DEEP "STRIPPING" AND SCATTERING OF Kr^+ *IONS IN SINGLE COLLISIONS WITH* Ne, Ar, Kr, *AND* Xe *ATOMS*

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The angular dependences of the charge distribution were measured, in the energy range 250—850 keV, in a beam of krypton ions experiencing single collisions with Ne, Ar, Kr, and Xe atoms. The total differential scattering cross sections of Kr^+ ions were also measured in these gases. From the results, it was concluded that the inner M-shell electrons of krypton ions participate considerably in the interaction process; moreover, the dependence of the average ionization energy of Kr^+ ions on the nature of the target atoms was established. It was discovered that the average ion charge for single collisions and angles $\theta \neq 0$ was directly proportional to the ion velocity. The data obtained also made it possible to determine the integral cross sections for the loss and capture of electrons by Kr^+ ions. The measurements were carried out in the angle range $\theta = 0—3°$.

1. INTRODUCTION

IN the last few years, the processes of ion scattering involving a change of charge in inelastic collisions with gas atoms have been investigated in the keV range of energies. Relatively extensive experimental data have been obtained in these investigations on the angular and energy distributions of charge in beams of certain ions which had experienced single collisions with atoms.[1-4] However, even in the case of the closest approach between nuclei, no ions were observed having a degree of ionization which involved the loss of electrons from the inner atomic shells. For this reason, the theory developed by Russek[5,6] makes the assumption that, when a fast ion collides with an atom, the excitation energy is shared at random but only between the electrons in the outer atomic shells.

The purpose of the present investigation was to study the process of ion scattering, accompanied by the deep "stripping" of electrons, and to solve the problem of the participation of the inner-shell electrons in the interaction of colliding particles.

As the subject of our investigation, we chose krypton, for which we measured the charge fractions in single collisions of singly-charged ions with Ne, Ar, Kr, and Xe atoms. We measured also the differential cross sections for the scattering of krypton ions in these gases and determined the partial integral cross sections for the electron loss by singly charged ions in the angle range 1—3°. Direct measurements were carried out of the partial integral cross sections for the electron loss and capture by singly-charged krypton ions in the angle range 0—1°.

2. EXPERIMENTAL METHOD

The investigations described below were carried out using apparatus employed by us earlier.[7] Slight modifications were made in the system of slits which collimated the scattered beam, but these modifications were restricted to a certain reduction in the slit widths for the purpose of decreasing the angular divergence of the scattered beam which then became 40′. The divergence of the primary Kr^+ beam did not exceed 4×10^{-4} radians.

The method of measurement remained essentially unchanged, with the exception of the measurements of the intensity of the ion beams having a degree of ionization higher than 8. The intensities of the components with ions carrying charges from 9+ to 12+ were measured by a Faraday cylinder located furthest from the primary beam direction. The separation of these beams in accordance with their charge was achieved by a suitable change in the electric field of the capacitor of an electrostatic analyzer. The region of single collisions was in each case determined from the linear dependence of the ratio J^{n+}/J_0 on the gas pressure in the collision chamber. Such dependences were obtained for Kr^+ ions in Ne, Ar, Kr, and Xe for the whole investigated range of energies and scattering angles.

An additional check on the completeness of the collection of the components of a beam into the corresponding receivers was made using photographic film. For this, the film—in the form of a long ribbon—was fixed in such a way that it covered all the receivers. The positions of the beams having different ion charge and the distribution of the intensities within the beams were found from the degree of blackening of the photographic emulsion after developing the film. This check showed that the separation of the beams in accordance with their charge matched well the receiver distribution and that the receiver dimensions were sufficient to ensure the practically complete collection of the particles.

Of the cases dealt with in the present investigation, we must consider separately the collisions of krypton ions with neon and argon atoms. In these cases, there is a limiting scattering angle θ_{max} in the laboratory system of coordinates (l.c.) and for each value of the angle $\theta < \theta_{max}$ there are two values of the energy loss by the incident particle. The difference between these energy losses increases as the scattering angle θ gets smaller. Thus, for example, for the largest scattering angle $\theta = 2°$ investigated by us, the relative energy losses in neon were either 0.7% or 63% in the elastic interaction for the scattering angle $\theta = 3°$; these energy losses in argon were 1.4% or 89%, respectively. Such large differences between the energy loss values are naturally due to large differences in the impact parameter. It is understood, of course, that low values of the impact parameter correspond to low collision probabilities. Estimates show that the errors due to ignoring close collisions in the measurements were within the limits of the experimental error.

3. RESULTS OF THE MEASUREMENTS AND DISCUSSION

The investigation of the scattering processes, which were accompanied by the stripping of electrons from the incident ion, was carried out in single collisions of krypton ions with Ne, Ar, Kr, and Xe atoms. The gases of these elements, which served as the targets, contained impurities in amounts not exceeding 0.1%. The highest energy of the accelerated krypton ions was 850 keV. This value was governed by the highest value of the magnetic field in the mass monochromator that we used.

a) Charge composition, average charge, and ionization losses of the ion energy. Figures 1—4 contain curves which represent the relative content of ions of different charge in a beam of krypton particles which has experienced single collisions by singly-charged ions with Ne, Ar, Kr, and Xe atoms. These curves are given in the form of dependences of the charge fractions F_n on the ion energy E for deviation angles $\theta_{l.c.}$, equal to 1, 2, and 3°.

As is evident from the figures, the curves representing ionic charges greater than 2—3 have maxima. In spite of the relatively narrow range of energies, the number of maxima is much greater than that arising in the interaction of argon ions with argon and krypton atoms.[7] Moreover, it is evident that even at low scattering angles the beam contains relatively large amounts of ions having a degree of ionization higher than 8. The presence in the beam of krypton ions whose degrees of ionization lie in the range 9—12 indicates that a considerable part of the inelastic energy loss is due to the excitation and ionization of the electrons from the inner M-shell of the krypton atom.

Comparison of the charge distributions, obtained in Ne, Ar, Kr, and Xe, shows that the curves for Ne, Kr, and Xe, representing the same number of lost electrons for the same scattering angles $\theta_{l.c.}$ are displaced, compared with Ar, in the direction of higher energies and this displacement is more noticeable for Xe than for Kr.

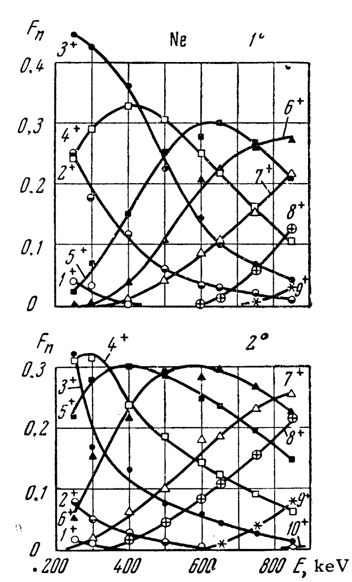

FIG. 1. Dependence of the distribution of charge states on the energy of Kr ions in Ne.

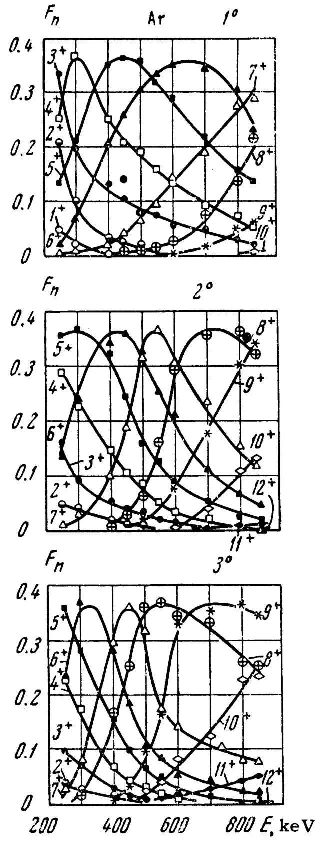

FIG. 2. Dependence of the distribution of charge states on the energy of Kr ions in Ar.

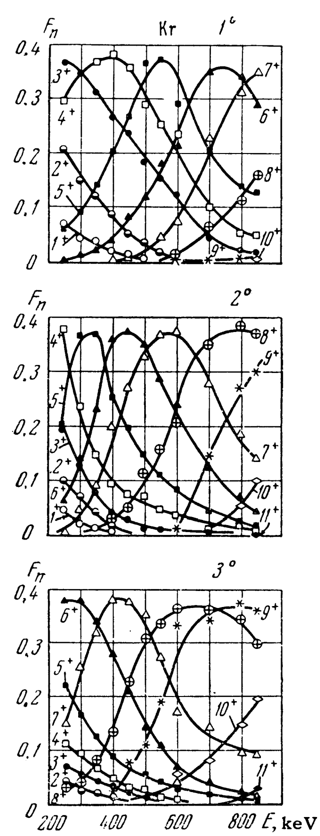

FIG. 3. Dependence of the distribution of charge states on the energy of Kr ions in Kr.

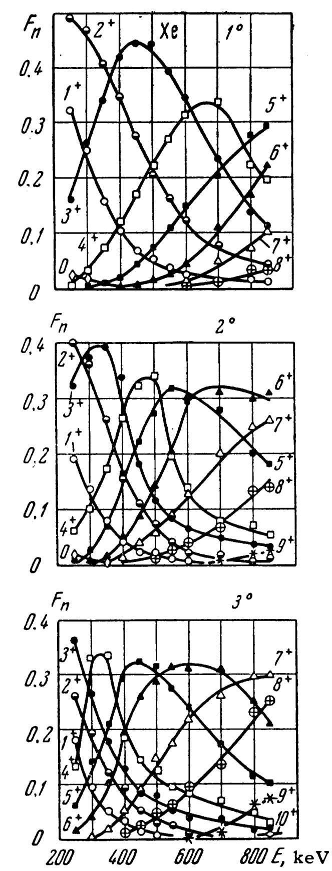

FIG. 4. Dependence of the distribution of charge states on the energy of Kr ions in Xe.

This difference can be observed more clearly in the dependence of the average ion charge $\bar{n} = \Sigma_n n F_n$ on the nature of the target atoms. The dependences of the average charge $\bar{n}$ on the velocity of krypton ions in Ne, Ar, Kr, and Xe are given in Fig. 5 for the scattering angles 1, 2, and 3°.

It is evident from Fig. 5 that, in the investigated range of energies, the charge $\bar{n}$ always increases linearly as the ion velocity v increases.

It is easy to show that, for single collisions, the distributions of the ion charge in a beam, plotted as a function of $(n - \bar{n})$, satisfy approximately the normal distribution. This observation stresses the random nature of the process of electron loss by the bombarding ions in single collisions of atomic particles in the investigated range of energies.

Since the total differential cross sections for the scattering of ions, reported in the present paper and in [7], are in satisfactory agreement with the values calculated by Everhart et al.,[8] we can determine, using the tables given in [8], in each investigated case the distance, r_0, of the closest approach between the nuclei of the interacting particles. Using the data on the charge distribution in ion beams and the calculated

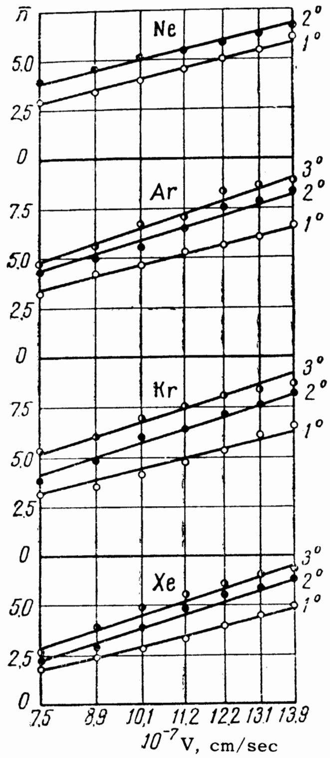

FIG. 5. Dependence of the average charge in a beam of Kr ions, in the case of single collisions with Ne, Ar, Kr, and Xe atoms, on the velocity of the ions.

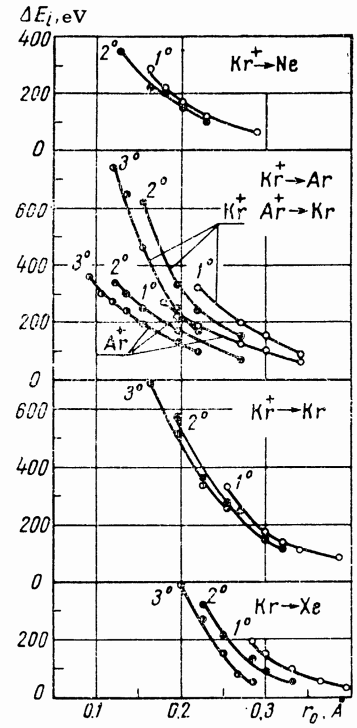

FIG. 6. Dependence of the energy loss in the ionization of the incident Ar or Kr ion on the distance of closest approach between the nuclei for θ = 1–3° in Ne, Ar, Kr, and Xe.

values of the ionization potentials,[9] we can plot the dependence of the average energy loss due to the ionization of the bombarding ions, ΔE_i, as a function of the distance of closest approach between nuclei, r_0.

Figure 6 gives such dependences for the interaction of argon ions with krypton atoms and for the interaction of krypton ions with Ne, Ar, Kr, and Xe atoms for the angles θ = 1, 2, and 3°. (The data for argon ions in krypton were taken from [7].) It is evident from Fig. 6 that the average ionization losses ΔE_i for krypton ions increase as the distance of closest approach r_0 gets smaller; the steepness of the rise of ΔE_i is a function of r_0 and in some parts of the curves the slope is quite steep. Comparison of the data given in Figs. 1—4 and in Fig. 6 shows that the rapid rise of ΔE_i occurs when the electrons of the M-shell of the krypton atom begin to make a considerable contribution to the interaction.

Apart from the dependence of ΔE_i on r_0, we observe some systematic increase of ΔE_i as the ion energy E increases for fixed values of r_0. This follows from the fact that for fixed values of r_0 the lower angles θ correspond to considerably higher values of the ion energy; it is also evident from the figure that for the same r_0 the ionization energy losses ΔE_i are greater for low angles θ.

In the case of Kr^+ collisions with Ne and Kr atoms, the dominant influence on the value of the average ionization energy loss by these ions, ΔE_i, is the distance of closest approach r_0. However, in the case of Kr^+ collisions with Ar and Xe atoms, the value of the energy of the incident ion E also has a considerable influence. It is worth noting the large difference between the values of the average ionization energy losses ΔE_i of argon ions in krypton and of krypton ions in argon for the same distances of closest approach and the same scattering angles, i.e., for the same energies. The value of the ionization energy losses of krypton is considerably greater than that of argon and the difference becomes particularly large at r_0 less than 0.2 Å. It is possible that this causes some reduction in the probability of the loss of several electrons on going over from Ar atoms to Xe atoms. As the atomic number increases in going from Ar, through Kr, to Xe, the incident-ion share of the energy lost in the ionization of the colliding particles becomes relatively smaller, compared with the energy loss in the ionization of the target atom.

Some new features of the interaction between atomic particles were discovered in the recently published investigations of Afrosimov et al.[10,11] In the case of single collisions of atoms and of singly-charged argon ions with argon atoms, Afrosimov et al. found that in any process involving a change in the charge state of the interacting particles the inelastic energy loss has several discrete values. It is also shown that the excess energy loss has discrete characteristic values and that the process of ionization on collision is associated with the excitation of some "line" of the excess energy loss.

The present investigation shows that the inner-shell electrons take a considerable part in the collective excitation.

These observations were not allowed for, and, moreover, could not be allowed for by the existing theories of the interaction between many-electron atoms, and one could not expect agreement between the theoretical and experimental data. However, for Ar^+[7] and Kr^+ in collisions with Ar and Kr atoms, a more or less close agreement was obtained between the experimental data on the distribution of charge states and the theoretical data of Russek,[5] obtained on the assumption that the ionization energy was independent of the number of lost electrons. In the case of the interaction of Kr^+ with Ne and Xe atoms, the curves which gave the dependence of the charge fractions on the energy had lower maxima than those which followed from Russek's theory. The present measurements have shown that the nature of the interaction between atomic particles depends also on the nature of the target atoms, which was not allowed for in Russek's theory. It is evident that to develop further the ideas on the mechanism of the interaction between atomic particles it is essential to accumulate more experimental data and, as pointed out by Afrosimov et al.,[10] to develop new theoretical representations, without rejecting the possibility of modifying the existing theories.

b) Differential scattering cross sections and integral cross sections for the capture and loss of electrons. Figure 7 shows the results of the measurements of the total differential cross sections for the scattering of krypton ions σ^* in their interactions with Ne, Ar, Kr, and Xe atoms for the scattering angles $\theta_{l.c.} = 1-3°$; the random error in the measurement of σ was of the order of 25%. The same figure shows, as continuous lines, the dependences of the total differential cross sections for elastic scattering on the energy of the krypton ions, calculated on the assumption of a Coulomb interaction with the exponential screening given by Everhart et al.[8]

It is evident from Fig. 7 that the experimental data are in satisfactory agreement with the calculated curves. This indicates that the energy and angular distribution curves for the elastic and in-

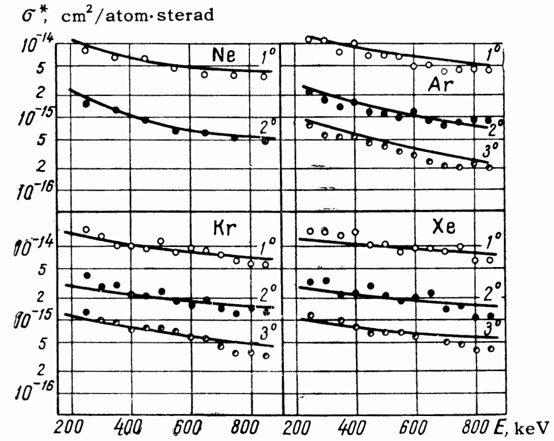

FIG. 7. Total differential cross sections for the scattering of Kr^+ ions in Ne, Ar, Kr, and Xe for $\theta = 1-3°$, as a function of the ion energy.

elastic scattering of Kr^+ ions in Ne, Ar, Kr, and Xe are practically the same over the whole investigated range of angles and energies. The values obtained here of the total differential scattering cross sections σ^* and of the charge fractions F_n make it possible to calculate the differential cross sections for the loss of (n − 1 electrons) by singly-charged krypton ions using the formula

$$\sigma_{1n}^* = \sigma^* F_n. \tag{1}$$

The dependences $\sigma_{1n}^*(\theta)$ were determined for the angular range 1−3% at energies of 250−850 keV in steps of 100 keV. Using these data, we carried out a numerical integration over a range of angles for the purpose of determining the partial integral cross section for the electron loss by singly-charged ions, corresponding to the range of deviation angles $\theta = 1-3°$, in collisions with Ar, Kr, and Xe atoms, and for $\theta = 1-2°$ in collisions with Ne atoms.

The partial effective cross sections for the electron loss, $\sigma_{1n}(0-1°)$, by singly charged krypton ions in the angular range $\theta = 0-1°$ were measured directly.

In the angular range 0−1°, the measured effective cross sections for the electron capture by singly-charged krypton ions σ_{10} were practically equal to the total cross sections, since in this case the scattering of ions through angles larger than 1° was very weak in all the investigated gases and throughout the whole energy range.

The total integral effective cross sections for the electron loss by singly charged krypton ions can be determined as the sum of the partial cross sections corresponding to the angular ranges

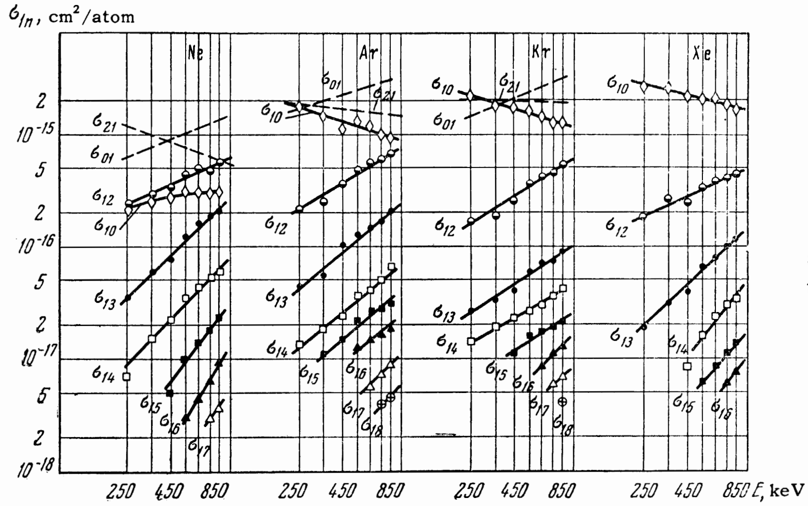

FIG. 8. Energy dependence of the total cross sections for the capture σ_{10} and loss σ_{1n} of electrons by Kr ions and Ne, Ar, Kr, and Xe.

from 0 to 180°:

$$\sigma_{1n} = \sigma_{1n}(0-1°) + \sigma_{1n}(1-3°) + \sigma_{1n}(3-180°). \quad (2)$$

In those cases when the value of $\sigma^*_{1n}(\theta)$ in the angular range 1—3° (1—2° for neon) decreases rapidly and approaches zero, as the angle θ increases, we can, without committing a large error, neglect the quantity σ_{1n} (3—180°), and assume θ_{1n} to be the total effective cross section for the loss of (n − 1) electrons by singly-charged krypton ions.

The values of the integral effective cross sections for the electron loss σ_{1n}, obtained on this assumption, are given in Fig. 8 in the form of the dependences σ_{1n} on the ion energy. The same figure includes the results of the measurements of the effective cross sections for the electron capture σ_{10} by singly charged krypton ions.

Since the probabilities of the simultaneous loss and capture of several electrons are less than the probability of the loss and capture of one electron, the cross sections for the loss and capture of several electrons may be neglected and we can estimate the cross sections for the capture of electrons σ_{21} by doubly-charged krypton ions and the cross sections for the electron loss by fast krypton atoms σ_{01}, using the relationships

$$\sigma_{21} = \sigma_{12}F_{1\infty} / F_{2\infty}, \qquad \sigma_{01} = \sigma_{10}F_{1\infty} / F_{0\infty}, \quad (3)$$

where $F_{0\infty}$, $F_{1\infty}$ and $F_{2\infty}$ are the corresponding charge fractions in an equilibrium beam of krypton ions. The values of the quantities $F_{0\infty}$, $F_{1\infty}$ and $F_{2\infty}$ for Ne, Ar, and Kr were obtained by us in an earlier investigation of equilibrium fractions of ions in gases.[12] The corresponding values of σ_{01} and σ_{21} are shown by dashed lines in Fig. 8. Since the cross sections for the loss and capture of several electrons were neglected, we can obtain only a rough approximation of the cross sections σ_{01} and σ_{21}, but the largest error in this determination is of the order of 40%.

Unfortunately, the experimental data with which we should compare the results of the present work are completely absent in the published literature. It can be seen from Fig. 8 that, in the investigated range of energies, the cross sections for the electron capture σ_{10} increase systematically as the atomic number of the target atom goes up. There is no such clear dependence on the nature of the target atom in the cross sections for the electron loss σ_{1n} by singly-charged ions. However, the energy dependence of the electron-loss cross sections σ_{1n} is given by an approximately linear function on logarithmic scale, i.e., the total effective cross sections for the electron loss by krypton ions are power functions of the energy or velocity of ions. The experimental errors in the determination of the total cross sections did not exceed 15—20%.

In conclusion, we regard it as our pleasant duty to express our gratitude to the accelerator operators K. M. Khurgin and V. G. Rubashko for their help in the measurements.

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