Ionization, charge exchange, and stripping in K^+–He and K^+–Ne collisions at ion energies 0.7–7.0 keV

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The total cross sections for ionization, charge exchange, and stripping of ions in K^+–He and K^+–Ne collisions have been measured for ion energies over the range 0.7–7.0 keV. The ionization and charge-exchange cross sections were found by a refined version of the potential method. The stripping cross sections were found by detecting fast doubly charged potassium ions. Correlation diagrams are plotted for the electronic terms of the systems of colliding particles. The experimental data and the correlation diagrams are used to discuss the mechanisms for ionization, charge exchange, and stripping in these collisions. It is shown that in each case the charge exchange is caused by capture to the ground state of the atom. In K^+–He collisions, corresponding quasimolecular terms are populated through $^1\Sigma$–$^1\Sigma$ transitions in nonadiabatic regions. An interaction of inelastic changes gives rise to structural features on the energy dependence of the cross sections. The ionization mechanism involves the filling of quasimolecular autoionization terms, which decay in the stage in which the quasimolecule exists. In K^+–He collisions, these terms are populated as a result of Σ–π and Σ–π–Δ transitions; in K^+–Ne collisions, they are populated as a result of Σ–Σ transitions. The stripping in K^+–He collisions occurs by a mechanism involving a transition of a diabatic term into the continuum.

Information on the absolute values of the cross sections for ionization and charge exchange in collisions of K^+ ions with He and Ne atoms and information on the energy dependence of these cross sections are of interest because the cross sections in these collisions may be one or two orders of magnitude smaller than in, say, collisions of K^+ ions with atoms of other gases, as has been pointed out in several places.[1–5] A determination of the structure of the cross sections in these collisions is important for reaching an understanding of the mechanisms for inelastic transitions in the outer shells of colliding atomic particles. Tests of the existing theories require data on both the energy dependence of the cross sections and the absolute values of the cross sections. Despite the many studies of these particle pairs which have been carried out, by a variety of methods,[1,2,4,6–11] the data available on the absolute cross sections for ionization[1,2,5,7,8,11] are contradictory, while the data on the charge-exchange cross sections[6] are unreliable.

In order to make use of the measured cross sections for electron production it is necessary to know the ionization cross sections of the target atoms and the absolute cross sections for stripping of the incident ions. Since there have been no previous measurements of the stripping cross sections in K^+–Ne, Ne collisions, it was also necessary to measure these cross sections.

Charge-exchange cross sections were measured in Ref. 6 through the detection of fast neutral particles in a bounded interval of scattering angles. As was shown in Ref. 12, the restriction on the interval of collection angles in Ref. 6 resulted in an underestimate of the measured cross sections by a factor of tens in measurements of the charge exchange in K^+–Ar, K^+–Kr, and K^+–Xe collisions in the energy range considered there. The charge-exchange cross sections in Ref. 6 may also have been underestimated for K^+–He and K^+–Ne collisions, so that it was necessary to carry out these measurements by a method free of this deficiency.

For the ionization measurements we selected the method of collecting charged particles in a transverse electric field (the capacitor method[13]). In charge-exchange measurements this method may result in significant errors, because the scattered particles may strike the measurement electrodes in cases in which the scattering by the target atoms is pronounced, as is the case, e.g., in K^+–Ne collisions at low collision energies. We accordingly used a refined version of the capacitor method[14] in the present experiments. In this refined version, the effect of scattering on the measured results is substantially reduced.

MEASUREMENT PROCEDURE

1. The method of collecting charged particles in a transverse electric field yields direct measurements of the cross sections for the production of secondary positive ions (σ^+) and electrons (σ^-) as the primary beam passes through the gas under study. These measured quantities are related in an obvious way to the capture cross section σ_c and the apparent ionization cross section σ_i, which are to be determined

$$\sigma^+=\sigma_c+\sigma_i, \quad \sigma^-=\sigma_s+\sigma_i;$$

here σ_s is the cross section for the stripping of the incident ions. The cross section σ_i is always larger than the cross section for single ionization, σ_i^1; only if the cross sections for multiple ionization and for ionization with capture are small does the relation $\sigma_i \approx \sigma_i^1$ hold.

The cross sections σ^+ and σ^- are measured in a mass-spectrometric apparatus similar to the arrangements which have been used in previous measurements by means of a

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transverse electric field (e.g., Ref. 15). The apparatus and procedure of the present measurements are described in detail in Ref. 14.

Ions from a surface-ionization source are accelerated and focused by an ion-optics system and mass-analyzed by a magnetic mass spectrometer. They then enter the collision chamber, filled with the test gas, and are detected by a receiving collector. Two rows of plate electrodes in the collision chamber run parallel to the beam, on each side of it. A uniform transverse electric field is produced by applying potentials to these electrodes and to grids in front of them. This electric field extracts the charged particles produced in the collisions from the collision region and collects them.

To reduce the effects of the scattering of the incident ions, we use the electrode nearest the entrance slit (the first electrode along the beam path) as the measurement electrode in the measurements of σ^+. The customary procedure is to use one of the central electrodes as the measurement electrode; the change of the electric field near the first electrode, because of fringing effects, is the reason for not using the first electrode. In the present experiments, we installed a system of auxiliary electrodes between the first electrode and the entrance slit; these auxiliary electrodes impose a uniform potential near the first electrode. The first electrode, the auxiliary electrodes, and the entrance slit are all positioned as close together as possible. This close arrangement limits the scattering region on the beam-entrance side, so that only those ions which are scattered through angles greater than 70° can reach the electrode.

To check the need for and the efficiency of these changes in the measurement procedure, we measured the energy dependence of the ion current i^+ separately for each of the measurement electrodes in both K^+–Ne and K^+–He collisions. The most representative results come from a comparison of the energy dependences found through the use of the first electrode and one of the central electrodes. In K^+–Ne collisions in the energy interval 5–6.5 keV, the currents drawn by the electrodes are essentially identical, but at an energy of 1 keV the current drawn by the central electrode is roughly four times that drawn by the first electrode. This difference increases with decreasing collision energy.

To determine the reason for this discrepancy we measured the currents drawn by the electrodes as functions of the potential (which retards ions) applied to these electrodes.[14] These measurements showed that, while ions are essentially prevented from reaching the first electrode when the electrode potential is on the order of ten volts, an electrode potential of 110 V is required to achieve the same result at a central electrode (when the energy of the ions in the beam is 1.0 keV). This happens because primary ions were prevented from striking the first electrode (we recall that in K^+–Ne collisions the maximum ion scattering angle in the laboratory coordinate system is 31°), while primary ions were able to strike the central electrode. Estimates show that the potential of the central electrode must be precisely 110 V in order to prevent the incidence of scattered ions. It can thus be concluded from these measurments that this difference i^+ in the currents is a consequence of the incidence of scattered primary ions on the central electrodes.

A similar conclusion follows from measurements in the K^+–He collisions. In this case we know that the maximum angle through which the ions are scattered is 5.9°, so that we could rule out the possibility that ions strike either the first electrodes or the central electrodes (the minimum angle through which ions would have to be scattered in order to reach these electrodes was 18–20°). The measurements showed that in this case, as expected, the currents drawn by the central and first electrodes were identical over the entire ion energy interval. These measurements and also measurements of the currents in the interval 5–6.5 keV in K^+–Ne collisions verify that it suffices to correct for the edge effect near the first electrode and that this first electrode can be used as the measurement electrode.

In measurements of the electron current in the determination of σ^-, it was inadvisable to use the first electrode as the measurement electrode because of the incomplete suppression of electron emission from the edges of the entrance slit of the collision chamber. We accordingly used the central electrodes in these measurements. They can be used in this case because as the electrons are extracted the potentials on the grids and electrodes are positive and can be chosen at levels such that the scattered ions are prevented from reaching the electrode, without any significant deflection of the primary beam.

The stripping cross sections were measured in an independent experiment. A beam of K^+ ions from a surface-ionization source is accelerated and focused and then passes through the collision chamber. It is then analyzed for charge composition by a 90° magnetic mass spectrometer. The ratio of the number of double charged ions, K^{2+}, produced in the stripping to the current of the K^+ ion beam is determined from the ratio of the areas under the corresponding lines in the mass spectrum. Since inelastic processes, apparently including stripping, may be accompanied by the scattering of particles through comparatively large angles in collisions between alkali metal ions and inert gas atoms,[3,4,12] we took special measures to arrange a complete collection of K^{2+} ions. Control experiments showed that in K^+–He collisions there is a complete collection of K^{2+} ions, while in K^+–Ne collisions the collection of K^{2+} ions could reach 50%.

2. The error in the measurements of the absolute values of the cross sections σ^+ and σ^- is estimated to be 15% over the entire energy interval studied for both pairs of colliding particles. This error is determined primarily by the error in the measurement of the pressure of the target gas in the collision chamber.

The error in the measurement of the cross section σ_s in K^+–Ne collisions is estimated to be 1.5–2 times as large.

The error in the measurement of the ionization cross section σ_i is estimated to be $\approx 20\%$ over the entire energy range. The large value of this error in comparison with that in the measurement of the cross section σ^- is a consequence of the presence of an additional error in the measurements of σ_i, because of the measurements of the cross sections for the stripping of K^+ ions.

At ion energies < 2.0 keV the cross section σ^+ is significantly larger than σ^- in both cases. Accordingly, the error in the determination of the capture cross section σ_c in this energy region is determined primarily by the error in the measurement of σ^+. With increasing ion energy the cross sections σ^+ and σ^- become more nearly equal, and as a result the error in the determination of σ_c increases; at an ion energy of 5 keV it is estimated to be 35%.

MEASUREMENT RESULTS AND DISCUSSION

1. Figures 1–3 show the energy dependence of the absolute cross sections for ionization, charge exchange, and stripping in K^+–He and K^+–Ne collisions. We have also estimated the energies of the electrons liberated in the collisions. These estimates were found from measurements of the electron current as a function of the potentials applied to the measuring electrodes in order to collect these currents. In K^+–Ne collisions, the energy of most of the liberated electrons is below 10–15 eV; in the K^+–Ne collisions, most of the liberated electrons have energies below 18–21 eV.

The ionization cross sections found for both pairs of colliding particles in these experiments differ significantly from the "old" data of Refs. 1 and 11 but agree satisfactorily with the data of Ref. 2. Only the data of Ref. 6 are available for a comparison of charge-exchange cross sections. In K^+–Ne collisions, the charge-exchange cross sections found in Ref. 6 at potassium ion energies <4 keV are 2–3 times smaller than those found in the present experiments. In K^+–He collisions these cross sections are also lower but to a lesser extent. The reason is that, as was mentioned above, the undercount of neutral particles in Ref. 6 due to their scattering was smaller than in K^+–Ne collisions.

A distinctive feature of the ionization and charge-exchange cross sections in K^+–He, Ne collisions is their small magnitude. Another feature of these cross sections is a sharp difference in the energy dependence for the ionization and a charge-exchange cross sections. While the ionization cross sections are small at low ion energies and increase monotonically with increasing energy, the charge-exchange cross sections have a complex structure and generally decrease with increasing collision energy.

The data obtained in this study can be used to draw certain conclusions about possible reasons for these features

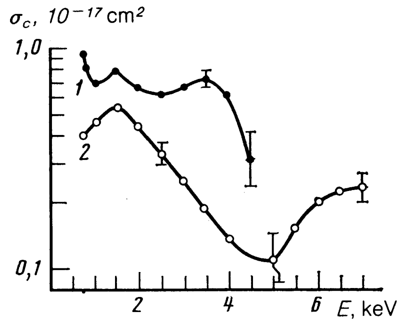

FIG. 2. Charge-exchange cross section versus the ion energy in (1) K^+–Ne collisions and (2) K^+–He collisions.

of the cross sections and the mechanisms of the corresponding processes.

In discussing the mechanisms for the processes, we use schematic correlation diagrams of the diabatic quasimolecular terms of the systems of colliding particles which we constructed by the Barat-Lichten rules.[16] These diagrams are shown in Figs. 4 and 5.

2. In determining the processes responsible for the charge exchange in K^+–He collisions, we compare the cross section which we found with the cross section with the decay of resonant levels of the potassium atom from Ref. 17. Taking account of the selection rules and the ratio of oscillator strengths for the transitions, we can show that the decay of any of the levels of the potassium atom culminates in about half the cases with a transition of the atom to a resonant state, which then decays. According to the data of Ref. 17, the decay cross section of the resonant levels of the potassium atom in K^+–He collisions increases with increasing ion energy, reaching $\approx 2\cdot 10^{-20}$ cm^2 at an ion energy of 3 keV and $7\cdot 10^{-20}$ cm^2 at 5–7 keV. At low collision energies these cross sections are less than 1%, and at high collision energies are $\approx 5\%$ of the total charge-exchange cross section found in the present measurements. It follows that in these collisions the cross section for the capture of an electron to an excited state of atom is less than $\approx 10\%$ of the total charge-exchange cross section. In other words, the charge exchange results

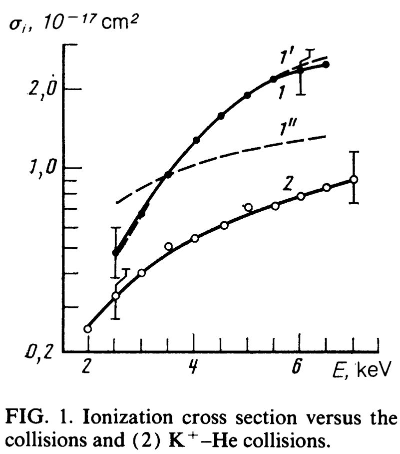

FIG. 1. Ionization cross section versus the ion energy in (1) K^+–Ne collisions and (2) K^+–He collisions.

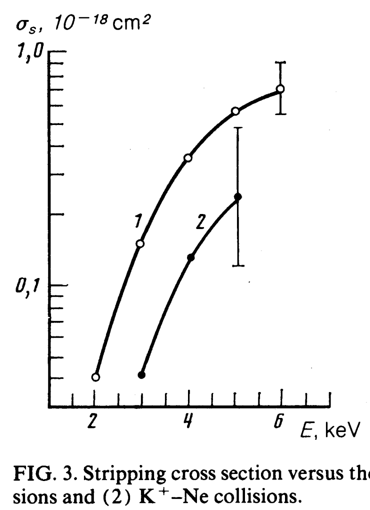

FIG. 3. Stripping cross section versus the ion energy in (1) K^+–He collisions and (2) K^+–Ne collisions.

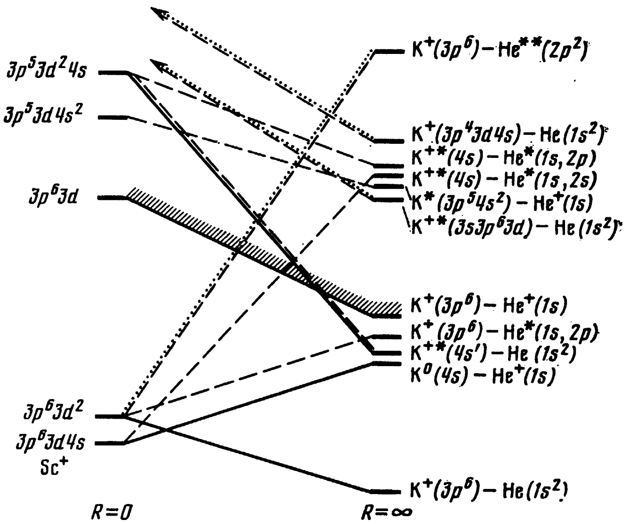

FIG. 4. Schematic correlation diagram of the diabatic terms of the K^+–He system. Solid line—Σ state; dashed line—Π state; dotted line—Δ state.

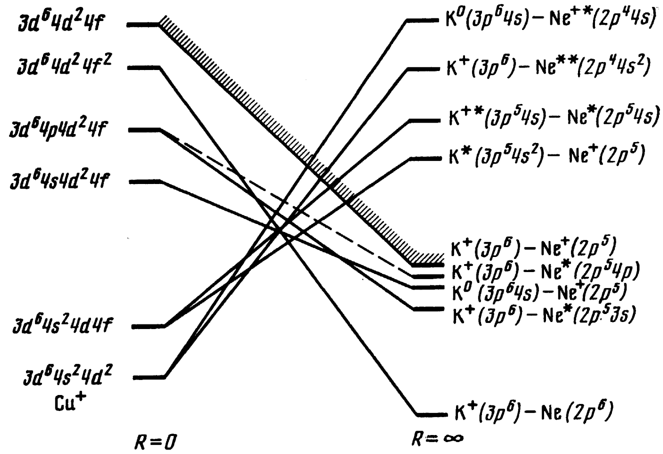

FIG. 5. Schematic correlation diagram of the diabatic terms of the K^+–Ne system (the notation is the same as in Fig. 4).

primarily from the capture of an electron to the ground state of the atom. The target ions are produced in these processes primarily in the ground state. The processes involving capture accompanied by the excitation of the ion contribute little to the charge exchange, apparently because the energy defect of these processes is on the same order of magnitude as the collision energy (the total kinetic energy of the particles in the c.m. system).[13] The energy defect of these processes is ≈ 61 keV, while the collision energy at an ion energy of 700 eV is only 65 eV. We thus find that the charge exchange is governed primarily by the capture of an electron to the ground state of the atom, accompanied by the formation of an ion, also in the ground state

$$K^+(3p^6)-He(1s^2) \rightarrow K(4s)-He^+(1s). \tag{1}$$

This process can occur, as can be seen from the diagram in Fig. 4, as a result of a direct pseudocrossing of the term corresponding to the state $K(4s)$–$He^+(1s)$ with a term of the ground state of the system, as can be seen from the diagram in Fig. 4. Since a system in the $K(4s)$–$He^+(1s)$ state, as in the ground state, has only Σ symmetry (i.e., a vanishing projection of the orbital angular momentum onto the line connecting the nuclei), it follows from this result that Σ–Σ transitions play a dominant role in the charge exchange.

Since the mass of the incident particle in K^+–He collisions is much larger than the mass of the target particle, a significant decrease in the velocity of the relative motion of the particles when the region of the term pseudocrossing is passed is observed at significantly larger initial ion energies (on the order of 1 keV) in these collisions than in cases which this relation between masses does not hold. The reason is that the collision energy and the potential energy of the interaction of the particles near the pseudocrossing are comparable; the difference between these energies determines the relative velocity. For example, at a potassium ion energy of 700 eV the collision energy (65 eV) is only slightly above the expected energy of the interaction of the particles in the region of this pseudocrossing (50–60 eV). In this situation, the only particles which can approach each other to a distance at which the terms undergo a pseudocrossing are those particles for which the impact parameters are much smaller than this distance. The small value of the charge-exchange cross section in these collisions in comparison with the cross sections in collisions of certain other pairs of particles, e.g., K^+–Ar, K^+–Kr, and K^+–Xe, at ion energies 0.7–1.0 keV, can be attributed to precisely this effect.[14] For these pairs of particles, the mass of the incident particle is less than or roughly equal to the mass of the target particle so that there is no significant decrease in the relative velocity, in comparision with the initial velocity of the ion. Correspondingly, there is no significant decrease in the impact parameters at which the pseudocrossing regions are reached.

In the two-channel approximation, the charge-exchange cross section should increase with increasing ion energy, approaching the value $\sigma_{\max} = 0.5\pi R_0^2$, where R_0 is the position of the pseudocrossing region.[18] Using a limiting value of 65 eV as the interaction energy of the particles in the pseudocrossing region, and using the potential curve for the ground state of the K^+–He system from Ref. 19, we find $R_0 \approx 0.7$ Å and, correspondingly, $\sigma_{\max} \approx 0.7 \cdot 10^{-16}$ cm^2. It can be seen from Fig. 2 that the cross section actually increases (to $\sigma = 5.5 \cdot 10^{-18}$ cm^2) with increasing ion energy only up to 1.5 keV. As the energy increases further, the cross section decreases; it increases again only at ion energies above ≈ 5 keV. This behavior of the cross section indicates that at the ion energy of 1.5 keV the charge-exchange mechanism does not reduce to an interaction exclusively between the entrance and exit channels; the interaction of these channels with other channels becomes important. In particular, the decrease in the cross section at ion energies 1.5–5.0 keV which we have just mentioned can be related to the interaction of the exit channel with the channel corresponding to the state $K^+(3p^5[1/2]4s')$–He (Fig. 4). That an interaction of these channels occurs is confirmed by the agreement of the position of the minimum on the energy dependence of the charge-exchange cross section with the position of the maximum on the energy dependence of the cross section for the decay of the resonant level of the ion, $K^+(3p^5 4s')$, measured in Refs. 9 and 20. The value of the decay cross section at the maximum ($1.1\cdot 10^{-17}$ cm^2) corresponds roughly (Fig. 2) to the depth of the dip on the energy dependence of the charge-exchange cross section.

3. The charge exchange in K^+–Ne collisions, as in K^+–He collisions, primarily involves the capture of an electron to the ground state of the potassium atom. This conclusion follows from measurements of the emission of resonant lines of the potassium atom in such collisions.[17] According to the data of Ref. 17, the cross section for the decay of the $4p$ levels of the K atom at an energy of 1.5 keV is $3.0\cdot 10^{-20}$ cm^2, while that at 5 keV is $8.5\cdot 10^{-20}$ cm^2. We can conclude from these figures that the contribution of capture to excited states of the atom is less than 1–2%, at least for energies up to 4 keV.

It apparently follows from these results that at low energies (0.7–2.0 keV) charge exchange is the primary inelastic process. Although the cross sections have not been measured for all the inelastic processes in these collisions, all of the cross sections which are known are smaller than the charge-exchange cross section. Included here are the cross section for the decay of the resonant levels of the K atom, which we mentioned above, the cross section for emission in the visible part of the spectrum of lines of the K^+ ion,[21] the ionization cross sections found in the present experiments, and the cross sections for the decay of resonant levels of the Ne atom which we measured in calibration experiments in the ultraviolet part of the spectrum. According to preliminary data, the latter cross sections at an ion energy of 2.0 keV are $3\cdot 10^{-18}$ cm^2 (the energy dependence of the cross section, in arbitrary units, had been found previously[10]).

It is difficult to discuss the mechanism for the charge exchange because of the complicated energy dependence of the cross section. The structure of the dependence is evidently determined by the interaction of inelastic channels. Of the cross sections which we know for the various processes, only that for the excitation of the Ne atom at energies above 1–1.5 keV is comparable in magnitude to the charge-exchange cross section, so that the interaction of these channels might be responsible for the structure observed in the cross sections. Unfortunately, there is no clear correlation between the structural features on these cross sections in K^+–Ne collisions, so that the reason for these features is not known at this point.

4. It follows from the results of the present measurements of the energies of the electrons liberated in K^+–He collisions (see the discussion above) and, in part, from the data of Ref. 22, where the electron spectrum was measured over the interval 5–24 eV, that the liberation of mostly slow electrons (with energies less than 10–15 eV) is characteristic of the ionization mechanism in K^+–He collisions. In order to determine this mechanism, we estimated the contribution to the ionization cross section of several inelastic processes which result in the emission of slow electrons. The contribution of direct ionization, which is linked in the quasimolecular model to the transition of a diabatic term into the continuum in the region of the nonadiabatic interaction of molecule orbitals with orbital angular momenta which are indentical in the limit of the combined atom,[23] is estimatec from

$$\sigma=\frac{2\pi v k|R_{nl}|^2}{E_{nl}\,\mathrm{Im}\,R_{nl}}\exp\left(-\frac{2E_{nl}\,\mathrm{Im}\,R_{nl}}{v}\right). \qquad (2)$$

Here v is the relative velocity of the particles in the nonadiabatic region; k is the number of electrons of the combined atom in the state with quantum numbers n, l; E_{nl} is the binding energy of an electron in the nonadiabatic region; and $\mathrm{Im}\,R_{nl}$ and $\mathrm{Re}\,R_{nl}$ are the coordinates of the point where the potential surfaces cross in the complex plane. In the estimates of these coordinates we use the expressions

$$\mathrm{Im}\,R_{nl}=\frac{[2l(l+1)]^{1/2}}{Z_{\mathrm{eff}}},\qquad \mathrm{Re}\,R_{nl}=\frac{l(l+1)}{Z_{\mathrm{eff}}}\quad (m=0), \quad (3)$$

where Z_{eff} is the effective charge of the nucleus of the combined atom for the electron with quantum numbers n, l. This formula was derived by the same approach as was used to derive expression (26) in Ref. 23; it differs from that expression (26) only in that the population of the initial orbital is taken into account, and the binding energy is introduced as a parameter. We do not use an expression for it in terms of the principal quantum number of the hydrogen-like atom. In this form, expression (2) is slightly better suited for estimating the cross section for the emission of electrons from multielectron atoms, since it allows us to also take into account the dependence of the binding energy on the orbital angular momentum of the electron.

Analysis of the correlations of the molecular orbitals in the K^+–He system shows that in the limit of the combined atom the $1s$ electrons of the He atoms become $3d$ electrons of the Sc^+ ion. Since this result is of importance for evaluating the contribution of direct ionization, we note that it agrees both with the Barat-Lichten correlation rules[16] and the Eichler-Wille rules.[24] Consequently, the value $l=2$ was chosen for evaluating the cross section. The binding energy E_{nl} of the electrons in the nonadiabatic region was chosen equal to the binding energy of the $3d$ electrons of the Sc^+ ion. The charge Z_{eff} was determined through interpolation of the data of Ref. 25. For the $3d$ electrons of the Sc^+, the value $Z_{\mathrm{eff}}=5.5$ was found. Estimates of the cross section for direct ionization with these parameter values show that at an ion energy of 2.5 keV the contribution of direct ionization to the total ionization cross section is $\lesssim 0.1\%$, while that at 6.5 keV is $\lesssim 5\%$; i.e., this contribution is insignificant over the entire energy range studied.

Double ionization of the He atom and capture accompanied by ionization of the He atom evidently contribute little to ionization because of the large energy defect for these processes (79 and 74.6 eV, respectively) and because of the absence (as follows from an analysis of the correlation diagram) of pseudocrossings of the corresponding quasimolecular terms with the ground-state term. It can be seen from the electron spectrum found in Ref. 22 that the resultant intensity of the discrete lines associated with capture to autoionization states of the K atom and ultimately corresponding to ionization of the He atom is several times lower than the resultant intensity of the lines of the K^+ ion corresponding to stripping processes. Since the stripping cross section is $\leqslant 10\%$ of the ionization cross section, we find that capture to autoionization states of the K atoms also plays no important role in the ionization of the He atom. Consequently, by systematically evaluating the contributions of various inelastic processes to the ionization of the target atoms in K^+–He collisions, we find that this ionization may be caused primarily by the decay of quasimolecular autoionization states. These states could be expected to be states with two excited electrons, since precisely such states in a quasimolecule decay with a high probability, with the liberation of mainly slow electrons with a continuous energy distribution.[26,37] Both of these circumstances agree with the conclusions which follow from an analysis of the correlation diagram of the system, and they add a few refinements to the ionization mechanism.

It can be seen from the diagram that the ground state of the system goes over in the limit of the combined atom into the $3p^63d^2(^1D_2)$ single state of the Sc^+ ion. Below this state, the Sc^+ ion has only three triplet states and one singlet state (with the configuration $3p^63d\,4s$).[28] Only terms which go over these states in the limit of the combined atom can evidently cross the ground term of the system. It follows that the ground-state term with symmetry $^1\Sigma$ is crossed by only a single term of the same $^1\Sigma$ symmetry (which corresponds, as we have already mentioned, to the charge exchange K^+–He$\rightarrow$K$(3p^44s)$–He$^+$]. Noting that the electron transitions occur primarily between terms of the same multiplicity, we find that the autoionization results from the filling of primarily terms of 1Π and 1Δ symmetry. These may be terms which correspond in the limit of separated atoms to the states $K^{+*}(4s)$–He$^*(1s2s)$, K^+–He$^{**}(3d\,4s)$ and K^+–He$^{**}(2p^2)$ (Fig. 4). All of these terms, as expected, correspond to a two-electron excitation of the system. Since the ground-state term has the symmetry $^1\Sigma$, the terms are populated as a result of Σ–Π and Σ–Π–Δ transitions. This filling of the terms is associated with a rotation of the line connecting the nuclei.

5. It follows from our estimates of the energy of the liberated electrons and from measurements of the electron spectrum in K^+–Ne collisions in Refs. 29 and 30, carried out over the energy interval 12–23 eV, that in these collisions, as in K^+–He collisions, the ionization arises primarily from processes which result in the emission of slow electrons with a continuous energy distribution. In contrast with K^+–He collisions, the total cross section in these collisions of electrons with discrete energies[29–30] is more important and is determined by capture to autoionization states of the K atom. The reasons for this circumstance are, as can be seen from the correlation diagram for the K^+–He pair (Fig. 4), that the molecular terms corresponding to the capture of an electron to the state K^+–He and to other autoionization states of this atom do not cross the ground term of the system. In K^+–Ne collisions, on the other hand (Fig. 5), these terms do cross the ground term, so that the probability for their population may be substantially higher than in K^+–He collisions.

An estimate of the contribution of direct ionization in these collisions to the total cross section for the yield of electrons shows that at an ion energy of 6.5 keV it is $\approx 2\%$, while at 2.5 keV it is 0.02% of the total cross section. This estimate was found in the following way. The parameter $|R_{nl}|^2$ [see (2)] was estimated from (3), and the parameter E_{nl} Im R_{nl} was chosen in such a way that the calculated cross section did not exceed the measured cross section at ion energies up to 20 keV, at which experimental data are available.[2] The cross section was not calculated directly since it would obviously have been difficult to accurately determine $Z_{\rm eff}$ and E_{nl} for the $4f$ electrons of the Cu^+ ion in the excited state with the configuration $(3p^64d\,^24f^2)$ as follows from the diagram in Fig. 5, these electrons correspond to $2p$ electrons of the Ne atom. Although the estimate which we found is less accurate than a direct calculation for the process would be, it apparently is a sufficient basis for concluding that this process makes only a small contribution to the total ionization cross section.

Systematically evaluating other possible mechanisms for the liberation of electrons with a continuous energy distribution, we conclude that the primary mechanism for their appearance is the decay of quasimolecular autoionization states in the region in which the corresponding terms go into the continuum. These terms are apparently filled primarily as a result of transitions between terms of identical orbital symmetry (i.e., $^1\Sigma$–$^1\Sigma$ transitions, since the ground term has the $^1\Sigma$ symmetry). The basis for this conclusion is the sharp difference between the measured energy dependence of the cross section (curve 1 in Fig. 1) and the typical dependence of the cross section for transitions between terms of different orbital symmetry[18] (curve 1″; the cross section given in arbitrary units). The measured dependence of the cross section can be approximated quite accurately, as we see from Fig. 1, by the theoretical dependence of the cross section for an inelastic transition between terms of identical orbital symmetry even in the linear 2-parameter Landau-Zener model[18] (curve 1′). The parameters of the dependence shown in this figure [$R_0 = 1.1$ a.u., $E^* = 1/2\mu(2\pi H_{12}^2/\hbar\Delta F)^2 = 4.8$ keV, where R_0 is the position of the crossing of the diabatic terms, E^* is a characteristic energy, μ is the reduced mass, and H_{12} and ΔF are the interaction matrix element and the difference between the slopes of the terms at the crossing] correspond to the agreement of this dependence with that measured at ion energies of 3.0 and 5.5 keV.

With regard to the parameters we note that they are obviously effective parameters, reflecting both the dependence of the cross section on several other parameters[18] and the possible contribution of several pseudocrossing regions to the cross section. The terms whose quasicrossing with the ground term may be responsible for this process may be (Fig. 5) the terms which correspond in the limit of separate atoms to the states K$(4s)$–Ne^{+*}, K^+–Ne**, and $K^{+*}(3p^54s)$–Ne$^*(4s)$ and also the state $K^*(3p^54s^2)$–Ne$^+$, whose filling, as we mentioned above, is verified by measurements of the spectrum of the liberated electrons.

6. One mechanism for the stripping in K^+–He collisions has already been mentioned: the excitation of autoionization states of the K^+ ion, followed by their decay. This mechanism is seen in the electron spectrum in the discrete lines which correspond to autoionization states of the K^+ ions, which were observed in Ref. 22. This mechanism is significantly less important in the stripping cross section in K^+–Ne collisions, since the corresponding lines have not been detected in the electron spectrum, as we have already mentioned.

According to our estimates, however, the governing mechanism for the stripping, at least for the K^+–He pair, is not this mechanism but one involving the transition of a diabatic term into the continuum. The stripping cross section determined by this mechanism was calculated for the K^+–He pair from (2). For the K^+–Ne pair, a calculation was not carried out, for the reason mentioned above. It can be seen from the diagram in Fig. 4 that in the case of the K^+–He pair the $3p$ electrons of the K^+ ion are correlated with the $3p$ electrons of the Sc^+ ion. Consequently, in evaluating the cross section we selected $l = 1$, while we took $Z_{\rm eff}$ to be the same as for the $3d$ electrons of the Sc^+ ion in evaluating the ionization cross section. As a result of the calculation of the stripping cross section with these parameter values, we found that at the edge of the ion energy region considered the difference between the calculated cross section and the experimental cross section is less than 25%, while the two are essentially identical in the energy region 2.5–3.5 keV. Although this agreement is fortuitous to some extent, it does support the conclusion that this mechanism is the governing mechanism for the stripping.

Let us summarize the results of this study.

1. Using a refined experimental procedure, we have measured the ionization and charge-exchange cross sections in K^+–He and K^+–Ne collisions.

2. The stripping cross section in these collisions have been measured for the first time.

3. Correlation diagrams have been plotted and for the systems of colliding particles. The data found and the correlation diagrams have been used to discuss the mechanisms for charge exchange, ionization, and stripping in these collisions.

We have reached several conclusions:

1) Charge exchange in K^+–He collisions results from capture to the ground state of the atom in regions of pseudocrossings of the potential curves of $^1\Sigma$ symmetry.

2) The primary ionization mechanism in K^+–He collisions is the filling, as a result of Σ–Π and Σ–Π–Δ transitions, of quasimolecular autoionization terms and their decay in the region of the transition into the continuum (in the stage in which a quasimolecule exists). The primary ionization mechanism in the K^+–Ne collisions is the filling of quasimolecular autoionization terms as a result of $^1\Sigma$–$^1\Sigma$ transitions in regions of pseudocrossings with the ground term of the system and the decay of these terms, again in the region of the transition into the continuum.

3) The stripping in K^+–He collisions occurs by a mechanism involving a transition of a diabatic term into the continuum in the region of a nonadiabatic interaction of molecular orbitals with orbital angular momenta which are identical in the limit of the combined atom.

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