma_{i,i-2}$ are measured experimentally.

Just as in the case of the capture of two electrons, autoionization probably results in a considerable decrease in the measured cross sections $\sigma_{i,i-3}$ for the capture of three electrons in neon. To evaluate the reduction of these cross sections in neon, we assume that this medium maintains the empirical relationships between the cross sections for the capture of one, two, and three elections in nitrogen and argon: $\sigma_{i,i-1}/\sigma_{i,i-2} \approx \sigma_{i,i-2}/\sigma_{i,i-3}$. It follows from these relations that the cross sections $\sigma_{i,i-3}$ in neon are reduced from their original values by a factor of 4 to 10 as i increases from 5 to 7.

5.3. Probability of radiative de-excitation

As we know,[27,28] highly excited states of ions can decay along two channels: an autoionization channel and a radiative channel. An estimate of the probability of the radiative decay of excited nitrogen ions can be obtained from the dependence of the cross sections $\sigma_{i,i-2}$ on i found in the present work. As is seen from Fig. 4, the experimental cross sections $\sigma_{i,i-2}$ in helium and neon for ions with charges $i=5-7$ and a vacancy in the K shell, which are reduced as a result of postcollisional autoionization, increase with i considerably more rapidly than the extrapolated cross sections $\langle \sigma_{i,i-2} \rangle$ for ions with a filled K shell. The stronger dependence of the cross sections $\sigma_{i,i-2}$ on i for ions with a vacancy in the K shell points to a diminished role of the autoionization channel for the decay of two-electron excitations and a corresponding increase in the probability W_r of radiative transitions as the ion charge i increases from 5 to 7.

The reason for the decrease in the probability of autoionization upon the transition from N^{5+}(1s2s) ions to N^{7+} ions is the increase the principal quantum number n of the state into which electrons are predominantly captured. Here the probability of autoionization should decrease as n^{-3} (Ref. 28). According to the calculations performed in the present work, when the charge i of the nitrogen ions increases from 5 to 7, the values of n increase from $n \simeq 3$ to $n \simeq 4$ in helium and from $n \simeq 2$ to $n \simeq 3$ in neon (see Fig. 6). An increase in the values of n with increasing charge i of the nitrogen ions was also noted in Refs. 6–8. When N^{5+} ions with velocity $v=0.4$–0.5 passed through helium and hydrogen, electron capture in states with $n \simeq 2$ and $n \simeq 3$, respectively, turned out to be most probable. In electron capture by N^{7+} nuclei, the optimal values of n increased to $n \approx 3$ in helium and to $n=3-4$ in hydrogen.

The ratio $\sigma_{i,i-2}/\langle \sigma_{i,i-2} \rangle$ between the experimental cross sections $\sigma_{i,i-2}$ in helium and neon for ions with $i=5-7$ and a vacancy in the K shell to the values of $\langle \sigma_{i,i-2} \rangle$ extrapolated into the range of charges $i>5$ for ions with a filled K subshell can be taken as an estimate of the probability W_r of the radiative decay of a two-electron excitation (Fig. 7). The value of W_r increases from $\sim 10\%$ for $i=5$ to $\approx 25\%$ for $i=7$ and can be described by the expression

$$W_r = \frac{\sigma_{i,i-2}}{\langle \sigma_{i,i-2} \rangle} = \frac{\eta}{(\eta+1)}, \tag{6}$$

where $\eta = 1.6(i/10)^4$. The values of W_r obtained are in good agreement with the theoretical estimate in Ref. 27.

5.4. Total charge-exchange cross section

The experimentally measured appreciable weakening of the dependence of the cross sections $\sigma_{i,i-1}$ on i in the range $i=5-7$ is probably due to competition between single and multiple charge-exchange processes. An analysis of the cross sections $\sigma_{i,i-1}$ and $\sigma_{i,i-2}$ presented in Fig. 4 points out a clear-cut correlation between the weakening of the dependence of $\sigma_{i,i-1}$ on i and the value of the ratio $\sigma_{i,i-2}/\sigma_{i,i-1}$ (here the extrapolated values of the cross sections $\langle \sigma_{i,i-2} \rangle$ corrected for autoionization, which are indi-

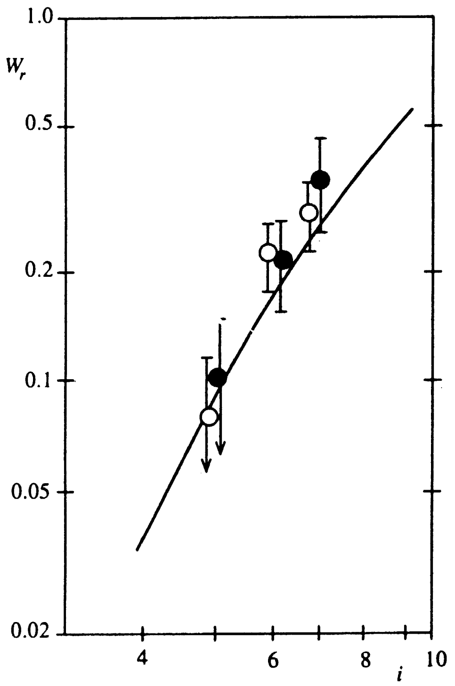

FIG. 7. Dependence of W_r on the ion charge i: points – experiment in helium (●) and in neon (○); solid curve – calculation based on Eq. (6).

cated in Fig. 4 by a dashed line, were taken as the cross sections $\sigma_{i,i-2}$ in helium and neon): the greater the value of this ratio, the smaller the value of the exponent k_1 in the power dependence. To account for this correlation, let us consider the total charge-exchange cross section of fast ions

$$\sigma_i = \sum_m \sigma_{i,i-m}. \qquad (7)$$

The multiplier m takes into account the fact that the charge of the ion decreases by m units as a result of m-fold charge exchange. In the range $i<5$ the values of σ_i are essentially the same as the cross sections $\sigma_{i,i-1}$ for the capture of one electron and become significantly greater than these cross sections when $i=7$, at which the values of $\sigma_i/\sigma_{i,i-1}$ in helium, nitrogen, neon, and argon are approximately 1.1, 1.4, 1.7, and 1.3, respectively. The dependence of the total charge-exchange cross sections σ_i on i was found to be identical and close to $\sigma_i \propto i^3$ in all media.

An analysis of the experimental data on the charge-exchange cross sections of oxygen and fluorine ions[29–31] revealed that the dependence of the cross sections $\sigma_{i,i-1}$ on i for these ions with charges $i>Z-2$ (Z is the charge of the nucleus of the ion) weakens markedly, while the corresponding values of the total charge-exchange cross sections $\sigma_{i,c}$ increase monotonically in nearly all cases as $\sigma_i \propto i^{k_1}$, where the values of k_1 for $v \approx 5$ are close to 3.

Equation (7) for the cross sections $\sigma_{i,c}$ follows from the model of the description of collisions between independent particles in Ref. 20, in which

$$\sigma_{i,i-1} = C_1^p \bar{w}(1-\bar{w})^{p-1}\pi\bar{b}^2,$$

$$\sigma_{i,i-2} = C_2^p \bar{w}^2(1-\bar{w})^{p-2}\pi\bar{b}^2,$$

....

$$\sigma_i = \sum m\sigma_{i,i-m} = p\bar{w}\pi\bar{b}^2, \qquad (8)$$

where $\bar{w}$ and $\bar{b}$ are the mean probability of electron capture and the corresponding impact parameter, and p is the number of equivalent electrons in the shell of the target atom. The validity of the model is confirmed by the common empirical dependence of the cross sections for the capture of m electrons on i: $\sigma_{i,i-m} \propto i^{3m} \propto \bar{w}^m$.

The theoretical calculations of the charge-exchange cross sections of lithium ions in atomic nitrogen (i.e., in a target with a single electron, in which there are no multiple charge-exchange cross sections) performed in Ref. 32 led to a cubic dependence on i, in agreement with experiment. The calculations were performed in various approximations: the semiclassical (OBK) approximation, the eikonal approximation, the continuum intermediate-state approximation, and the continuum distorted-wave approximation. The calculations performed in the present work in the OBK approximation to determine the charge-exchange cross sections of nitrogen ions with charges $i=4-7$ in many-electron media also lead to a cubic dependence of the charge-exchange cross sections on i.

6. CONCLUSIONS

An investigation of the charge-exchange cross sections of nitrogen ions in various media has revealed an appreciable influence of the postcollisional autoionization process on the values of the experimentally measured capture cross sections of one or more electrons. For metastable helium-like N^{5+} ions the cross sections for the capture of one electron were found to be 2–10 times smaller in all media investigated, the greatest reduction being observed in helium and neon, where the probability of electron capture in the K shell is small. At the same time, in the case of the capture of two or three electrons by ions with a K vacancy, autoionization results in considerable reduction of the measured cross sections only in helium and neon and does not have an appreciable influence on the values of the corresponding cross sections in nitrogen and argon.

The degree of reduction of the cross sections for double charge exchange in helium and neon has made it possible to estimate the probability of radiative de-excitation of nitrogen ions.

When the total charge-exchange cross sections σ_i determined with consideration of postcollisional autoionization were considered, it was established that the dependence of the cross sections σ_i on the ion charge i is nearly cubic in all the media investigated. This experimental finding is consistent with the independent-electron model, as well as with the calculations of the charge-exchange cross sections in the OBK approximation.

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