MANY-ELECTRON IONIZATION IN CLOSE COLLISIONS OF Ar *AND* Kr *IONS AND ATOMS*

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A scintillation counter was used to measure the angular and energy dependences of the charged fractions in Ar and Kr ion beams resulting from single collisions with Ar and Kr atoms. The results were used to determine the average energy lost in the ionization of colliding particles and the total effective cross sections for the loss of many electrons by Ar^+ and Kr^+ ions in Ar and Kr. The measurements were carried out on Ar ions of 250—1700 keV energies and on Kr ions of 200—850 keV energies in the angular range 1—11°.

1. INTRODUCTION

EARLIER investigations of the processes of ion scattering and stripping at energies of 200—1800 keV indicated an appreciable participation of inner-shell electrons of Ar and Kr atoms in the interaction of colliding particles.[1,2] The results of these measurements showed that even in the range of investigated scattering angles, not exceeding 2—3°, there was a tendency for the highly charged fractions to increase considerably when the distance between the nuclei of colliding particles decreased. The shortest internuclear distances reached in these measurements were 5×10^{-10} cm in collisions of Ar^+ ions with Ar atoms and 2×10^{-9} cm in collisions of Kr^+ ions with Kr atoms.

The method used in the measurement of the scattered-ion beam intensities in the case of short internuclear distances was unsatisfactory. Therefore, our aim was to develop a more sensitive method for measuring low-intensity ion beams and for studying the scattering of such ions through large angles. Our measurements were carried out in the energy range 250—1700 keV in the case of Ar ions and in the range 200—850 keV in the case of Kr ions; the angular range was 1—11°.

2. APPARATUS AND EXPERIMENTAL METHOD

We used an electrostatic accelerator and a magnetic mass monochromator, which had been employed earlier.[1-3] In other respects the apparatus was different. A schematic diagram of the apparatus used to carry out the measurements described below is given in Fig. 1.

A beam of accelerated ions, selected by a mass monochromator, was directed into a collision chamber 2 through a diaphragm 1. The constancy of the ion beam direction and its collimation were ensured by two diaphragms, one of which was placed at the entry to the mass monochromator and the other at the entry to the collision chamber. The divergence of the primary ion beam did not exceed 4×10^{-4} rad.

The diaphragm 1 was in the form of two halves which were insulated from one another, and connected respectively to two arms of a differential amplifier. This diaphragm stabilized the accelerator voltage and maintained the direction of the beam axis for a given value of the magnetic field in the monochromator.

The scattering angle was selected by rotation of an analyzer with respect to an axis passing through the center of the collision chamber. A beam of ions scattered at a definite angle was selected by two circular diaphragms 5 and 6 with apertures of 0.6 mm diameter. The distance between these diaphragms was 125 mm and the divergence of the scattered beam was $\approx 10^{-2}$ rad. The primary beam current of singly charged ions, entering the collision chamber, was measured with a Faraday cylinder 4 connected to a system of collimating slits. To avoid errors in the value of the primary-beam current, the secondary electron emission was suppressed by a potential supplied to an electrode 3, and the external surface of the measuring trap was fully protected by a grounded screen.

A scintillation counter 9, developed earlier and described in[4], was used as a detector of the fast ions scattered out of the primary beam. This counter consisted of a photomultiplier FÉU-38 and a CsI crystal which was in direct optical contact with the multiplier photocathode. The photomultiplier signal was recorded with an electronic circuit consisting of an amplifier, a pulse amplitude discriminator, and accounting unit. In

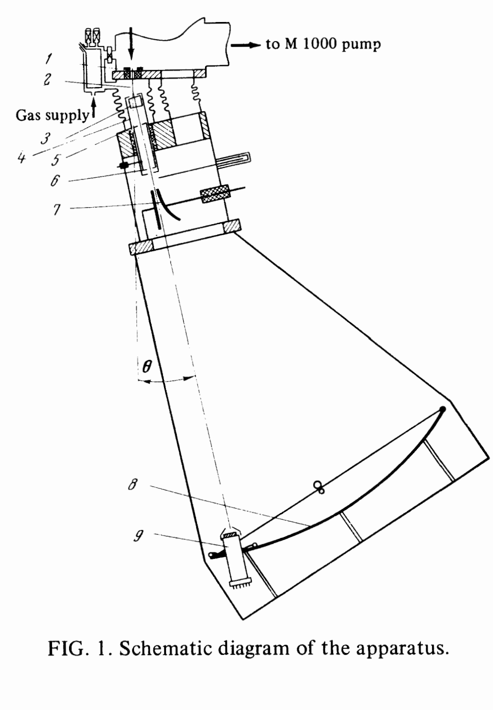

FIG. 1. Schematic diagram of the apparatus.

those cases when the average current at the photomultiplier output had to be measured, we used an electrometer amplifier of the ÉMU-3 type.

The narrow beam of ions selected by the collimating slits was split into charged components by the electric field of a capacitor 7. The distribution of the intensities of these components was investigated by moving the counter along a fixed-radius arc 8. The counter was set in motion by remote control using a servomotor, which transmitted rotation through the vacuum seal of the analyzer chamber. A potentiometric indicator placed on the reference arc 8 was used to determine and set the position of the counter.

The construction of the collision chamber, the vacuum conditions, the pressure measurements, and the method used in measurements of the differential and integral cross sections were the same as in[3].

3. RESULTS OF MEASUREMENTS AND DISCUSSION

A considerable increase in the sensitivity of the method which was used to detect fast ions enabled us to extend the range of overlapping velocities and internuclear distances in the interaction of Ar and Kr ions and atoms.

Figure 2 shows typical distributions of the charged fractions F_n resulting from single collisions of singly charged Ar ions with Kr atoms and singly charged Kr ions with Ar atoms; these distributions are plotted as a function of the distance of closest approach between the respective nuclei in the case of fixed ion velocities. We should mention also that in the measurements reported here we ensured that the collisions were of the single type because we were able to use very low target-atom concentrations, thanks to the high sensitivity of the ion detection system. The amplitudes of the maxima and the intersections of the charged fraction distributions obtained in the present study agreed, within the limits of the experimental error, with those obtained earlier.[1-3] This agreement refuted the objection of Everhart and Kessel[5] that the results of measurements of the charged fractions could be distorted by multiple collisions.

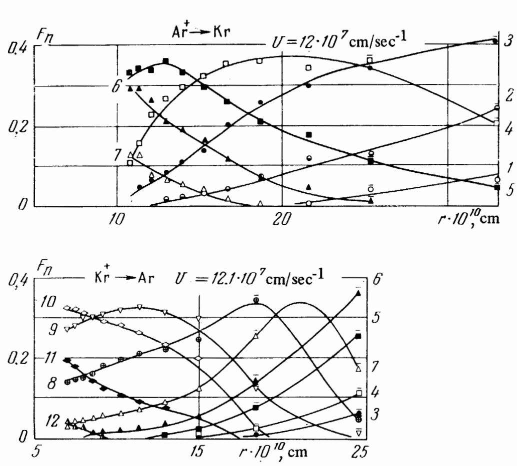

FIG. 2. Dependence of the distribution of charged states on the distance of closest approach between the nuclei of Ar and Kr particles in Ar and Kr. The points marked with a bar are taken from[1-3]. The numbers alongside the curves indicate the ion charge.

Figures 3 and 4 show the average energy ΔE lost in the ionization of incident particles which is plotted as a function of the distance of closest approach r between the nuclei of the colliding particles at fixed values of the ion velocities.

It is evident from Fig. 3 that the dependence of the ionization losses on the velocity of ions in the $Kr^+ \to K$ interaction is relatively weak over the whole range of

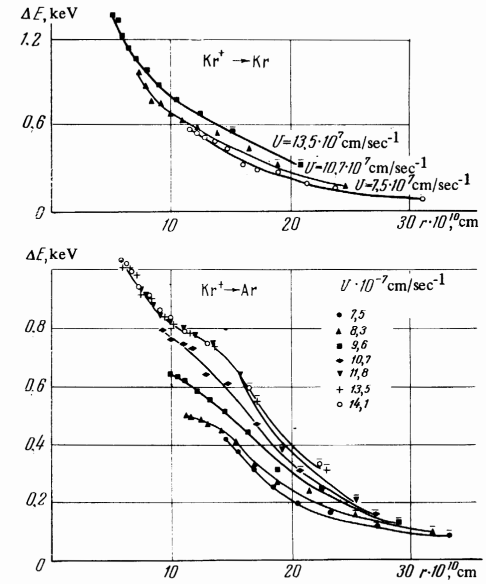

FIG. 3. Dependence of the average energy lost in the ionization of an incident Kr^+ ion on the distance of closest approach between the nuclei of the colliding particles. The points marked with a bar are taken from[1].

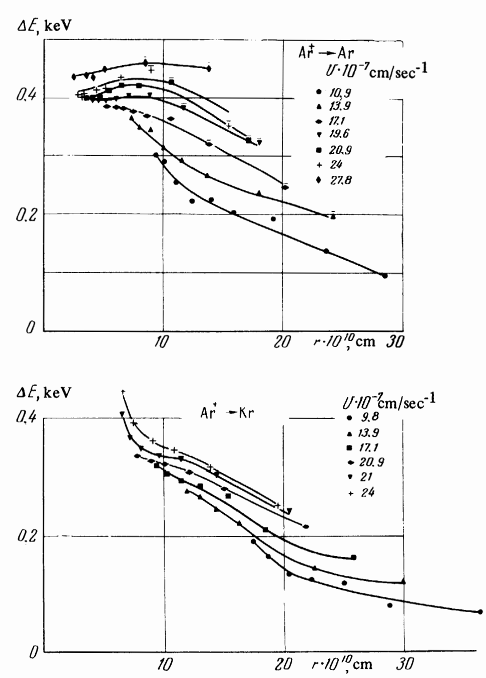

FIG. 4. Dependence of the average energy lost in the ionization of an incident Ar^+ ion on the distance of closest approach between the nuclei of the colliding particles. The points marked with a bar are taken from[2,3].

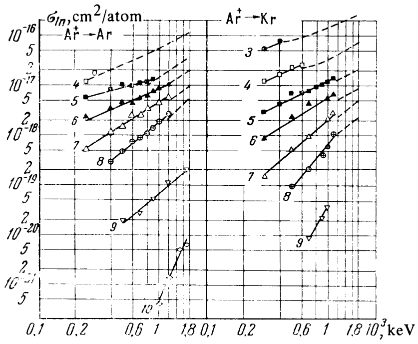

FIG. 5. Energy dependence of the total cross sections σ_{1n} for the loss of (n − 1) electrons by Ar⁺ in Ar and Kr. The dashed curves represent the results reported in[2,3]. The numbers alongside the curves are the values of n.

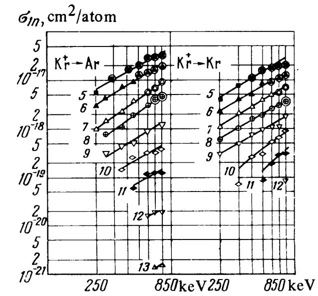

FIG. 6. Energy dependence of the total cross sections σ_{1n} for the loss of (n − 1) electrons by Kr⁺ in Ar and Kr. The points which are encircled represent the results reported in[1]. The numbers alongside the curves are the values of n.

investigated velocities. These energy losses depend more strongly on the internuclear distance, particularly in the range of small values of r. In the $Kr^+ \to Ar$ collisions, ΔE is practically independent of the Kr^+ ion velocity at the highest investigated velocities. In all other cases we can easily see that the ionization losses increase rapidly when the ion velocity is increased and when the internuclear distance between the colliding particles is reduced. The only exception are the $Ar^+ \to Ar$ collisions at very small values of r, corresponding approximately to the K-shells, where the ionization losses depend in practice only on the ion velocity.

It is interesting to compare the "opposite" pairs $Kr^+ \to Ar$ and $Ar^+ \to Kr$ for the same internuclear distances and relative velocities. It is evident from Figs. 3 and 4 that the ionization losses under the same conditions are about 2–2.5 times larger for the Kr atoms than for the Ar atoms. This indicates that the energy losses in the inelastic interaction of Ar and Kr particles are distributed in such a way that the atoms with a larger atomic number lose more energy by ionization. On the other hand, the ionization losses of ions of a given type (Ar^+ or Kr^+) do not depend strongly on the nature of the target atom. Similar results have been obtained earlier in a study of the interaction of Ne and Ar ions and atoms.[2] This conservation of the individual properties of particles suggests that electrons are lost by excited atoms after and not during collisions.

Our measurements showed (as before) that when the distance of approach between the colliding atoms was small, the experimental and calculated values of the total differential cross sections agreed within the limits of the experimental error. The data on the total differential scattering cross sections and on the values of the charged fractions obtained in the present study allowed us to determine the differential cross sections for the electron loss as a function of the scattering angle and the ion energy.

By integrating over the angles we calculated, whenever possible, the total effective cross sections for the electron loss by Ar^+ and Kr^+ ions in Ar and Kr. The results are presented in Figs. 5 and 6. These figures give also the values of the total cross sections for the loss of (n − 1) electrons which have been obtained earlier for smaller scattering angles. It is worth noting the relatively large values of the total cross sections for the loss of many electrons, including electrons from the inner shells of atoms. This observation is of theoretical and practical interest.

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