Experimental study of the loss and capture of electrons by fast multiply charged nitrogen and neon ions in various gases

I. S. Dmitriev, Yu. A. Tashaev, V. S. Nikolaev, Ya. A. Teplova, and B. M. Popov

Nuclear Physics Institute of the Moscow State University
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Measurements were made of the cross sections for the loss and capture of one or two electrons by nitrogen and neon ions with charges from 1 to 7 or 8 as they pass through helium, nitrogen, neon and argon with velocities v equal to 2.7×10^8, 4×10^8, and 8×10^8 cm/sec. At $v\leq4\times10^8$ cm/sec a substantial difference was observed between the cross sections for electron capture in states with different values of the principal quantum number n at equal binding energies. A nonmonotonic dependence of the investigated cross section of the charge Z_c of the nuclei of the atoms of the medium at $v\sim10^9$ cm/sec is observed and investigated.

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1. INTRODUCTION

It is known that, in accordance with the periodic variation of the properties of the outer electron shells of atoms and ions, the average energy losses and ranges of charged particles have a nonmonotonic dependence on the charges Z and Z_c of the nuclei of the particle and atom of the target.[1–3] The relative number of vacancies produced in the inner shells of iodine and chlorine atoms in collisions with atoms has also been found to be a nonmonotonic function of Z_c.[4,5] At the same time, a study of the cross sections for the loss and capture of electrons by fast ions in helium, nitrogen, argon, and krypton has shown that they have a nonmonotonic dependence only on the charge of the ion nuclei, and the electron-loss cross section has been observed to decrease with increase of Z_c from 18 to 36.[6] To examine the singularities of the cross sections of the losses and capture of electrons by fast ions as they pass through different gases, and to verify the assumption that the cross sections may have a nonmonotonic dependence on Z_c, we have measured these cross sections for nitrogen and neon ions with charges i from 1 to 7 or 8 as they passed through neon, a gas in which the outer electrons have the largest average velocities, as well as through helium, nitrogen, and argon at ion velocities v equal to 2.7×10^8, 4×10^8, and 8×10^8 cm/sec. Some of the results were discussed briefly in[7].

2. DESCRIPTION OF EXPERIMENT

The electron loss and capture cross section were determined by mass spectroscopy with the apparatus described in[8]. In the present experiment, the ions N^{+1}, N^{+3}, Ne^{+2}, and Ne^{+3} were extracted from a 72-cm cyclotron. Ions with other charges were produced either by charge exchange of the ions with the residual gas in the ion duct, or by passing the accelerated particles through a celluloid film approximately 2–3 μg/cm² thick, placed at a distance $R\approx14$ cm from the center of the magnetic separator used to direct ions with a definite charge i into the collision chamber. For most ions, in addition to the cross sections for the loss and capture of one electron $\sigma_{i,i\pm1}$, we determined also the cross sections $\sigma_{i,i\pm2}$, for the loss and capture of two electrons, and in some cases also the cross sections $\sigma_{i,i\pm3}$ for the loss and capture of three electrons. The errors in the estimate of the cross sections $\sigma_{i,i\pm1}$, $\sigma_{i,i\pm2}$, and $\sigma_{i,i\pm3}$ do not exceed 15, 25, and 35%, respectively.

The cross sections $\sigma_{i,i\pm m}$ (m is the number of lost or captured electrons) for the nitrogen and neon ions with charges $i\leq4$ in helium, nitrogen, and argon agreed in most cases, within the limits of experimental errors, with the results of our earlier measurements,[8–11] while the values of σ_{12} and σ_{13} for neon ions in neon at $v=2.7\cdot10^8$ cm/sec agreed with the cross sections given in[12,13]. Most cross sections obtained for the first time are shown in Figs. 1 and 2. In all cases, the cross sections are given per atom of the medium.

It follows from the experiments described in[14] and

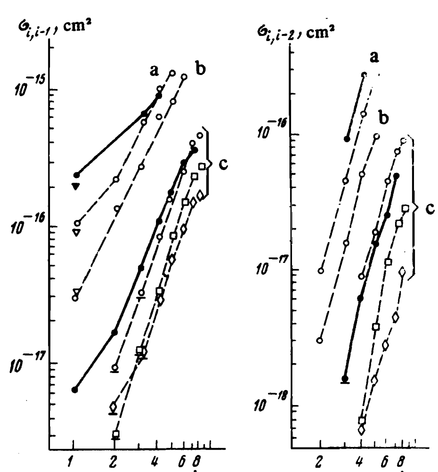

FIG. 1. Cross sections for the capture of one ($\sigma_{i,i-1}$) and two ($\sigma_{i,i-2}$) electrons by nitrogen ions (dark points and solid lines) and neon ions (light points and dashed lines) in helium (◊), nitrogen (□) and neon (●, ○) as functions of the ion charge i at ion velocities v equal to 2.7×10^8 (a), 4×10^8 (b) and 8×10^8 (c) cm/sec. A bar under the symbol denotes a cross section determined by interpolation of the cross sections for other velocities from[8–11]; ▼, ▽—cross sections from[13].

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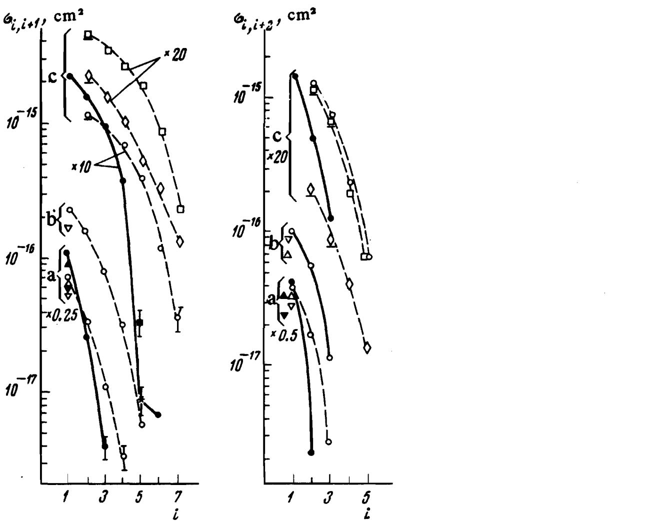

FIG. 2. Cross sections for the capture of one ($\sigma_{i,i-1}$) and two ($\sigma_{i,i-2}$) electrons by nitrogen and neon ions as functions of the ion charge. The notation is the same as in Fig. 1. *—cross sections for unexcited N^{+5} ions, and ■—for ions N^{+5} that have passed through a solid film. ▲, △ and ▼, ▽—cross sections from[13,12].

from the results of[15] that all the obtained cross sections $\sigma_{i,i\pm m}$, with the only exceptions of the cross sections for electron loss by N^{+5} ions at $v=8\cdot10^8$ cm/sec, pertain to unexcited particles. The beam of N^{+5} ions was produced by passing the ions through a celluloid film, and contained $(13\pm2)\%$ metastable particles.[15] The cross section for electron loss by the unexcited N^{+5} ions were obtained from the obtained values of σ_{56} by the method described in[15].

3. RESULTS OF INVESTIGATION OF ELECTRON-CAPTURE CROSS SECTIONS

1. Relations between the cross sections for the capture of one electron by different ions

In all the investigated media, the cross sections $\sigma_{i,i-1}$ for the nitrogen and neon ions having equal charges i are practically equal at large values of i. At $v=8\cdot10^8$ cm/sec this equality of the cross section is observed at $i\geqslant6$. With decreasing v, the value of i starting with which the cross section $\sigma_{i,i-1}$ is determined only by the ion charge decreases and depends on the medium. An analysis of the results shows that this equality of the cross section occurs when the condition $I_{i-1}\geqslant\bar{I}=\frac{1}{3}I_v+3I_c$ is satisfied, where I_{i-1} is the binding energy of the outer electrons in the atoms of the medium, and $I_v=\frac{1}{2}\mu v^2$ is the transport energy of the electron.

As indicated previously,[15] a qualitatively similar result follows also from the simplest quantum-mechanical Brinkman-Kramers formula[16,17] for the cross section of the capture of an atomic electron by nuclei with charge Z, provided that the quantity Z/n in this formula is replaced in the case of fast ions with $N=Z-i>0$ electrons by the quantity $[I(n)/I_0]^{1/2}$, while $2n^2$ is replaced by the number $p(n)$ of the unoccupied states with principal quantum number n. We then have

$$\sigma_{i,i-1}=\frac{2^{17}}{5}\pi a_0^2 I_0^{7/2} I_v^4 Z_c^5 \sum_{n=n_0}^{\infty}\frac{p(n)[I(n)]^{5/2}}{\{I_v^2+2I_v[I(n)+I_c]+[I(n)-I_c]^2\}^5} \qquad (1)$$

where $I_0=13.6$ eV and $a_0=5.3\times10^{-9}$ cm. It follows therefore that at $I(n_0)>\frac{1}{3}I_v+I_c$, where $I(n_0)$ is the average binding energy of the electron in the vacant states of the unfilled electron shell closes to the nucleus and with principal quantum number $n=n_0$, the electron is captured predominantly in excited states with $n>n_0$, and therefore the cross section $\sigma_{i,i-1}$ is practically independent of the number N of the electrons contained in the ion, and is the determined by the ion charge i and velocity v.

At small i, when $I(n_0)<\frac{1}{3}I_v+I_c$, the electron capture, according to (1), is predominantly into states with $n=n_0$, so that the cross sections $\sigma_{i,i-1}$ for the nitrogen ions are always larger than for neon ions having the same charge i, and the ratios of these cross sections in different media differ by not more than 25%. The plots of the cross sections $\sigma_{i,i-1}$ divided by the number of vacancies $p_i(n_0)$ in the unfilled electron shell closest to the nucleus, i.e., of the quantities $S_i=\sigma_{i,i-1}/p_i(n_0)$ for the neon and nitrogen ions with electron numbers N from 2 to 9, as functions of I_{i-1}, are in accordance with (1) practically identical curves close to the $I(n_0)$ curves (Fig. 3). The previously considered[15] values of S_i for ions of other light elements with 2 and 3 electrons also fall on the same curves, as well as the experimental cross sections for electron capture in states $2s$ and $2p$ by helium nuclei, determined on the basis of[18,19] for $v=2.7\cdot10^8$ cm/sec (Fig. 3).

At all v, the values of S_i for ions with $N=2-9$, for which $n_0=2$, turn out to be smaller than the values of S_i obtained from the results of[8,20–22] for nuclei and hydrogenlike ions with N equal to 0 or 1, for which $n_0=1$ (at the same values of I_{i-1}). The small relative difference between the values of S_i for ions with n_0 equal to 1 and 2 (i.e., for ions that capture electrons predominantly in the K and L shells), is observed in the region of small

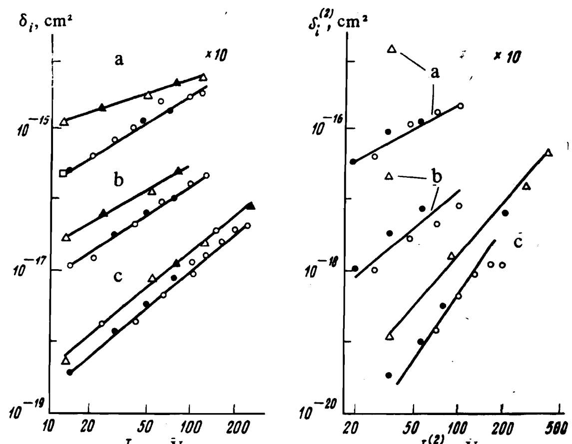

FIG. 3. Values of S_i and $S_i^{(2)}$ as functions of I_{i-1} and $I_{i-1}^{(2)}$ for nitrogen (●) and neon (○) ions, for atomic nuclei (△), and for hydrogenlike ions (▲) in nitrogen: a) $v=2.7\times10^8$, b) $v=4\times10^8$, and c) $v=8\times10^8$ cm/sec. The values of S_i for nuclei and hydrogenlike ions were taken from,[8,20–22] while the values for the nuclei were taken from[11,20,21]; (□) are the cross sections for the capture of an electron in states $2s$ and $2p$ for helium nuclei in nitrogen.[18,19]

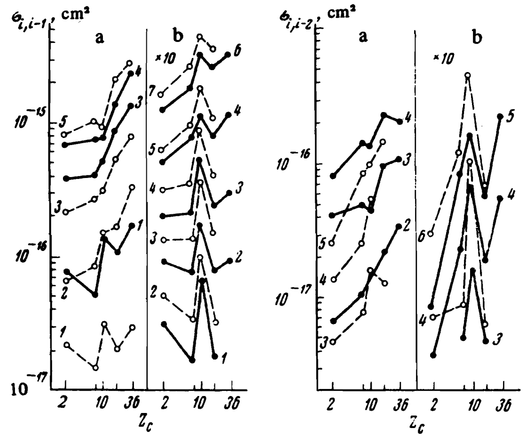

FIG. 4. Cross sections for the capture of one ($\sigma_{i,\,i-1}$) and two ($\sigma_{i,\,i-2}$) electrons by nitrogen ions (solid lines and dark points) and neon (dashed lines and light points) in various media with $Z_c = 2$, 7, 10, 18, and 36 at a) $v = 4\times10^8$ and b) $v = 8\times10^8$ cm/sec. The numbers indicate the charges i of the ions.

values of v and I_{i-1} (Fig. 3). It should be noted that at $v \geq 2.7\cdot10^8$ cm/sec the hydrogen and helium nuclei, as follows from the experimental cross sections for their capture of an electron in different states,[18,19,23–25] capture the electron in the 1s state in no less than in 80% of the cases. The dependence of S_i on I_{i-1} for different I_c and v corresponds qualitatively to formula (1), but the dependence of S_i on the principal quantum number n_0, which we have observed, does not follow from (1).

2. Dependence of the cross sections for the capture of one electron on the charge Z of the nuclei of the atoms of the medium

With increasing Z_c, the values of $\sigma_{i,i-1}$ for the nitrogen and neon ions with charges i from 2 to 5 at $v = 2.7\cdot10^8$ and $v = 4\cdot10^8$ cm/sec increase on the average, although the cross sections in ion, compared with the cross sections in nitrogen and argon, are slightly lower for ions with large charges and slightly higher for singly charged ions. At $v = 8\cdot10^8$ cm/sec, however, the dependence of $\sigma_{i,i-1}$ on Z_c becomes essentially nonmonotonic. For ions with $i = 1$ and 2 the values of $\sigma_{i,i-1}$ in neon are approximately 3–4 times larger than in nitrogen and argon (Fig. 4). For ions with $i = 5$–8 the excess of $\sigma_{i,i-1}$ in neon over that in nitrogen and argon decreases to a factor 1.5–2. The latter is due to the fact that the dependences of the cross sections $\sigma_{i,i-1}$ on i and of the values of S_i on I_{i-1} in neon are almost the same as in helium and are weaker than in nitrogen and argon. With further increase of Z_c on going from argon to krypton, as shown by experiments with nitrogen ions,[8] the cross sections $\sigma_{i,i-1}$ again increase. A nonmonotonic dependence of $\sigma_{i,i-1}$ on Z_c for nitrogen and neon ions with $i = 2$–7 is observed also at $v = 10^9$ cm/sec.[7,26] However, at $v \approx 3\cdot10^9$ cm/sec, as follows from the experimental values of $\sigma_{i,i-1}$ for carbon and nitrogen nuclei in nitrogen, neon, and argon,[27] the values of $\sigma_{i,i-1}$ again increase monotonically with increasing Z_c. Thus the anomalous increase of the electron-capture cross sections in neon takes place only in a relatively small region of velocities $v \sim 10^9$ cm/sec.

In the analysis of these results it is necessary, of course to recognize that nitrogen, unlike the other emplpyed media, is a molecular gas, so that the considered electron capture cross sections per atom of the medium differ in general from the cross sections in the case of collision of the same particles with nitrogen atoms. There are no grounds, however, to expect an appreciable difference between these cross sections in the region $v \geq 3\cdot10^8$ cm/sec, since the proton charge exchange cross sections in atomic hydrogen are merely 20% smaller than in molecular hydrogen,[28,29] and the cross sections for the capture of an electron by the ions N^+ and O^+ in atomic oxygen are 40–50% larger than in molecular oxygen.[13] Thus, when molecular nitrogen is replaced by atomic nitrogen, the general character of the dependences of the electron capture cross sections per atom on Z_c remains essentially the same.

3. Cross sections for the capture of two electrons

In all media, at $v \leq 4\cdot10^8$ cm/sec, the cross sections $\sigma_{i,i-1}$ for the capture of two electrons are always larger for the nitrogen ions than for neon ions having the same charges i, whereas at $v = 8\cdot10^8$ cm/sec these values come closer together. At all ion velocities v, the ratio of the cross sections $\sigma_{i,i-2}$ for nitrogen ions to the cross sections for neon ions having the same charges i are always smaller in neon than in nitrogen and argon (by a factor of two on the average). Since in most cases the relation $I_{i-1}^{(2)} \equiv (I_{i-1}\cdot I_{i-2})^{1/2} \leq \bar{I}$ is satisfied, it follows that the electron is capture, in accord with the foregoing, predominantly in vacant states of the unfilled electron shell closest to the nucleus. The larger values of $\sigma_{i,i-2}$ for the nitrogen ions than for the neon ions correspond in this case to the larger number of vacancies p_i in the unfilled electron shell closest to the nucleus in the nitrogen atoms. The two-electron capture cross sections referred to a single pair of such vacancies, i.e., the quantities $S_i^{(2)} = 2\sigma_{i,i-2}/p_i(p_i - 1)$ for the nitrogen and neon atoms, fall on a common plot of $S_i^{(2)}$ against $I_{i-1}^{(2)}$, although in a number of cases the scatter of the individual points exceeds the limits of the measurement errors (Fig. 3). The values of $S_i^{(2)}$ for neon ions in nitrogen and argon are on the average somewhat lower, and in neon somewhat higher, than for nitrogen ions. At $v \leq 4\cdot10^8$ cm/sec, the dependence of $S_i^{(2)}$ on $I_{i-1}^{(2)}$ is close to the dependence of S_i on I_{i-1}, and at $v = 8\times10^8$ cm it becomes somewhat stronger. The values of $S_i^{(2)}$ for nitrogen and neon ions that capture electrons predominantly in vacant states of the L shell ($n_0 = 2$) are substantially smaller, at all v, than the values $S_i^{(2)}$ obtained from the results of[11,20,21] for atomic nuclei that capture electrons principally in vacant states of the K shell ($n_0 = 1$), and when v decreases from 8×10^8 to 2.7×10^8 cm/sec, the difference between these quantities increases from 3 to 10 times (Fig. 3).

The dependence of the cross sections $\sigma_{i,i-2}$ on Z_c agrees qualitatively with the corresponding dependence of the cross sections $\sigma_{i,i-1}$, but at $v = 8\cdot10^8$ cm/sec, particularly for neon ions, it is stronger (Fig. 4). The ratios

$$\eta_{i-1} = S_i^{(2)}/S_i = \frac{2}{p_i - 1}\frac{\sigma_{i,i-2}}{\sigma_{i,i-1}},$$

which are proportional to the average probability of electron capture in one of the vacant states, with $n=n_0$, of ions with charge $i-1$ amount to $(0.1-6)\times10^{-2}$. At $v=8\cdot10^8$ cm/sec they depend little on Z_c, except for a few cases: for neon ions in neon they are larger than in other gases and are close to ~0.05, while for nitrogen and neon ions in helium they are smaller by a factor 4–6 than in neon. For helium nuclei, the values of η_{i-1} are larger than for nitrogen and neon ions with the same values of I_{i-2}, by an amount that increases from 2 to 10 in nitrogen and from 5 to 20 in helium when v is decreased from 8×10^8 to 2.7×10^8 cm/sec.

4. Explanation of singularities in the cross sections for electron capture by fast ions in neon

Simple approximate theoretical formulas for the electron capture cross sections in collisions of complex atomic systems[30,31] were obtained by using the statistical model of atoms and had therefore led only to a monotonic dependence of $\sigma_{i,i-1}$ on Z_c. In particular, according to Bohr and Lindhard,[30] we have

$$\sigma_{i,i-1}=\pi a_0^2 Z_c^{1/3} i^2 (v_0/v)^3, \tag{2}$$

where $v_0=2.19\cdot10^8$ cm/sec.

At $v=8\times10^8$ cm/sec the values of $\sigma_{i,i-1}$ calculated by formula (2) for nitrogen and neon atoms with $i>4$ in helium, nitrogen, and argon differ from the experimental values by a factor of more than 1.5, and in neon the difference reaches a factor of 2.5. The explanation of the observed anomalous dependence of the cross sections $\sigma_{i,i-1}$ on Z_c should be sought in the singularities of the shell structures of the atoms of the medium. It should be noted in this connection that the dependence of the cross sections $\sigma_{i,i-m}$ on Z_c, obtained in our paper, agrees qualitatively with the Z_c-dependence obtained for the proton charge-exchange cross sections σ_{10} from calculations in[17] on the basis of the Brinkman-Kramers approximation.[16] The nonmonotonic dependence of these values on Z_c is connected with the fact that the charge-exchange cross section is determined by the capture, from the atoms of the medium, of electrons having orbital velocities v_c close to the ion velocity, and the electrons are captured from the atoms of the media in question mainly from the outer shell at $v\lesssim10^9$ cm/sec but from a deeper shell at $v\gtrsim2\cdot10^9$ cm/sec.[17] The average orbital velocities $\bar{v}_c$ of the electrons in the inner shells of the atoms of helium, nitrogen, neon, and argon are close, in units of v_0, to 1.7, 2.0, 2.8, and 2.7, respectively, if use is made of the Hartree-Fock wave functions,[32] and to 1.7, 2.0, 2.9, and 2.3 if Slater functions are used.[33] Since the value of v_c for the neon atoms turns out to be the largest, the number of electrons with orbital velocities $v_c\sim10^9$ cm/sec in these atoms, and consequently also the electron-capture cross sections at $v\sim10^9$ cm/sec turn out to be larger in neon than in the other considered media. The incomplete occupation of the outer M shell in argon atoms, due to the absence of $3d$ electrons, leads to an additional decrease of the number of electrons with orbital velocities $v_c\approx(0.7-1.5)\bar{v}_c$ and to a corresponding additional lowering of the cross sections of electron capture in argon at $v\sim10^9$ cm/sec.[17]

With increasing ion charge, as follows from (1), the capture of electrons from the inner shells of the atoms should assume a larger role, and consequently the degree of the increase of the electron capture cross sections in neon should decrease, as is indeed observed in experiment. At $v\gtrsim2\cdot10^9$ cm/sec, owing to the increased role of electron capture from the inner shells, the dependence of $\sigma_{i,i-1}$ on Z_c again becomes monotonic.[22,27] Thus, the appreciable excess of the electron capture cross sections in neon over those in argon and nitrogen at $v\sim10^9$ cm/sec can be attributed to the indicated singularities in the structure of the atoms.

4. RESULTS OF INVESTIGATION OF THE ELECTRON-LOSS CROSS SECTIONS

1. Relations between the cross sections for the loss of one electron by different atoms

In all the investigated media, the relations between the values of $\sigma_{i,i+1}$ for different ions are qualitatively the same. With increasing ion charge i the cross sections $\sigma_{i,i+1}$ for the nitrogen ions decrease more rapidly than for the neon ions, and at $i\geq3$ these cross sections are always smaller than for the neon ions with the same charge i, but at $i=1$ the relation is reversed (see Fig. 2). This difference between the cross sections $\sigma_{i,i+1}$ is due mainly to the difference between the number of the electrons q_i in the outer shells of the ions, and to the difference between their binding energies I_i. All this follows from an examination of the cross sections σ_i for the loss of an individual electron, which are expressed in terms of the experimentally measured cross sections $\sigma_{i,i+m}$ as follows[11]:

$$\sigma_i=\frac{1}{q_i}\sum_{m\geq1} m\sigma_{i,i+m}. \tag{3}$$

With increasing I_i, the cross sections σ_i decrease in all media, but not quite in like fashion. At $v=2.7\cdot10^8$ cm/sec the dependence of σ_i on I_i (in the I_i range from 30 to 100–150 eV) becomes weaker with increasing Z_c, but at $v=8\cdot10^8$ cm/sec the dependence of σ_i on I_i in neon and argon turns out to be stronger than in helium and in nitrogen (Fig. 5). Consequently at $v=8\cdot10^8$ cm/sec, for ions with $I_i\sim100$–250 eV, the dependence of σ_i on Z_c becomes nonmonotonic.

2. Dependence of the electron-loss cross sections on the charge C_z of the nuclei of the atoms of the medium

The dependences of the cross sections $\sigma_{i,i+1}$ and σ_i on Z_c changes strongly with changing ion charge i and with changing ion velocity v. At $v\leq4\cdot10^8$ cm/sec these cross sections increase as a rule when Z_c increases from 2 to 18, and with further increase of Z_c from 18 to 36, as follows from[10], they decrease (Fig. 6). At $v=8\cdot10^8$ cm/sec, the increase of the cross sections with increasing Z_c from 2 to 18 remains monotonic only for ions with charges $i=1$ and 2, for which $I_i<0.41\,I_v$, where $I_v=\frac{1}{2}\mu v^2=180$ eV. On the other hand for ions with $I_i=(0.6-1.4)\,I_v$, on the other hand, the cross sections in neon become smaller than in nitrogen and argon, by a

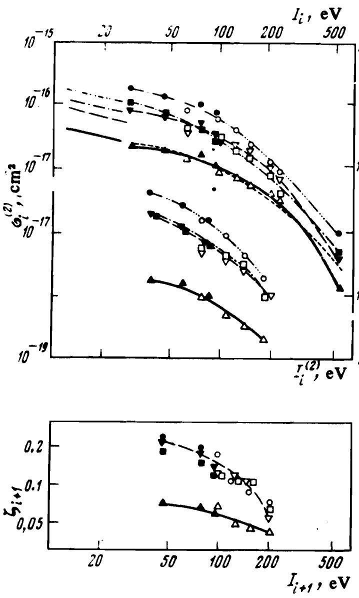

FIG. 5. Values of σ_i, $\sigma_i^{(2)}$, and σ_{i+1} as a function of the electron binding energy for nitrogen ions (dark points) and neon (light points) in helium (▲, △, solid lines), nitrogen (▼, ▽, dashes), neon (■, □, dash-dot lines) and argone (●, ○, dash and three dots) at an ion velocity $v = 8\times10^8$ cm/sec. The segments of the straight lines in the left-hand side of the figure were calculated from formula (5), dotted curve—cross section of electron losses for hydrogen-like ions in helium. [36,37]

factor 1.4–1.6 for the ions Ne^{+6} and Ne^{+7} with $I_i \approx 200$–250 eV. At the same time, for the N^{+5} ions with $I_i \approx 3I_v$ the dependence of the cross sections on Z_c remains monotonic. At $v = 10^9$ cm/sec, as follows from[7,26], the decrease of the electron-loss cross sections in neon is somewhat greater for all ions, and is observed also for singly and doubly charged neon and nitrogen ions and for N^{+5} ions. For the N^{+5} ions at $v = (2.6$–$3.8)\cdot10^9$ cm/sec, when $I_i < 0.3I_v$, the cross sections σ_{56} again increase monotonically with increasing Z_c.[27]

An examination of the experimental cross sections $\sigma_{i,i+1}$ for negative ions and atoms of hydrogen[22] and lithium atoms[34] has shown that at $v \sim (1$–$4)\cdot10^8$ cm/sec the values of $\sigma_{i,i+1}$ for these particles in neon is smaller than in nitrogen and argon. In this region of v, the indicated cross sections are close to the maximal value. Thus, lowering the electron-loss cross section in neon is observed for many ions in a relatively narrow velocity region $v \sim u_i \equiv (2I_i/\mu)^{1/2}$, where these cross sections reach a maximum.

To estimate the change of the electron-loss cross section because of the joining of the nitrogen atoms into a molecule, we can use the following information: at $v \geq 3\cdot10^8$ cm/sec the cross section for electron loss by hydrogen atoms is 20% higher in atomic hydrogen than in molecular hydrogen,[35] and the cross sections for electron loss by singly charged nitrogen and oxygen ions are 40% larger in atomic oxygen than in molecular oxygen.[13] For ions with high electron binding energy the difference between these cross sections should apparently be smaller, so that when the molecular nitrogen is replaced by atomic nitrogen the rate of decrease of the electron-loss cross sections when Z_c decreases from 7 to 10 should not decrease.

3. Cross sections for the loss of two electrons

In all media, the cross sections $\sigma_{i,i+2}$ decrease with increasing i more rapidly than $\sigma_{i,i+1}$. For singly charge nitrogen and neon ions, the values of σ_{13} are equal within the limits of measurement accuracy, and at $i \geq 2$ the cross sections $\sigma_{i,i+2}$ for neon ions are always larger than for nitrogen ions having the same charge i (Fig. 2). The causes of this relation between the values of $\sigma_{i,i+2}$ are the same as for $\sigma_{i,i+1}$, as can be ascertained by examining the cross sections for the loss of an electron pair $\sigma_i^{(2)}$,[11] the main contribution to which is made by the quantities $\sigma_{i,i+2}$:

$$\sigma_i^{(2)} = \frac{1}{C_q^2}\sum_{m\geq 2} C_m^2 \sigma_{i,i+m}. \tag{4}$$

In all cases the dependence of $\sigma_i^{(2)}$ on $I_i^{(2)} = (I_i I_{i+1})^{1/2}$ is stronger than the dependence of σ_i on I_i. However, just as for σ_i, at $v = 2.7\cdot10^8$ cm/sec the strongest dependence of σ_i on I_i in the investigated region of $I_i^{(2)}$ from 40 to 130 eV is observed in helium, and at $v = 8\cdot10^8$ cm/sec it is observed in argon (Fig. 5). As a result, the values of $\sigma_{i,i+2}$ and $\sigma_i^{(2)}$ change with changing Z_c approximately in the same way as $\sigma_{i,i+1}$ and σ_i. In particular, at $v = 8\cdot10^8$ cm/sec, when Z_c increases from 2 to 18, a general increase of the cross sections $\sigma_{i,i+2}$ and $\sigma_i^{(2)}$ is observed, but the cross sections in neon turns out to be practically the same as the cross sections in nitrogen, this being lower by a factor 1.4 than the value expected from their average monotonic dependence on Z_c (Fig. 6).

The ratios $\zeta_{i+1} = \sigma_i^{(2)}/\sigma_i$, which yield the average probability of loss of the second electron by the ion, referred to one electron of the outer shell of the ion,[11] change qualitatively with changing I_{i+1} and v in the same manner as the cross sections σ_i, but in contrast to the latter they are practically equal for all media except helium. The values of ζ_{i+1} in helium are smaller than in the heavier

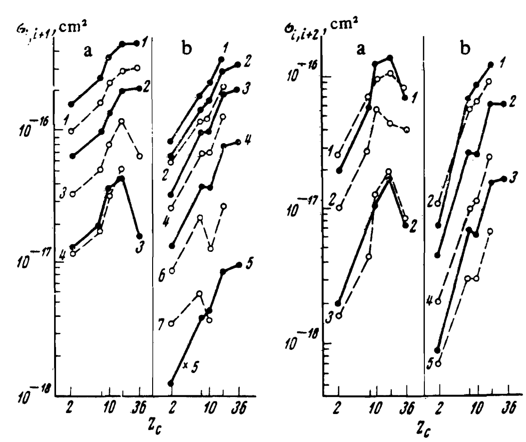

FIG. 6. Cross sections $\sigma_{i,i+1}$ and $\sigma_{i,i+2}$ for the loss of one and two electrons, respectively, by nitrogen (●) and neon (○) ions as functions of Z_c at $v = 4\times10^8$ (a) and $v = 8\times10^8$ (b) cm/sec. The numbers on the curve indicate the ion charges i.

media by factors from 1.6 to 5. The relations between the values of ζ_{i+1} in helium and in the heavier media hardly differ from the relations between the cross sections σ_i in helium and in argon.

4. Explanation of the singularities in the cross sections for electron loss by fast ions in neon

The values of σ_i for nitrogen and neon ions in helium are close to cross sections, calculated in the Born approximation, of electron loss by hydrogen-like atoms having the same binding energies I_i.[36,37] The dependence of σ_i on I_i and Z_c for ions with small charges i in all media agree qualitatively with the dependence that follows from the Bohr formula[30] derived in the classical analysis of electron scattering in the strongly screen field of the atoms:

$$\sigma_i \approx \pi a_0^2 Z_c^{2/3} (v_0^2/u_i v). \tag{5}$$

For ions with large charges, on the other hand, the dependence of σ_i on I_i is stronger than the one that follows from (5), while the dependence of σ_i on Z_c does not always agree, even qualitatively, with the Bohr formula derived with the aid of the statistical model of the atom.

The lower electron-loss cross sections in neon compared with nitrogen, as well as the higher cross sections for electron capture in neon, can be attributed to the larger average velocity $\bar{v}_c$ of the electrons in the outer shell of the neon atom. From a theoretical analysis of the electron loss by hydrogen-like ions in hydrogen, helium, and nitrogen[36–38] it follows that at low binding energies I_i of the lost electron, when $u_i \equiv (2I_i/\mu)^{1/2} \leqslant 2\bar{v}_c$, in the region $v > u_i^2/2\bar{v}_c$ the electron-loss cross sections $\sigma_{i,i+1}$ are substantially lowered by the screening of the coulomb field of the nuclei of the atoms of the medium by the atomic electrons. The greatest decrease of the cross sections takes place at an ion velocity $v \sim u_i$, when the cross sections are close to the maximal ones, and the role of the collisions accompanied by ionization or by excitation of the atoms of the medium is still small. In connection with the last circumstance, at an ion velocity $v \leqslant u_i$ the dependence of the cross sections $\sigma_{i,i+1}$ on Z_c is determined in the first Born approximation by the function

$$R_c(Q) = \{\sum_j N_j[1 - F_j(Q)]\}^2$$

in the region $Q \geqslant Q_{\min} = u_i^2/2v$, where N_j is the number of electrons in the j-th shell of the atoms of the medium (so that $\sum_j N_j = Z_c$), and $F_j(Q)$ is the form factor of this shell, which depends on the momentum $Q\mu$ transferred to the removed electron (the quantities $\sigma_{i,i+1}$ are proportional to the integral of $R_c(Q)$).

At small and large values of Q, the quantities $[1 - F_j(Q)]$ approach respectively $[Q/k_j \bar{v}_j]^2$ and unity, where $k_{1s} = 1.41$, $k_{2s} = 0.89$, and $k_{2p} = 0.76$. For the 1s, 2s, and 2p electrons of the nitrogen atom, according to[32], the quantities $\bar{v}_j/v_0$ are equal respectively to 6.7, 2.25, and 1.18, while for the neon atoms their values are 9.7, 3.4, and 2.6, i.e., approximately 1.5 times larger. Consequently at $Q \leqslant 2v_0$ we have $R_{\mathrm{Ne}}(Q)/R_{\mathrm{N}}(Q) < 1$, and at $Q \leqslant v_0$ the ratio $R_{\mathrm{Ne}}(Q)/R_{\mathrm{N}}(Q)$ is close to the absolute minimum value 0.58 for the region $Q \ll \bar{v}_j$. It follows therefore that for the ions with $u_i \leqslant 4v_0$, which corresponds to $I_i \lesssim 220$ eV, in the region $(u_i/2)^2/v_0 \lesssim v \leqslant u_i$ the cross sections $\sigma_{i,i+1}$ in neon should be somewhat lower than in nitrogen. Actually lower values of $\sigma_{i,i+1}$ in neon than in nitrogen are observed for nitrogen and neon ions with $I_i \sim 130$–250 eV, i.e., with $u_i \sim (3$–$4)\,v_0$ at $v \sim 3.6\,v_0$.

A similar result follows also from estimates of the ratio $\sigma_{i,i+1}(\mathrm{Ne})/\sigma_{i,i+1}(\mathrm{N})$ of the cross sections in neon and nitrogen, obtained by directly using the cross sections, calculated in the Born approximation, for electron loss by hydrogen-like ions in hydrogen and helium.[36] Since the binding energies of the outer electrons in the nitrogen and neon atoms are close respectively to the binding energies of the electrons in the atoms of hydrogen and helium, while the ratio of the mean velocities of these electrons is close to the ratio of the mean velocities of the electrons in the hydrogen and helium atoms, it follows that when account is taken of the difference between the number of the outer electrons in these atoms we obtain by way of estimate

$$\frac{\sigma_{i,i+1}(\mathrm{Ne})}{\sigma_{i,i+1}(\mathrm{N})} = \frac{16}{25}\,\frac{[\sigma_{i,i+1}^{\mathrm{y}}(\mathrm{He}) + {}^1/_4\sigma_{i,i+1}^{\mathrm{Hy}}(\mathrm{He})]}{[\sigma_{i,i+1}^{\mathrm{y}}(\mathrm{H}) + {}^1/_5\sigma_{i,i+1}^{\mathrm{Hy}}(\mathrm{H})]} \tag{6}$$

where $\sigma_{i,i+1}^{\mathrm{y}}(\mathrm{A})$ is the cross section for electron loss in collisions between the ions and the atoms A, as a result of which the state of the latter remains unchanged, while $\sigma_{i,i+1}^{\mathrm{Hy}}$ is the cross section for electron loss in collisions accompanied by excitation or ionization of the atoms A. For ions with binding energy $I_i \leqslant 20$ eV at $v \approx u_i$ this ratio turns out to be less than unity and amounts to 0.73 for $I_i \approx 15$ eV at $v \approx u_i$.

It follows from the foregoing analysis that the relation $\sigma_{i,i+1}(\mathrm{Ne}) < \sigma_{i,i+1}(\mathrm{N})$ should be observed in the region $v \sim u_i$ for all ions with $I_i \lesssim 200$ eV. Besides nitrogen and neon, such a relation, as already noted, is observed also for atoms and negative ions of hydrogen and atoms of lithium.[22,24]

5. CONCLUSION

Our results show that small differences in the qualitatively similar behavior of the cross sections for the change of nitrogen and neon ion charges in different media lead to a nonmonotonic dependence of the cross sections on the charge Z_c of the nuclei of the atoms of the medium at ion velocities $v \sim 10^9$ cm/sec. These anomalies at $Z_c = 10$ in the electron loss and capture cross sections are of opposite sign and substantially different in magnitudes, although their causes are the same. In the cross sections for the simultaneous loss or capture of two electrons these anomalies turn out to be approximately the same as the cross sections for the loss or capture of one electron, so that the anomalies are almost nonexistent in the ratios of these cross sections, and these ratios are quite close to one another for all media other than helium. Exceptions are the values of $\sigma_{i,i-2}$ for the neon ions, for which the anomalies in the neon as in the medium is more strongly pronounced than in the values of $\sigma_{i,i-1}$, and the ratios $\sigma_{i,i-2}/\sigma_{i,i-1}$ in neon are increased.

At lower velocities there is a substantial difference between the cross sections for electron capture in states with different values of the principal quantum number n_0 (at identical I_{i-1}). In contrast to the anomalous dependence of the cross sections on Z_c in two electron transitions this difference is, roughly speaking, twice as large as in single-electron transition, as a result of which it turns out to be approximately the same in the cross-section ratio $\sigma_{i,i-2}/\sigma_{i,i-1}$ as in the cross sections $\sigma_{i,i-1}$ themselves. While the cause of the nonmonotonic dependence of the cross sections on Z_c is in the main known, only more or less general assumptions can be made so far concerning the actual causes of the difference between the cross sections for the capture of an electron in states with different n_0.

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[1]Ya. A. Teplova, V. S. Nikolaev, I. S. Dmitriev, and L. N. Fateeva, Zh. Eksp. Teor. Fiz. **42**, 44 (1962) [Sov. Phys. JETP **15**, 31 (1962)].
[2]B. Fastrup and A. Borup, Can. J. Phys. **46**, 489 (1968).
[3]W. K. Chu and D. Powers, Phys. Lett. A **38**, 267 (1972).
[4]S. Datz, C. D. Moak, B. R. Appleton, M. D. Brown, and T. A. Carlson, Abstracts of Papers VII ICPEAC, 1971, Amsterdam, p. 409.
[5]L. Winters, M. D. Brown, L. D. Ellsworth, T. Chiao, E. W. Pettus, and J. R. Macdonald, Phys. Rev. A **11**, 174 (1975).
[6]V. S. Nikolaev, Usp. Fiz. Nauk **85**, 679 (1965) [Sov. Phys. Usp. **8**, 269 (1965)].
[7]Yu. S. Volodyagin, J. S. Dmitriev, V. S. Nikolaev, Yu. A. Tashaev, and Ya. A. Teplova, J. Phys. B **6**, 171 (1973).
[8]V. S. Nikolaev, I. S. Dmitriev, L. N. Fateeva, and Ya. A. Teplova, Zh. Eksp. Teor. Fiz. **40**, 989 (1961) [Sov. Phys. JETP **13**, 695 (1961)].
[9]V. S. Nikolaev, L. N. Fateeva, I. S. Dmitriev, and Ya. A. Teplova, Zh. Eksp. Teor. Fiz. **41**, 89 (1961) [Sov. Phys. JETP **14**, 67 (1962)].
[10]I. S. Dmitriev, V. S. Nikolaev, L. N. Fateeva, and Ya. A. Teplova, Zh. Eksp. Teor. Fiz. **42**, 16 (1962) [Sov. Phys. JETP **15**, 11 (1962)].
[11]I. S. Dmitriev, V. S. Nikolaev, L. N. Fateeva, and Ya. A. Teplova, Zh. Eksp. Teor. Fiz. **43**, 361 (1962) [Sov. Phys. JETP **16**, 259 (1963)].
[12]L. I. Pivovar, M. T. Novikov, and A. S. Dolgov, Zh. Eksp. Teor. Fiz. **50**, 537 (1966) [Sov. Phys. JETP **23**, 357 (1966)].
[13]H. H. Lo and W. F. Fite, Atomic Data **1**, 306 (1970).
[14]I. S. Dmitriev, Ya. A. Teplova, and V. S. Nikolaev, Zh. Eksp. Teor. Fiz. **61**, 1359 (1971) [Sov. Phys. JETP **34**, 723 (1972)].
[15]I. S. Dmitriev, V. S. Nikolaev, Yu. A. Tashaev, and Ya. A. Teplova, Zh. Eksp. Teor. Fiz. **67**, 2047 (1974) [Sov. Phys. JETP **40**, 1017 (1975)].
[16]M. C. Brinkman and H. A. Kramers, Proc. Acad. Sci. Amsterdam **33**, 973 (1930).
[17]V. S. Nikolaev, Zh. Eksp. Teor. Fiz. **51**, 1263 (1966) [Sov. Phys. JETP **24**, 847 (1967)].
[18]G. A. Khayrallah and J. E. Bayfield, Phys. Rev. A **11**, 930 (1975).
[19]M. B. Shah and H. B. Gilbody, J. Phys. B **7**, 256 (1974).
[20]S. K. Allison, Phys. Rev. **109**, 76 (1958); **110**, 670 (1958).
[21]S. K. Allison, J. Cuevas, and M. Garcia-Munoz, Phys. Rev. **120**, 1266 (1960).
[22]H. Tawara and A. Russek, Rev. Mod. Phys. **45**, 178 (1973).
[23]E. P. Andreev, V. A. Ankudinov, and S. V. Bobashev, Zh. Eksp. Teor. Fiz. **50**, 565 (1966) [Sov. Phys. JETP **23**, 375 (1966)].
[24]D. H. Crandall and D. H. Jaecks, Phys. Rev. A **4**, 2271 (1971).
[25]J. S. Risley, A. J. de Heer, and C. B. Kerkdijk, Abstracts of Papers IX ICPEAC, 1975, Seattle, p. 93.
[26]Yu. S. Volodyagin and V. S. Nikolaev, Depository Manuscript No. 7161-73, 1973.
[27]T. Tonuma, J. Kohno, Y. Miyazawa, F. Joshida, T. Karasawa, T. Takahashi, and S. Konno, J. Phys. Soc. Jpn. **34**, 148 (1973).
[28]A. B. Wittkower, G. Ryding, and H. B. Gilbody, Proc. Phys. Soc. London **89**, 541 (1966).
[29]T. F. Tuan and E. Gerjuoy, Phys. Rev. **117**, 756 (1960).
[30]N. Bohr and J. Lindhard, K. Dan. Vidensk. Selsk. Mat.-Fys. Medd. **28**, 7 (1954).
[31]G. J. Bell, Phys. Rev. **90**, 548 (1953).
[32]D. R. Hartree, Calculations of Atomic Structures (Russ. transl.), IIL, 1960.
[33]J. C. Slater, Phys. Rev. **36**, 37 (1930).
[34]E. H. Pedersen and P. Hvelplund, J. Phys. B **6**, 1277 (1973).
[35]A. B. Wittkower, G. Levy, and H. B. Gilbody, Proc. Phys. Soc. London **91**, 306 (1967).
[36]I. S. Dmitriev, Ya. M. Zhileĭkin, and V. S. Nikolaev, Zh. Eksp. Teor. Fiz. **49**, 500 (1965) [Sov. Phys. JETP **22**, 352 (1966)].
[37]V. S. Nikolaev, V. S. Senashenko, and V. Yu. Shafer, Vestn. Mosk. Univ. Fiz. Astron. No. 3, 357 (1973).
[38]V. S. Senashenko, V. S. Nikolaev, V. Yu. Shafer, and I. S. Dmitriev, Vestn. Mosk. Univ. Astron. No. 2, 136 (1970).

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