Differential scattering cross sections in K^+–Ar collisions

V. V. Afrosimov, Yu. S. Gordeev, and V. M. Lavrov

A. F. Ioffe Physico-technical Institute, USSR Academy of Sciences
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Elastic and inelastic scattering in K^+–Ar collisions is studied in the 1–4 keV energy range. The angular dependences are measured of the cross sections for elastic scattering, of the excitation of the K^+ ion and Ar atom, and of the charge exchange and autoionization of the Ar atom. The cross sections for the inelastic processes increase strongly when the threshold angle is reached and oscillate with further increase of the scattering angle. Comparison of the structures of the cross-section angular dependences show that effects related to the interaction of inelastic channels become important when some inelastic processes are excited.

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1. INTRODUCTION

The purpose of this study was to obtain data on the differential cross sections of elastic scattering and of all the principal inelastic processes occurring in K^+–Ar collisions in the energy range 1–4 keV.

The effectiveness of such a comprehensive approach to the study of inelastic processes was demonstrated in[1], where we compared the spectra of the inelastic ion energy losses with the luminescence spectra and determined from this comparison the relative probabilities of a number of inelastic processes, and estimated their cross sections. The investigations of[1] have also shown that the possibility of interpreting the experimental results depends significantly on the availability of data on the absolute cross sections of the inelastic processes. We have therefore carried out in the present study absolute measurements of the elastic-scattering and charge-exchange cross sections. We note that in spite of the intensive development of research on collision spectroscopy, there are relatively few data on the differential charge-exchange cross sections.

At velocities corresponding to the investigated range of ion energies, one can use a quasimolecular treatment of atomic collisions, and it can be assumed that the inelastic processes are the result of electronic transitions at the quasi-intersection points of the terms of the system produced in the collision process. The differential cross sections of the inelastic processes have therefore a threshold character with respect to the scattering angle. An investigation of the angular dependences of the differential cross sections of the elastic and inelastic scattering yields detailed information on the interaction of the particles during the course of the collision.

Preliminary results of a study of the angular dependences of the differential cross sections for the excitation and autoionization of Ar in K^+–Ar collisions are given in[2].

2. MEASUREMENT PROCEDURE

In this experiment we determined the dependences of the differential cross sections $d^2\sigma/d\omega dQ = f(Q, \theta)$ for ion scattering at fixed angles on the inelastic energy loss (the inelastic-loss spectra) and the angular dependences of the differential charge-exchange cross sections $d\sigma_{ce}/d\omega = f(\theta)$. The inelastic-loss spectra were used to obtain the angular dependences of the cross sections for the excitation of the inelastic transitions and of the elastic scattering.

A brief description of the experimental setup used for the measurement of the ion inelastic-loss spectra is given in[1,3]. A collimated ion beam was introduced into a collision chamber filled with the investigated gas. A rotating collimator was used to separate the ions scattered through fixed angles in the single collisions. These ions were energy-analyzed with a parallel-plate electrostatic analyzer and detected with a secondary-electron multiplier of the venetian-blind type. The inelastic energy-loss spectra were recorded automatically. The relative energy resolution of the apparatus was 1300, the angular resolution (the width of the apparatus function at half-height) was ~15′, and the relative error in the determination of the inelastic energy losses was 1–2%. The relative errors in the determination of the differential scattering cross sections depended on the types of the processes and will be considered in the appropriate sections. The spectra were investigated in the angle range 1–10°.

In the absolute measurements, the scattered ions or atoms were separated by a special rotating collimator with a controllable geometric factor. The construction of the collimator provided for shielding the beam against stray electric and magnetic fields and prevented passage of the particles as a result of reflections. In the determination of the charge-exchange cross sections it was assumed that the efficiency of the registration of alkali-metal atoms and ions of equal energies was the same. At the energies investigated by us this assumption is well satisfied[4].

All the angular dependences of this differential cross section are given in terms of the reduced coordinates[5]

$$\rho(\tau) = \theta \sin\theta \frac{d^2\sigma}{d\omega\, dQ}, \quad \tau = \theta E,$$

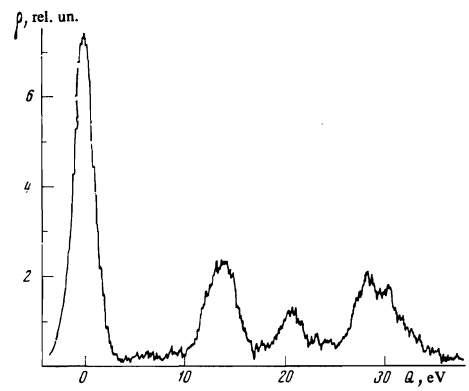

FIG. 1. Spectrum of the energy losses of K^+ ions on Ar atoms. $\rho = \theta \sin\theta\, d^2\sigma/dQd\omega$. $T_0 = 1.5$ keV, $\vartheta = 4°20'$.

where θ is the ion scattering angle in the c.m.s. and E is the kinetic energy of the ions in the c.m.s.

3. MEASUREMENT RESULTS

A typical ion energy-loss spectrum at a fixed scattering angle is shown in Fig. 1. The observed peaks correspond to elastic scattering of the ions (Q = 0 where Q is the inelastic energy loss), and also to the excitation and ionization of the Ar atoms and the excitation of the K^+ ions, T_0 is the kinetic energy of the ions in the laboratory frame, and is the ion scattering angle in the laboratory frame. A detailed identification of the loss spectra was carried out in[1]. We consider below the main features observed in the investigation of scattering via various channels.

1. Elastic Scattering

The elastic-scattering differential cross sections in absolute units, measured at several values of the ion energy, are shown in Fig. 2. The errors in the investigation of the shapes of the angular dependence curves can be described by the error with which the ratio of the cross sections measured in scattering through arbitrary two angles from the investigated range is determined, and in the present case this error is estimated at 10%. The error of the absolute measurements of the cross sections is 20%, and the error in the determination of the scattering angle is (2–3)′ (in the laboratory frame). The cross sections were investigated in the reduced scattering-angle region from 0.2 to 25 keV-deg.

In the range 0.2–5.0 keV-deg of angles τ (not shown in Fig. 2) the elastic-scattering cross sections in reduced coordinates depends little on the scattering angle and can be represented by an almost horizontal line slightly inclined towards the larger angles. This scattering-angle range corresponds to single-channel scattering with pure elastic interaction of the colliding particles.

For an analysis of the multichannel scattering, greatest interest attaches to the range of angles exceeding 5–6 keV-deg (Fig. 2). In ion scattering through angles larger than these so-called threshold angles, the elastic-scattering differential cross section decreases sharply. This is due to the attainment of internuclear distances at which the terms of the system intersect and transitions of the system from the ground state to excited states becomes possible. In the range of angles larger than 5–6 keV-deg, the angular dependences of the elastic-scattering cross sections contain structural singularities that can be connected with concrete inelastic transitions.

2. Ion Scattering and Charge Exchange

Figure 3 shows the summary differential cross sections for ion scattering with conservation of positive charge and with neutralization of the charge (charge exchange). In the former case we registered only the positive ions (of any multiplicity), and in the latter case the atoms. The error of the absolute measurements of the ion scattering cross section is estimated at 20%, and the error of the charge-exchange cross sections at 50%.

At angles smaller than 5.5 keV-deg the ion scattering is pure elastic. The decrease of the positive-ion scattering cross section in the large-angle region may be due to the inclusion of charge-exchange and double-capture processes, in which single positive ions become neutral atoms or negative ions.

The charge-exchange process as seen from Fig. 3 (curves 2 and 3) has a threshold character and is accompanied by scattering of particles in a wide range of angles. With increasing ion energy, the maximum of the cross section shifts somewhat towards the larger angles. This behavior of the maximum of the cross section is typical of processes that are excited when terms of like symmetry intersect[6,7].

By integrating the differential cross sections with respect to the scattering angle we obtained an estimate of the total charge-exchange cross section, which at an ion energy 2.0 keV amounted to 1.2×10^{-16} cm^2, to within a factor of 2. This cross section is approximately 25–30 times larger than that measured at the same energy by Ogurtsov, Kikiani and Flaks[8]. The reason for the decrease of the charge-exchange cross section in[8] is that, as seen from Fig. 3, when measuring the total charge-exchange cross section it is necessary to ensure that the charge-exchange particles be gathered from a sufficiently large range of scattering angles; the latter, in so far as one can judge from the description of the procedure, was not done in[8].

At angles larger than 5.5 keV-deg, a stripping process can set in in addition to the charge exchange and

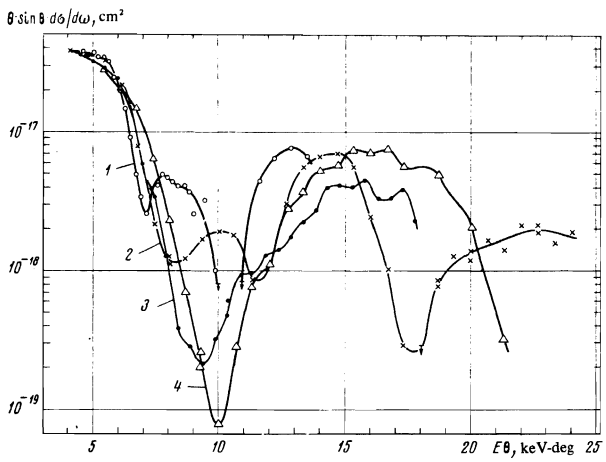

FIG. 2. Angular dependences of the differential cross sections for elastic scattering of K^+ by Ar atoms. Curves: 1) T_0 = 1.3 keV, 2) 2 keV, 3) 3 keV, 4) 4 keV.

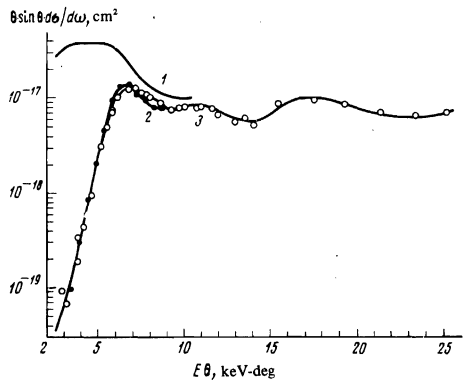

FIG. 3. Angular dependences of the differential cross sections for the scattering of K^+ ions by Ar: curve 1—with conservation of positive charge, T_0 = 2 keV; 2, 3—with neutralization of the ions (charge exchange); curve 2) T_0 = 1 keV, 3) T_0 = 2 keV.

double capture. As shown by measurements with the energy-analyzer voltage reduced to approximately one-half, so that the analyzer can pass only doubly-charged ions, the differential stripping cross section is $\rho < 10^{-19}$ cm^2 in the angle range (2–10) keV-deg and at an ion energy 2.0 keV.

3. Excitation of the Argon Atom

It was shown in[1] that in the energy-loss region corresponding to excitation of the argon atom, at an ion energy 2.0 keV, the levels excited with the largest probability are those with energy 13.0–14.0 eV, while the levels with energies 11.6–11.8 eV, with configuration $3p^5 4s$, have a much lower probability. Energies from 13.2 to 14 eV can correspond to excitation of levels with configurations $3p^5 4p$, $3p^5 3d$, and $3p^5 5s$. Since these levels are close in energy, the relative probabilities of their excitation were not determined, and therefore the total cross section of their excitation was measured.

Figure 4 shows the region of the first maximum of the angular dependences of the summary differential cross sections for the excitation of these levels and of the levels with configuration $3p^5 4s$. In spite of the fact that the levels $3p^5 4s$ correspond to the lowest-excited states of the Ar atom, the cross section for the excitation, as seen from the figure, is much smaller than the cross section for the excitation of the group of $3p^5 4p$, $3p^5 3d$, and $3p^5 5s$ levels. At the energy resolution employed in this study, this circumstance causes the measured cross section for the excitation of the $3p^5 4s$ levels in the region of small angles to be overestimated, and it can be used in the determination of the threshold excitation angles only for rough estimates.

In Fig. 5 are compared the summary differential cross sections for the excitation of the group of levels $3p^5 4p$, $3p^5 3d$, and $3p^5 5s$ at different ion energies. For convenience in the comparison, the curves are arbitrarily shifted along the ordinate axis. The oscillations of the cross sections are due to the interference of the scattering amplitudes. A similar oscillation mechanism was considered, for example, in[6,7]. With increasing ion energy, the second and third maxima in the angular dependences shift towards larger angles. In accordance with the oscillation theory[6,7], the shift of the first maximum should be much smaller than that of the second and third maxima, and when the ion energy changes from 2 to 4 keV it should amount to ~0.5 keV-deg. It is seen from the figure that the maximum shifts by a much smaller amount. At the same time, when the energy is increased from 1.0 to 2.0 keV, the shift of the maximum, as shown by analysis, agrees with the predictions of the theory.

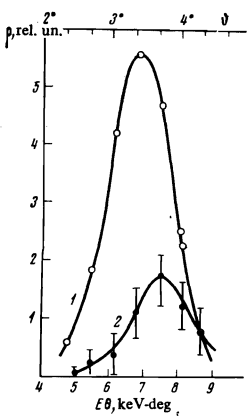

FIG. 4. Angular dependences of the summary differential cross sections for the excitation of the Ar levels $3p^5 4p$, $3p^5 3d$, and $3p^5 5s$ (curve 1) and of the Ar levels $3p^5 4s$ (curve 2) in the region of the first maximum in K^+–Ar collisions. $T_0 = 2.0$ keV.

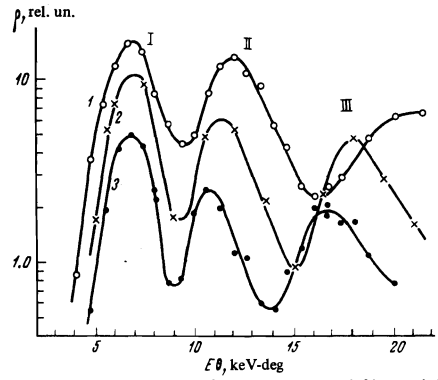

FIG. 5. Angular dependences of the summary differential cross sections for the excitation of the levels $3p^5 4p$, $3p^5 3d$, and $3p^5 5s$ of Ar atoms in K^+–Ar collisions. The numbers I, II, and III indicate the serial numbers of the maxima. Curves: 1) $T_0 = 4$ keV, 2) $T_0 = 3$ keV, 3) $T_0 = 2$ keV.

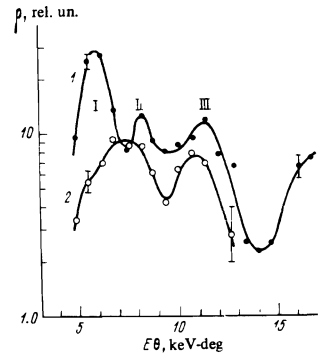

FIG. 6. Angular dependences of the differential cross sections for the scattering of K^+ ions by Ar atoms at fixed energy losses Q = 20 eV (curve 1) and Q = 24 eV (curve 2) (corresponding to excitation of the $3p^5 4s$ and $3p^5 4p$ states of the K^+ ions).

The excessively weak dependence of the position of the maximum on the ion energy in the 2–4 keV range can be attributed to the influence exerted on the position of the maximum by the finite angular resolution of the apparatus, the role of which, as can be easily seen, increases with increasing energy.

4. Excitation of the K^+ Ion

An analysis of the spectra of the ion energy losses has shown that the K^+-ion levels having the largest probability of excitation in K^+–Ar collisions are those with configuration $3p^5 4s$. It is also possible to separate in the loss spectra a region corresponding to excitation of levels with configuration $3p^5 4p$. The angular dependences of the differential cross sections for the excitation of the levels with these configurations are shown in Fig. 6

With increasing ion energy, the maxima of both angular dependences shift towards larger angles. The position of the threshold angle τ_{thr} and of the first, second, and third maxima of the excitation cross section of the levels $3p^5 4s$ at energies 2.0 and 4.0 keV are listed in Table I. The threshold scattering angle was chosen to be the one at which the excitation cross section reaches its half value at the maximum of the first peak of the angular dependence. The shifts of the maxima agree with the quasiclassical theory of oscillations[6,7].

5. Excitation of Autoionization States of Ar

At energies 1–4 keV, only states with energies 25–34 eV are excited with noticeable probability. These energies correspond to single-electron autoionization states connected with excitation of one 3s electron, and two-electron states connected with excitation of two 3p

TABLE I

T_0, keV	τ, keV-deg			
	τ_{thr}	$\tau_{max\ I}$	$\tau_{max\ II}$	$\tau_{max\ III}$
2.0	5.0	5.8	7.9	11.4
4.0	4.9	6.3	9.0	14.3

electrons of Ar. In the region corresponding to excitation of the autoionization states, the spectra take the form of maxima on which a structure due with partial resolution of the autoionization lines appears when the ion energy is lowered. The spectra in the region of the autoionization maxima were identified in accordance with the data on the energy of the autoionization levels from[9,10]. It should be noted that at the present time many autoionization states of Ar (for example the triplet states, S states, etc.), which are excited in ion-atom collisions, have either not yet been investigated or else their energy was determined with insufficiently high accuracy. This circumstance has made it difficult to identify the loss spectra. An investigation was made of the dependence of the differential scattering cross sections at various fixed values of the energy losses in the range 26–34 eV. A comparison of the angular dependences has shown that they differ somewhat in form (see Fig. 7) and obviously correspond to excitation of different groups of autoionization levels. It was found that the averaged energies of these level groups amount to ~26, 28.5, 30.5, and ~32 eV. The error in the energy determination is estimated at ± 0.3 eV. The level groups excited with the largest probability are those with energies 28.5 and 30.5 eV. A joint analysis of the inelastic-loss spectra and of the correlation diagram of the K^+–Ar system has shown that among the series of levels corresponding to the energy loss 28.5 eV one can separate the Ar levels $3p^4(^3P)4s(P)4p$ and $3p^4(^3P)4s^2$, which are close in energy, and for 30.5 eV one can separate the Ar level $3p^4(^3P)3d(P)4p$.

The angular dependences of the differential cross sections for the excitation of the groups of autoionization levels are shown in Fig. 7. Owing to the apparatus broadening of the lines in the loss spectrum, a mutual distortion of the shapes of these curves is possible. The degree of distortion can be quantitatively estimated from a comparison of curves 1 and 2 in the threshold region (~6 keV-deg). It is seen from the figure that the thresholds for the excitation of the levels differ significantly. In scattering of the ions through angles smaller than ~6.5 keV-deg there are excited in practice only the levels with Q = 28.5 eV, and in large-angle scattering there are excited also the levels with Q = 30.5 and 32 eV. The threshold angles τ_{thr} and the angular positions of the maxima of the differential cross sections $\tau_{max\ I,II,III,IV}$ at a few other ion energies are listed in Table II. The relative intensity of the autoionization lines in the loss spectra changes with changing ion energy. Thus, the intensity of the lines with Q

TABLE II

Q, eV	τ, keV-deg					Q, eV	τ, keV-deg				
	τ_{thr}	$\tau_{max\ I}$	$\tau_{max\ II}$	$\tau_{max\ III}$	$\tau_{max\ IV}$		τ_{thr}	$\tau_{max\ I}$	$\tau_{max\ II}$	$\tau_{max\ III}$	$\tau_{max\ IV}$
T_0=1.0 keV						T_0=2.0 keV					
26	~4.8	~5.4				26	4.9	5.7			
28.5	~4.6	~5.4				28.5	5.1	5.9	7.9	11.3	17.0
T_0=1.5 keV						30.5	>6.7	7.9	11.3	17.0	
26	4.8	5.7	8.0			T_0=4.0 keV					
28.5	4.7	5.7	8.0	9.8		26	>5.2	6.7	8.7	15.5	
30.5	~7.0	7.8				28.5	~5.3	<7.2	8.7	15.0	
						30.5	6.5	8.7	~14.5	20.5	

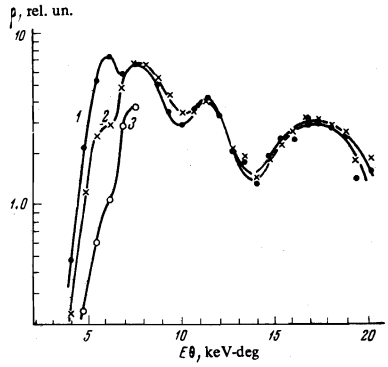

FIG. 7. Angular dependences of the differential cross section for the scattering of K^+ ions by A atoms at fixed energy losses: curves: 1) Q = 29 eV, 2) Q = 30 eV, and 3) Q = 32 eV. T_0 = 2.0 keV.

= 30.5 eV is much lower than the intensity of the lines with Q = 28.5 eV at an ion energy 1.0 keV, and somewhat larger at 4.0 keV. With increasing ion energy, the number of autoionization states whose excitation makes a noticeable contribution to the loss spectra increases, primarily on account of the states with the larger excitation energy. It should therefore be noted concerning the angles listed in Table II that at 4.0 keV the presented angles are averaged over a larger number of autoionization states than at 1–2 keV.

4. PRELIMINARY DISCUSSION OF THE RESULTS

A comparison of the angular dependences of the differential cross sections of the inelastic processes and angles corresponding to the maxima of these dependences, obtained in the present study (from Tables I and II), enables us to note the following features of the cross sections.

1. The positions of the maxima and other structure singularities of the angular dependences of the summary differential cross sections for the excitation of the K^+ ion levels with configuration $3p^54s$ (Fig. 6, curve with Q = 20 eV) and of the Ar autoionization levels with energies in the region 28.5 eV (Fig. 7, curve 1) coincide within the limits of experimental error.

2. The oscillations of the summary differential cross section for the excitation of the Ar levels with configurations $3p^54p$, $3p^53d$, $3p^55s$ (Fig. 5) have a large amplitude and a regular phase variation.

The correspondence, noted in Sec. 1, between the differential cross section for the excitation of the 28.5-eV autoionization levels of Ar and the $3p^54s$ levels of the K^+ ion shows that excitation of each of these channels cannot be regarded independently as a result of interaction of the ground term of the system with the corresponding term of the excited state. It is obvious that to explain the mechanism whereby the considered channels are excited it is necessary to take into account the interaction of the channels with one another. As to the excitation of the Ar levels, the large oscillation amplitude noted in Sec. 2 may be due to interference of only two scattering amplitudes. It follows from this that the process of Ar excitation can be analyzed within the framework of the approximation of two interacting terms.

Further progress in the clarification of the inelastic process mechanisms presupposes a detailed analysis of the interaction of the inelastic channels and is possible on the basis of a comparison of the experimental data

with the correlation diagram of the electronic terms of the system of colliding particles.

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