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CAPTURE OF SEVERAL ELECTRONS BY FAST MULTICHARGED IONS

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The capture cross sections of two or more electrons by multicharged ions of light elements in helium, nitrogen, argon and krypton have been measured for velocities from 2.6×10^8 to 12×10^8 cm/sec. In most cases, the electron capture probability is determined by the magnitude of the ionization potential of the resulting ions and depends weakly on the number of captured electrons. It is shown that the simultaneous capture of several electrons in a beam of particles with an equilibrium charge distribution is the chief mode of formation of low charge ions.

1. INTRODUCTION

In the collision of multicharged ions with atomic matter, the simultaneous capture of several electrons can take place in addition to the capture of a single electron by the ion. As a consequence of the great change in the charge of the ion in such collisions, the latter can have a significant effect on the charge composition of a beam of ions passing through the material.

However, the actual role of these phenomena, especially for ionic velocities close to those of the orbital electrons, has been insufficiently discussed. The cross sections for capture of several electrons by multicharged ions of Ne, Ar, and Kr are known for ionic velocities $v < 10^8$ cm/sec.[1-3] For higher velocities, there are data on capture cross sections of two electrons by He ions[4] and estimates of the cross sections for N ions.[5] Theoretical calculations of the cross sections for capture of two electrons by He ions in helium have been carried out.[6]

In the present research, results are given of an experimental study of the capture cross sections of several electrons by multicharged ions of He, Li, B and N for velocities from $(2.6-4) \times 10^8$ to 12×10^8 cm/sec, by Ne ions for $v = (2.6-6) \times 10^8$ cm/sec, by P and Ar ions for $v = 2.6 \times 10^8$ and 4.1×10^8 cm/sec, and by Na, Mg, Al and Kr ions for $v = 2.6 \times 10^8$ cm/sec. The measurements were carried out in helium, nitrogen, argon and krypton. The two-electron capture cross sections $\sigma_{i,i-2}$ were determined for all the ions. Values of the three-electron capture cross sections of $\sigma_{i,i-3}$ were obtained for B, N, P, and Ar ions. An estimate of the simultaneous capture of four electrons, not previously observed, was obtained for N ions. The capture of more than two electrons was not observed in the passage of the ions through helium, as was to be expected.

The method for determining the cross sections and the experimental setup were described in a previous paper.[7] In the determination of the capture cross sections of several electrons, statistical errors were the most important, and also those errors produced by the small background of random pulses. In most cases, the total error did not exceed 15 — 20 percent for $\sigma_{i,i-2}$ and 20 — 30 percent for $\sigma_{i,i-3}$. The values of $\sigma_{i,i-4}$ were determined with an accuracy ~ 50 percent.

The resultant cross sections refer to cases of capture of electrons accompanied by scattering of the ions through an angle θ which did not exceed 0.005 radian on the average. For scattering at larger angles, a much smaller part of the scattered ions were incident on the recording system than in the case $\theta < 0.005$. In this case, the ratio of the number of recorded ions to the total number of ions scattered through an angle θ was proportional to the geometrical factor $S(\theta) = 1 - 50\theta$ for $0 \leq \theta \leq 0.0036$, and $S(\theta) \approx \exp(0.9 - 300\theta)$ for $\theta > 0.0036$. In particular, for $\theta = 0.003$, 0.005, and 0.010, the relative fraction of recorded particles $S(\theta)$ was equal to 85, 53 and 13 percent, respectively. The number of recorded ions with scattering angle $\theta \gtrsim 0.008$, which are produced principally by entrance into the counter close to the edges of the input window, was small and did not exceed the background of random pulses. This means that, in comparison with the cross sections obtained, the part of the capture cross section of the electrons associated with the scattering of the

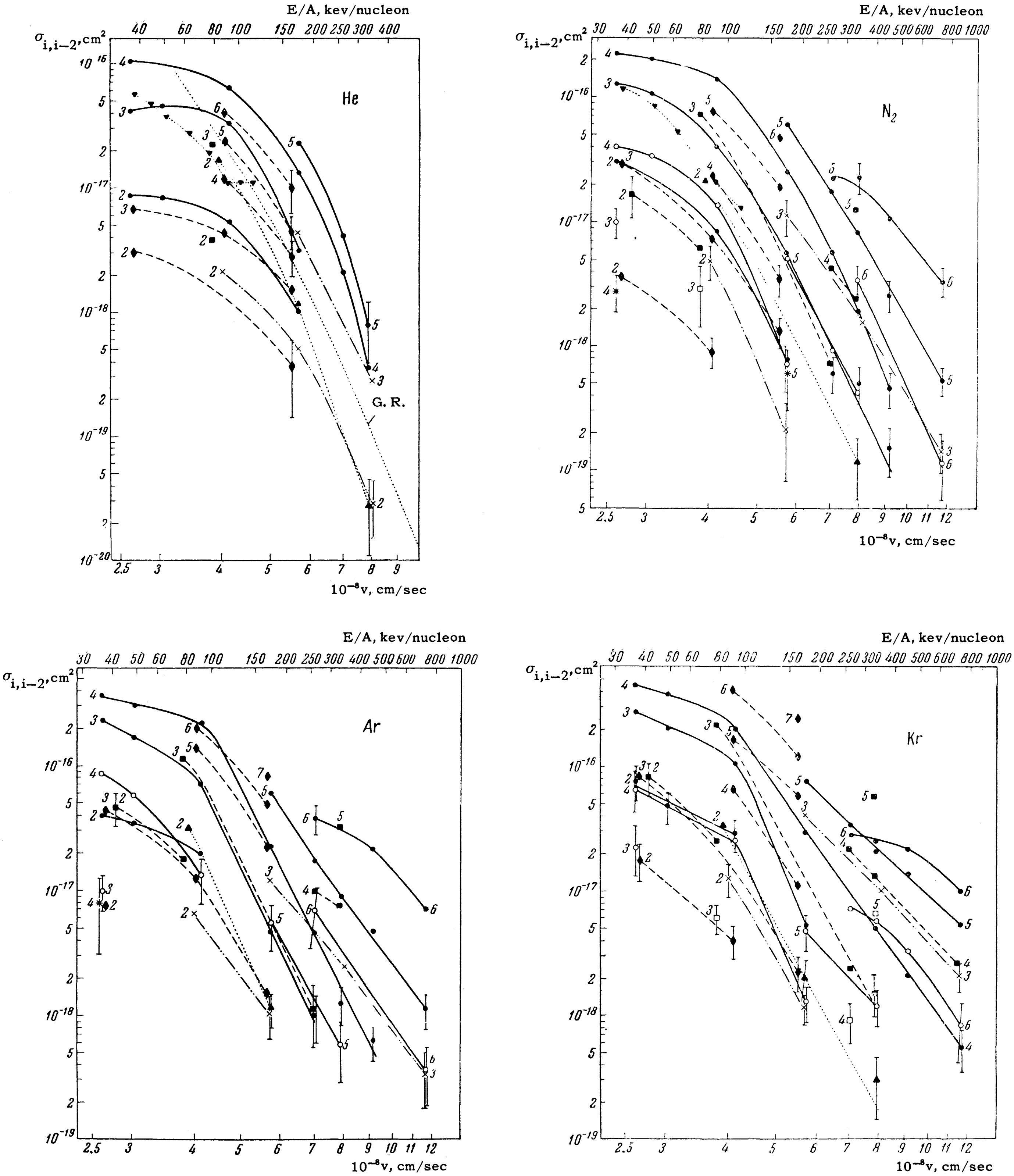

FIG. 1. Cross sections for capture of several electrons in different gases as a function of the velocity v and the energy per nucleon of the ion, E/A, for the ions He (▲), Li (×), B (■, □), N (●, ○) and Ne (◆). The blackened points correspond to the cross section $\sigma_{i,i-2}$, the clear ones to $\sigma_{i,i-3}$, × to $\sigma_{i,i-4}$ for the N ion. The numbers on the points and curves denote the initial charge of the ions, i; ▼ is the value of σ_{20} for helium ions from,[4] G. R. is the theoretical curve of Gerasimenko and Rozentsveig.[6] The measurement errors are shown only if they exceed 20 per cent.

ions by an angle of $\theta \gtrsim 0.008$ is usually small and does not exceed the range of random error.

2. EXPERIMENTAL RESULTS

The results of measurements of capture cross sections of several electrons (referred to a single atom) have been plotted in Figs. 1, 2, and 3.

As is seen from Fig. 1, the two-electron capture cross sections $\sigma_{i,i-2}$ decrease with increase in speed of the ions, while for a given gas the dependence of $\sigma_{i,i-2}$ on v is approximately the same for all ions. For increase in velocity, the capture cross sections of two electrons decrease more rapidly than the single-electron capture cross section $\sigma_{i,i-1}$.[7] An especially large difference is observed in the dependence of $\sigma_{i,i-2}$ and $\sigma_{i,i-1}$ on v for v ~ (6 — 8) × 10^8 cm/sec in helium:

$$-d\log \sigma_{i,i-1}/d\log v = 5—6, \quad -d\log \sigma_{i,i-2}/d\log v = 8—14.$$

With increase in the ionic charge i, the two-electron capture cross sections increase monotonically, approximately as i^m, while the index m is approximately 1.5 times larger than the corresponding exponent for the single-electron capture cross section. With change in charge of the nucleus of the ions Z, the two-electron capture cross section $\sigma_{i,i-2}$, as well as the single-electron capture cross section $\sigma_{i,i-1}$, do not change monotonically (Fig. 2). The dependence of the cross section $\sigma_{i,i-2}$ on the medium (Fig. 3) is qualitatively similar to the corresponding dependence of $\sigma_{i,i-1}$.

From the experimental data which are given in the present work and elsewhere,[7] one can determine the ratio of the two-electron capture cross sections to the single-electron capture cross section, $\eta_{i,i-2} = \sigma_{i,i-2}/\sigma_{i,i-1}$. Typical values of $\eta_{i,i-2}$ are shown in Figs. 4 and 5. In all cases, $\eta_{i,i-2} < 1$. The largest values of $\eta_{i,i-2} \sim 0.2$ were obtained for N, P, Ar, and Kr ions with i = 4 — 6, and the smallest values, $\eta_{i,i-2} \sim 0.01$, for doubly charged ions of He, Li, B, Ne, Na, and Mg. For ions of a given element the values of $\eta_{i,i-2}$ increase along with increase of i; however, for large values of $\eta_{i,i-2} \sim 0.2$, the dependence of $\eta_{i,i-2}$ on i weakens and the $\eta_{i,i-2}$ become practically constant. With increase in the velocity, the values of $\eta_{i,i-2}$ decrease (Fig. 5).

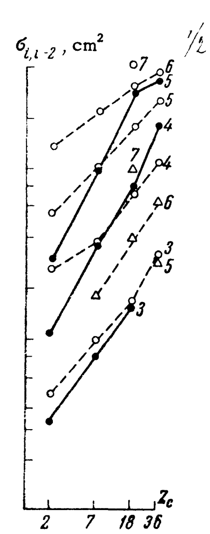

FIG. 3. Capture cross sections of two electrons by ions of phosphorus (●) and nitrogen (○) in gases with atomic number Z_c for v = 4.1 × 10^8 cm/sec. The values of $\sigma_{i,i-3}$ (△) are also given for argon ions. The initial charge of the ions is shown on the curves.

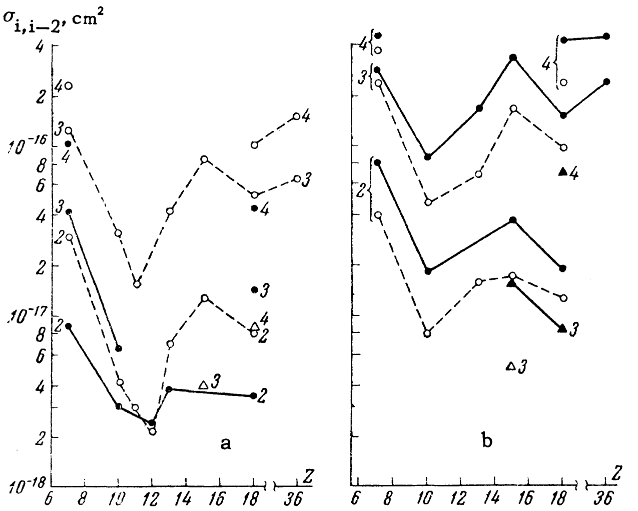

FIG. 2. Dependence of $\sigma_{i,i-2}$ on the charge of the ion nucleus Z for v = 2.6 × 10^8 cm/sec; a – in helium (●) and nitrogen (○); b – in krypton (●) and argon (○). For P and Ar ions (Z = 15 and 18), the values of $\sigma_{i,i-3}$ are also shown (△ and ▲). The values of i are given at the points and curves.

The values of $\eta_{i,i-2}$ depend weakly on the medium (Fig. 4) and only in helium at v ≥ 8 × 10^8 cm/sec are they much less than in the other gases: for all ions, $\eta_{i,i-2} < 0.01$.

Like the one- and two-electron capture cross sections, the values of $\eta_{i,i-2}$ depend strongly on Z. The dependence of $\eta_{i,i-2}$ on i and Z can usually be reduced to a dependence of this quantity on I — the binding energy of the electron in the ground state of an ion with charge i − 2 (Fig. 4). Exceptions are the ratios $\eta_{i,i-2}$ for neon ions with various charges i and for the ions Na^{+3} and Ar^{+2}, which are shown to be much smaller than for the other ions. As is seen from Fig. 4, at v = 2.6 × 10^8 cm/sec, the values of $\eta_{i,i-2}$ are identical in the case of capture of electrons by the L and M shells, while for v = 4.1 × 10^8 cm/sec, they differ by not more than a factor of two. For ions with i = Z at v ≥ 4 × 10^8 cm/sec, the values of $\eta_{i,i-2}$ are approximately one-half those for the capture of L electrons.

The three-electron capture cross sections $\sigma_{i,i-3}$, as the experimental results for ions of B, N, and Ar show, are changed more strongly with a

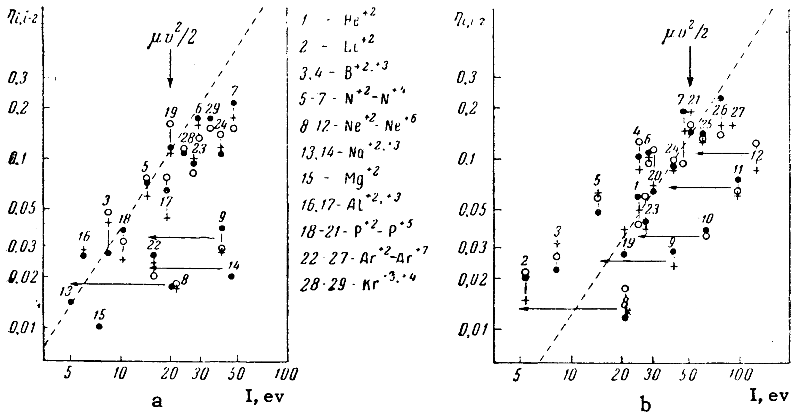

FIG. 4. Values of $\eta_{i,i-2} = \sigma_{i,i-2}/\sigma_{i,i-1}$ for different ions in nitrogen (●), argon (+) and krypton (○) as a function of the binding energy I of the electron in the ground state of the ion that is formed; a – for v = 2.6 × 10^8 cm/sec, b – for v = 4.1 × 10^8 cm/sec. The arrows indicate the maximum value of the binding energy of the electron (for Ne and Na ions) for its capture by the M shell. The dashed lines correspond to a dependence of the form $I^{3/2}$ (μ = mass of the electron).

change of i than the two-electron capture cross sections. Therefore, for increase of i, the ratio of the three-electron capture cross section to the two-electron capture cross sections ($\eta_{i,i-3} = \sigma_{i,i-3}/\sigma_{i,i-2}$) increases, as does $\eta_{i,i-2}$. Moreover, for all ions for which the three-electron capture cross sections have been determined, the values of $\eta_{i,i-3} = \sigma_{i,i-3}/\sigma_{i,i-2}$ coincide, within the limits of experimental error, with the values of $\eta_{i-1,i-3} = \sigma_{i-1,i-3}/\sigma_{i-1,i-2}$ for ions of the same element with initial charge smaller by one. For N ions in nitrogen, this coincidence is shown in Fig. 5.

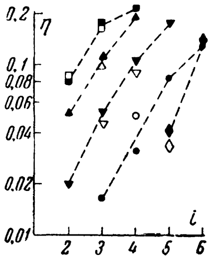

FIG. 5. Values of $\eta_{i,i-2} = \sigma_{i,i-2}/\sigma_{i,i-1}$ (blackened points) and $\eta_{i+1,i-1} = \sigma_{i+1,i-2}/\sigma_{i+1,i-1}$ (clear points) as a function of i for N ions in nitrogen at the velocities: □, ■ – 2.6 × 10^8; ▲, △ – 4.1 × 10^8; ▼, ▽ – 5.7 × 10^8; ●, ○ – 8.0 × 10^8; ◆, ◇ – 10.7 × 10^8 cm/sec.

In a similar way, the four-electron capture cross sections $\sigma_{i,i-4}$ give values of $\eta_{i,i-4} = \sigma_{i,i-4}/\sigma_{i,i-3}$ close to $\eta_{i-1,i-4} = \sigma_{i-1,i-4}/\sigma_{i-1,i-3}$. Thus for ions of a given element, $\eta_{i,i-2} \approx \eta_{i+1,i-2} \approx \eta_{i+2,i-2}$ or $\sigma_{i,i-2}/\sigma_{i,i-1} \approx \sigma_{i+1,i-2}/\sigma_{i+1,i-1} \approx \sigma_{i+2,i-2}/\sigma_{i+2,i-1}$; that is, the ratio of the cross sections for the capture of s and s – 1 electrons, $\eta_{i,i-s}$, is determined by the value of the charge of the ions formed, i – s and i + 1 – s, and for fixed value of the latter does not depend on s.

If we compare the cross section for the capture of different numbers of electrons, leading to the formation of ions with the same final charge k, then it is shown that the cross sections $\sigma_{k+s,k}$ decrease with increase in the number of captured electrons, while the ratio of the cross sections $\sigma_{k+s+1,k}/\sigma_{k+s,k}$ does not exceed 0.5. For approximate estimates, one can assume that $\sigma_{k+s,k} \sim \exp(-as)$ with an exponent a ~ 1 – 3.

3. DISCUSSION OF RESULTS

Experimental data which can be directly compared with the results of the present research exist only for ions of He in helium and air at v < 5 × 10^8 cm/sec in the work of Allison.[4] For v = 4 × 10^8 cm/sec, the value of σ_{20} in helium which we obtained is the same as the result of Allison, while the value of σ_{20} in nitrogen is 25 percent smaller than σ_{20} in air, i.e., the difference lies within the limits of experimental error. For v = 4.7 × 10^8 cm/sec, the values of σ_{20} of Allison[4] are evidently too high, since the experimental data of the present work and theoretical calculations[6] demonstrate the rather rapid drop in the cross section σ_{20} with increase in the speed of the ions. Experimental data on two-electron capture cross sections of nitrogen ions, which we obtained earlier,[5] are in agreement with the results of the present research. The values of σ_{20} for He ions in helium, computed in the Born approximation by Gerasimenko and Rozentsveĭg,[6] are approximately twice as large as the experimental; the dependence of the computed cross sections on v is close to the experimental dependence. The speed of the ions in our cases is still not so large that one can expect better agreement with experiment from calculations in the Born approximation.

According to representations of the capture of electrons formulated in a general form by Bohr[8] and developed in application to multicharged ions in the researches of our group,[7,9] the single-electron capture cross section $\sigma_{i,i-1}$ can be represented in the form of a product $\sigma'_i n f_{i,i-1}$, where σ'_i is the collision cross section of an ion possessing a charge i with an electron of an atom of the medium, with a transfer to the latter of an energy of the order of $\mu v^2/2$ (μ is the mass of the electron); n is the number of electrons in an atom of the medium which effectively take part in the capture; $f_{i,i-1}$ is the capture probability of the electron after the collision mentioned, as a result of which an ion is formed with charge i – 1.

Applying a similar consideration to the phenomena of capture of several electrons, we can write

$$\sigma_{i,i-2} = \sigma_i' n f_{i,i-1} w_2 f_{i,i-2},$$
$$\sigma_{i,i-3} = \sigma_i' n f_{i,i-1} w_2 f_{i,i-2} w_3 f_{i,i-3} \text{ etc.}$$

where w_2 and w_3 are the collision probabilities of an ion with the second and third electrons of the atom of the medium, in the presence of a collision with one and two electrons, respectively; $f_{i,i-2}$ and $f_{i,i-3}$ are the capture probabilities of the second and third electrons with the formation of ions possessing charges of $i-2$ and $i-3$, respectively. It is then seen that in comparison with the s-electron capture cross section, $\sigma_{i,i-s}$, the ratio of the s- and (s − 1)-electron capture cross sections, $\eta_{i,i-s} = \sigma_{i,i-s}/\sigma_{i,i+1-s}$, is a much simpler quantity, equal to $w_s f_{i,i-s}$, while the quantities w_s must by their physical meaning be determined by the properties of the atoms of the medium, and the quantities $f_{i,i-s}$ should be functions of the ionic parameters.

In correspondence with what has been pointed out above, the experimentally observed dependence of the ratio $\sigma_{i,i-2}$ on I should be due to the dependence of the quantity $f_{i,i-2}$ on I. The decisive influence of the electron binding energy I on the capture probability f, established in the present research, is seen to be in full correspondence with the electron-capture probability estimated by a statistical method suggested by Bohr.[8] The general experimental dependence of $\eta_{i,i-2}$ on I for most ions is close to the dependence of f on I, which was suggested by one of us,[9] according to which $f \approx (2I/\mu v^2)^{3/2}$ for $I < \mu v^2/2$ and $f \sim 1$ for $I > \mu v^2/2$. The difference is that the actual transition to constant values $\eta_{i,i-2}$, at least for $v \sim 3 \times 10^8$ cm/sec, takes place at values of I somewhat larger than $\mu v^2/2$ (Fig. 4). As experimental results show, there also exists a certain dependence of the quantity $f_{i,i-2}$ on the number of the shell being filled (Fig. 4b).

The presence of a decisive influence of the binding energy of the electron in the ground state of the ion that is formed on the probability of capture $f_{i,i-2}$ indicates that for $I < \mu v^2/2$ the capture of electrons takes place predominantly into the ground state or in a state close to it with the smallest possible values of the principal quantum number and with a binding energy close to I, since the binding energy of the electron captured from the next shell depends essentially on the charge of the ion i, and is weakly associated with the value of I. The weakening of the dependence of the ratio $\eta_{i,i-2}$ on I for $I \gtrsim \mu v^2/2$ can be considered as proof of the growth of the role of electron capture in highly excited states. Inasmuch as the velocity of the captured electrons relative to the ion is on the order of v, then for $I \gtrsim \mu v^2/2$ the electrons should be captured principally in states with binding energy $\sim \mu v^2$.

As can be seen from Fig. 4, in the case of capture of different (in order of enumeration) L or M electrons, the values of $\eta_{i,i-2}$ for the same I are practically identical. This means that the probability of capture of the second electron $f_{i,i-2}$ does not depend on the number of electrons in the outer shell of the ion. Only in the capture of the last (eighth) M electron (η_{20} for Ar^{+2} ions) and in the capture of the seventh and eighth L electrons ($\eta_{i,i-2}$ for the ions $Ne^{+2,+3}$ and Na^{+3}) does a decrease in the probability of capture $f_{i,i-2}$ take place, which can explain the filling of the shell. A similar decrease of $f_{i,i-2}$ obviously takes place also in the capture of K electrons, as a result of which the values of $\eta_{i,i-2}$ for the ions He^{+2}, Li^{+3} and B^{+5} are shown to be one half the size of $\eta_{i,i-2}$ corresponding to capture of L electrons.

Similarly, small values of $\eta_{i,i-2}$ for the ions $Ne^{+5,+6,+7}$ cannot be explained by a decrease in the probability of electron capture as a consequence of the filling of the L shell, since a decrease in the values of $\eta_{i,i-2}$ is not observed for nitrogen ions with the same number of electrons. Decrease in the probability of capture in these cases can be brought about by the small dimensions of the region occupied by the L electrons in the neon ions. In the case of a sharp decrease in the capture probability of electrons in the L shell, the electrons should be captured principally in the following M shell. If the experimental values of $\eta_{i,i-2}$ for neon ions refer to the maximum binding energy of the electron in the M shell, then they are shown to be on the general curve of the dependence of $\eta_{i,i-2}$ on I for other ions which capture electrons in the M shell (Fig. 4). This gives us a basis for assuming that the neon ions capture the second electron in the M shell.

In consideration of the values of $\eta_{i,i-2}$, attention is called to the sharp decrease in the values of $\eta_{i,i-2}$ in helium for $v > 6 \times 10^8$ cm/sec, as a result of which (for $v \gtrsim 8 \times 10^8$ cm/sec) the values of $\eta_{i,i-2}$ for arbitrary ions in helium become much less than in other gases. The atoms of helium differ from the atoms of other gases used in that electrons with orbital velocities of the order of 10^9 cm/sec are lacking. In this connection, the observed decrease in the probability of capture of electrons in helium at $v > 6 \times 10^8$ cm/sec can be regarded as a direct verification of the general results of theoretical calculations carried out in the Born approximation[10,11] and the corresponding qualitative considerations of Bohr,[8] according to which the probability of electron capture reaches a large value only in those cases when the orbital velocity of the captured atomic electron is close to the velocity of the ion. It then follows that in all cases (except for capture of electrons in helium at $v \gtrsim 8 \times 10^8$ cm/sec) we are dealing with the capture of electrons with orbital velocity close to the velocity of the ion. Inasmuch as the velocities of the electrons found in the different shells differ widely, then one can establish the result that the electrons are almost always captured from one definite shell of the atoms of the medium for a given velocity of the ions. This conclusion is also supported by the coincidence of the ratios of one-electron capture cross sections in different gases with the ratios of the number of electrons in the corresponding shells of the atoms of these gases.[7]

As the resultant experimental data show, in the presence in the atoms of the medium of electrons with orbital velocities close to the velocity of the ions v, the values of $\eta_{i,i-2} = w_2 f_{i,i-2}$ depend weakly on the atomic number of the medium Z_m. It then follows that the probability w_2 of collision of the ion with the second electron is approximately the same in all the gases used.

One can determine the value of w_2 from the values of $\eta_{i,i-2}$ for those ions for which $\eta_{i,i-2}$ does not depend on I, when one can assume that $f_{i,i-2} \approx 1$. In such estimates, $w_2 \sim 0.1 - 0.2$. One can then draw the conclusion that in such a collision of the ion with one of the atomic electrons, which is necessary for capturing the latter, a similar collision with another electron takes place only in the case in which the distance R between the two electrons is not very large. The size of the distance R can be estimated from the relation $w_2 \sim (4/3)\pi R^3 \rho$, where ρ is the mean density of the electrons remaining after removal of the first electron in the shell of the atom of the medium from which capture takes place. If one assumes that the electrons are captured from the outer shell of the atoms at low ion velocities, and from the next shell when $v \sim 10^9$ cm/sec, then it is shown that in the first case $R \sim (0.5 - 0.7)\, a_0$, and in the second, $R \sim 0.15\, a_0$, where $a_0 = 0.53 \times 10^{-8}$ cm. These values of R amount to between 0.5 and 1.0 of the mean radius of the electron shell from which the electrons are captured.

Inasmuch as the experimental data obtained for different ions of the same element yield $\eta_{i,i-2} \approx \eta_{i+1,i-2} \approx \eta_{i+2,i-2}$, one can assume that $w_2 \approx w_3 \approx w_4$ and $f_{i,i-2} \approx f_{i+1,i-2} \approx f_{i+2,i-2}$. The equality of values of f means that the probability of electron capture depends only on the charge of the ion formed, and does not depend on the number of captured electrons or the initial charge. The latter is quite natural, since the interaction between the electrons is weaker than their interaction with the field of the atom and the ion, and therefore the electrons can be regarded as noninteracting with one another in the capture process.

In this connection, it should be expected that the probability of capture of the first electron $f_{i-1,i-2}$ must also enter into the equation for f. If we assume that $f_{i,i-1} = f_{i+1,i-1} = \eta_{i+1,i-1}/w_2$, then the total collision cross section of the ion with electrons of the atom of the medium $n\sigma_i' = \sigma_{i,i-1}/f_{i,i-1}$ can be determined from the experimental values of $\sigma_{i,i-1}$ (Fig. 6). If the ion in the collision of ion with electron were to act as a point charge of value i, then $n\sigma_i'$ would be proportional to i^2. Actually, for all ions except the ions of Ne, the values of $n\sigma_i'$ increase very slowly with increase of i. This means that the principal change in the momentum of the electron takes place at such small distances from the nucleus of the ion that the effective charge of the ion i* acting on the electron is larger than the charge of the ion i, and therefore depends weakly on i.

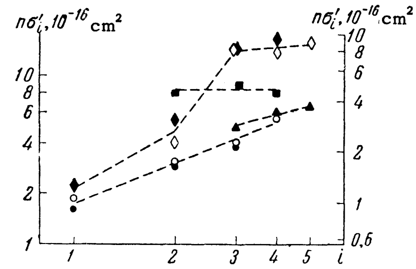

FIG. 6. Values of $n\sigma_i' = \sigma_{i,i-1}/f_{i,i-1} = \dfrac{w\sigma_{i,i-1}\sigma_{i+1,i}}{\sigma_{i+1,i-1}}$ as a function of i for N ions (●, ○), Ne ions (◆, ◇), P ions (□, ■) and Ar ions (▲, △) in nitrogen. The scale at the left and the blackened points correspond to $v = 4.1 \times 10^8$ cm/sec, the scale at the right and the clear points correspond to $v = 5.6 \times 10^8$ cm/sec; w = 0.2.

This conclusion is also substantiated by the fact that $n\sigma_i' \lesssim \pi R_i^2$, where R_i is the radius of the outer electron shell of the ion. The difference in values of $n\sigma_i'$ for ions of different elements, excluding the ions of Ne, and also the values of R_i of these ions, can be found qualitatively from the differences in the values of i*. Thus the assumption that $f_{i,i-1} = f_{i+1,i-1}$ for most ions does not contradict experimental data and is acceptable.

For the ions of Ne, for which the probability of capture of a second electron is anomalously small, and corresponds to its capture by the M shell

(Fig. 4), the values of $n\sigma_i'$ calculated under the assumption that $f_{i,i-1} = f_{i+1,i-1}$ are several times larger than those for the other ions (Fig. 6). Therefore, if this assumption is made, then it is necessary to assume that the effective charge for Ne ions is at least 1.5 times larger than for N ions. The latter can take place at distances from the nucleus less than $\sim 0.6\,a_0$,[12] while $n\sigma_i' \approx 10\,a_0^2$.

Thus the assumption that the capture probability of the first electron for neon ions, $f_{i,i-1}$, is close to the capture probability of the second electron, $f_{i+1,i-1}$, leads to contradictions. If we now assume that $f_{i,i-1}$ is larger than $f_{i+1,i-1}$, and is identical with the capture probability of the L electron for other ions with the same values of I, then the values of $n\sigma_i'$ are shown to be approximately as for N ions, and no difficulties arise in their interpretation. It then follows that the significant decrease in the electron capture probability because of the small dimensions of Ne ions takes place only in the capture of two (or more) electrons.

This phenomenon becomes understandable if we take it into account that for $v \sim (3-5) \times 10^8$ cm/sec, the capture of several electrons usually takes place from a region with dimensions $(0.5 - 0.7)\,a_0$ in a state with mean radius of the electron orbit greater than this quantity. However, with Ne ions, the radius of the L shell is known to be less than this value. Therefore, the electrons of the atom of the medium located at a distance of $(0.5 - 0.7)\,a_0$ from the first captured electron cannot be trapped in this shell; capture of several electrons in the L shell of Ne ions will take place from a smaller region than usual and the probability of capture of several electrons will be diminished. The probability of capture of the first electron is not associated with the dimensions of this region and therefore should not be diminished.

In contrast with the capture of electrons for $v < 10^8$ cm/sec,[1-3] a definite connection between the cross sections and the resonance defect ΔE was not observed in the region studied by us (ΔE is the change in binding energy of the electron in its transition from the atom of the medium to the ion). The resonance charge-exchange cross sections corresponding to $\Delta E = 0$ (σ_{20} for He ions in helium and Ar ions in argon) are not at all distinguished from the remaining cases of electron capture. At the same time, it is interesting to note that a change in velocity by one order of magnitude (from $2-5$ to 26×10^7 cm/sec) cause the ratios of the cross sections for nonresonance capture of electrons by ions of Ne, Ar and Kr (σ_{20} and σ_{31} in krypton) to be changed by no more than a factor of two. The dependence of the cross section on the medium is also little changed (σ_{20} for Ne ions in helium, argon and krypton, σ_{31} for Kr ions in nitrogen and argon). The latter means that the behavior of the number of electrons effectively participating in the capture in atoms of the media under consideration and in the velocity range from $\sim 0.3 \times 10^8$ to $\sim 4 \times 10^8$ cm/sec changes very slowly. Since the cross sections for electron capture decrease with increase in velocity for $v > 2.6 \times 10^8$ cm/sec, while they increase for $v \lesssim 5 \times 10^7$ cm/sec in a majority of cases of nonresonance capture, a maximum cross section should be observed in the unstudied range of velocities between the values mentioned.

The given results make it possible to clarify the relative role of capture of a different number of electrons in the formation of charged groups of an equilibrium charge distribution which is established in the ion beam as a result of multiple collisions of ions and atoms of the material. Inasmuch as the capture cross sections of several electrons are much less than the cross sections of capture of a single electron, they do not show any significant effect on the distribution of ions among the most intense charge groups. However, the relative number of ions comprising low intensity groups, with charge i several units less than the mean charge $\bar{i}$, should be determined by the cross sections of capture of several electrons.

Actually, the number of ions of charge i formed from ions with charge j is proportional to the quantity $\Phi_j\sigma_{ji}$, where Φ_j is the relative number of ions with charge j in the equilibrium distribution. If i differs from $\bar{i}$ by not more than $2-3$, then the values of Φ_j, as established in our earlier work,[13] are proportional to $\exp[-(j-\bar{i})^2/2\sigma^2]$. The cross sections σ_{ji}, as shown in Sec. 2, are approximately proportional to $\exp[-(j-i)/a]$. It then follows that

$$\Phi_j\sigma_{ji} \sim \exp[-(j-i_0)^2/2\sigma^2],$$

where $i_0 = \bar{i} - \sigma^2 a$. Since $j \geq i+1$, then the value of $\Phi_j\sigma_{ji}$ for $i \geq i_0 + 1$ takes on a maximum value for $j = i+1$, while for $i \lesssim i_0 - 2$, it does so for $j \sim i_0$. The latter means that ions with charges $i \lesssim i_0 - 2$ are formed principally from ions with charge $j \sim i_0$ as the result of simultaneous capture of several electrons; in this case $\Phi_i \approx \Phi_{i_0}\sigma_{i_0,i}/\sigma_{i,i+1}$.

For $i < i_0 - 2$ significant deviations from the Gaussian distribution should exist in the equilibrium distribution of ions. This Gaussian distribution holds in the region of values of i where the capture and loss of several electrons have little effect on the equilibrium distribution of the charges and $\Phi_i \approx \Phi_{i+1}\sigma_{i+1,i}/\sigma_{i,i+1}$. For $i < i_0 - 2$ we have $\Phi_{i_0}\sigma_{i_0,i} > \Phi_{i+1}\sigma_{i+1,i}$; therefore, the values of Φ_i should be larger than the values given by the Gaussian formula. In most cases $a \sim 1 - 3$ and $\sigma^2 \sim 0.5 - 1$. Therefore, $\sigma^2 a$ is of the order of several units. For example, for N ions and $v \sim 8 \times 10^8$ cm/sec, the value of $a \approx 2 - 2.5$, $\sigma^2 \approx 0.6$, $i \approx 4$, so that $i_0 \sim 2.5$; it then follows that the particles with $i = 0$ should be formed principally from doubly and triply charged ions as the result of simultaneous capture of two or three electrons.

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22