SOVIET PHYSICS JETP VOLUME 30, NUMBER 1 JANUARY, 1970

EXOTHERMAL CAPTURE PROCESSES WITH IONIZATION PRODUCED IN COLLISIONS BETWEEN He^{3+} IONS AND INERT GAS ATOMS

Z. Z. LATYPOV, I. P. FLAKS, and A. A. SHAPORENKO

A. F. Ioffe Physico-technical Institute, U.S.S.R. Academy of Sciences

Submitted January 27, 1969

Zh. Eksp. Teor. Fiz. **57**, 50–58 (July, 1969)

The cross sections $\sigma_{0\eta}$ for formation of Ne^{n+}, Ar^{n+}, Kr^{n+} or Xe^{n+} ions (n = 1, 2, 3) in collisions between doubly charged He^{2+} ions and the respective atoms are measured at energies $0.1 \leq T \leq 8$ keV. An analysis of the dependence of the components of the cross sections $\sigma_{0\eta}$ on the collision energy T shows that the appearance of peaks in the $\sigma_{0\eta}(T)$ curves in the case of the formation of Ar^{2+}, Kr^{2+}, Xe^{2+}, and Xe^{3+} ions is due to exothermal capture processes concomitant with ionization. The correlation observed between the cross sections σ_{01} and σ_{02} for Ar, Kr, or Xe indicated that exothermal capture with ionization may not only occur directly but also via intermediate competing processes. The magnitudes of the cross sections for exothermal capture with ionization are estimated.

1. INTRODUCTION

AMONG the various inelastic processes that occur in atomic collisions, processes of capture with ionization have lately attracted the attention of researchers. The possibility of realizing such processes was first indicated by Fedorenko et al.,[1, 2] and these processes were subsequently investigated by many workers.[3–7] Depending on the sign of the defect of the internal energy ΔE, these processes can have an endothermal ($\Delta E < 0$) or an exothermal ($\Delta E > 0$) character. In the latter case they produce multiply charged ions at a high efficiency.[3]

Afrosimov et al.[6, 7], using collisions of protons with inert-gas atoms as an example, investigated endothermal processes of capture with ionization. In these processes, the release of an electron from the shell of the target atom is due to the kinetic energy of the proton. The effective cross sections of capture with ionization increase monotonically with increasing proton energy T, and reach a maximum in the energy region $25 < T < 30$ keV, i.e., at proton velocities close to $v = e^2/\hbar$. The position of the maxima of these cross sections depends little on the number of electrons taking part in the process, or on the energy loss ΔE necessary to realize the process.

Exothermal processes of capture with ionization take place, as a rule, in collisions between multiply charged ions and atoms.[3,4] The final result of this collision is such that one or several atomic electrons go over to the ion, and electrons can be emitted from the shell of the atom as a result of the energy released in such an exothermal charge exchange. The intermediate state of the colliding ion and atom is the formation of a strongly excited system, capable of relaxing via autoionization. In exothermal capture with ionization, the kinetic energy of the relative motion of the ion and atom does not take part, therefore the cross section of this process can be larger in a region of small collision energies.

Exothermal capture with ionization was analyzed theoretically by Kishinevskiĭ and Parilis[8] using a model of two Coulomb centers with two electrons. They have shown that in this model, capture with ionization can occur both directly and via an intermediate state.[1)] Different channels of the process of capture with ionization are realized during the time of collision between the ion and the atom, owing to the electronic transitions due to the coming together of the terms at relatively large internuclear distances. The cross sections of these processes, in the collision-velocity range $5\times10^5 \leq v \leq 10^8$ cm/sec, are estimated at 10^{-16}–10^{-15} cm^2, and the maxima of the cross sections lie in the same velocity range.

In [4], in an experimental study of the collisions of the ions Ne^{2+}, Ne^{3+}, Ne^{4+} with Xe atoms, at accelerating potentials $3 \leq V \leq 30$ keV, large values were obtained for the free-electron production cross sections σ_-. This is attributed to the contribution made to σ by the cross sections of the processes of capture with ionization, besides the cross sections for the pure-ionization and stripping processes.

It is convenient to investigate experimentally the exothermal processes of capture with ionization by using simple systems and low energies, for under these conditions the number of possible competing processes is reduced to a minimum, and the cross sections of the exothermal capture with ionization can exceed in magnitude the cross sections of the other processes in this energy region. These requirements are best satisfied by the He^{2+} ions, since they have no electron shells and they have large electron recombination energies.

To obtain information concerning the processes of capture with ionization, we have investigated the production of singly, doubly, and triply charged slow ions by collision between He^{2+} ions and Ne, Ar, Kr, and Xe atoms in the energy interval $0.1 \leq T \leq 8$ keV. These processes are represented schematically in the form

$$He^{2+} + A \rightarrow He^{m+} + A^{n+} + (m + n - 2)e. \qquad (1)$$

[1)] The possibility of realizing inelastic atomic collisions via intermediate competing states was indicated earlier [9].

Here A is the target atom; n = 1, 2, 3; m = 0, 1, 2, −1. Since the particles He^{m+} are not registered in the method employed by us, the measured cross sections σ_{0n} for the production of slow ions with charge n turn out to be summed over all the states of the unobservable fast particles He^{m+}: $\sigma_{0n} = \sum_m \sigma_{0n}^{2m}$, where σ_{0n}^{2m} is the cross section of the elementary process in which the charged states of both colliding particles are changed.[5]

Starting from the values of the electron binding energies in inert-gas atoms, we can predict in what cases exothermal processes of capture with ionization become possible among the processes (1) with n = 2 and 3. We can expect that information concerning the presence of exothermal processes of capture with ionization and concerning the order of magnitude of the cross sections of these processes can be obtained by analyzing the $\sigma_{0n}(T)$ dependence and comparing the values of σ_{0n} and of the $\sigma_{0n}(T)$ plots for different processes (1) with n = 1, 2, and 3 and for different targets.

It should be noted that the number of investigations devoted to the collisions of doubly-charged helium ions with various atoms is quite limited. One can name only several experimental studies of the interaction of He^{2+} ions with certain atoms and molecules in the energy region $T > 1$ MeV, on single- and double-electron charge exchange of He^{2+} ions with He atoms at $T > 1$ keV, and several theoretical papers in which the cross sections of the resonant charge exchange of He^{2+} ions in He were estimated. Therefore an investigation of inelastic collisions of He^{2+} ions with Ne, Ar, Kr, and Xe atoms, and the determination of the cross sections of these processes in the energy interval $0.1 \leq T \leq 8$ keV is of interest in itself.

2. EXPERIMENTAL METHOD

The employed experimental setup was described in our earlier paper.[10] Doubly-charged helium ions were produced and accelerated in an ion source of the Nier type. After passing through a magnetic mass-monochromator and before entering the collision chamber, the He^{2+} beam passed through a system of diaphragms with decelerating potentials. As a result, the final kinetic energy of the He^{2+} ions could be varied in the range $0.1 \leq T \leq 8$ keV. The helium isotope ^4He was used for the present investigations. Since the value of m/e is the same for He^{2+} and H_2^+, measures were taken to clean the beam of the He^{2+} ions and to monitor the admixture of the H_2^+ impurity in the He^{2+}. To obtain the He^{2+} beam and to produce gas targets in the collision chamber, we used in the present investigation spectrally pure He, Ne, Ar, Kr, and Xe gases, so that the number of hydrogen-containing molecules in the vacuum system of the apparatus was reduced to a minimum. Further, knowing the mass spectrum of the hydrogen (the ratio of the intensities of the H^+ and H_2^+ ion currents), we could estimate the content of H_2^+ in the He^{2+} beam. Such estimates have shown that in our case the He^{2+} beam contains not more than 4% of H_2^+. Finally, our experimental estimates of the cross sections for the production of slow Ne, Ar, Kr, and Xe ions following the passage of a beam of H_2^+ ions through the respective gases show that the cross sections for the production of slow ions are much lower in this case than the cross sections obtained with the He^{2+} beam. Thus, it can be assumed that the admixture of H_2^+ in the He^{2+} beam does not distort the results of our investigations.

All the cross sections for the production of slow ions, σ_{0n}, obtained in the present paper, were measured with accuracy not worse than ± 15%, with the exception of the cross section σ_{03} for the production of Ne^{3+} ions, the accuracy of which is estimated at ± 40%.

3. MEASUREMENT RESULTS AND DISCUSSION

For convenience in the analysis and discussion of the measurement results, the table lists the fundamental elementary processes in which slow ions are produced and the values of the internal-energy defect ΔE_∞ of these processes, or their possible limits, taken as the differences between the unperturbed electronic levels of the particles at large distances. As seen from the table, the processes of single- and two-electron charge exchange are exothermal, and can therefore include reaction products in various excited states, and to each charge-exchange process there corresponds a number of values of ΔE_∞, as indicated in the second and fifth lines of the table. The lower limit is calculated with allowance for the maximum excitation, and the upper limit with allowance for the minimum excitation of the particles as a result of the charge exchange. For the single-electron charge exchange processes 2, the parentheses contain the values of ΔE_∞ for the case when unexcited particles are produced.[2)] It should also be noted that a fraction of the excitation energy of the system can be carried away in the form of the kinetic energy of the outgoing particles.

The measured cross sections σ_{0n} for the production of slow Ne^{n+}, Ar^{n+}, Kr^{n+}, and Xe^{n+} ions (n = 1, 2, 3) as functions of the kinetic energy T of the He^{2+} ions are given in Figs. 1–4, respectively.

a) Cross sections for the production of singly-charged ions. The cross sections σ_{01} for the production of the ions Ne^+, Ar^+, Kr^+, and Xe^+ are the sums of the cross sections of the processes of pure ionization 1 and single-electron charge exchange 2 (see the table). On the basis of general considerations we can expect the cross section of the processes 1 to increase monotonically with increasing energy T in the investigated energy interval. In single-electron charge exchange of He^{2+} ions in Ne, Ar, and Kr, the ions Ne^+, Ar^+, and Kr^+ are produced in different excited states, including high-

No.	Process	ΔE_∞, eV			
		Ne	Ar	Kr	Xe
1	$He^{2+} + A \to He^{2+} + A^+ + e$	—21.56	—15.75	—13.99	—12.13
2	$\to He^{+*} + A^{+*}$	0—5.94 (32.84)	11—25 (38.65)	15.84—26.84 (40.4)	0—31.07 (42.27)
3	$He^{2+} + A \to He^{2+} + A^{2+} + 2e$	—62.53	—43.35	—38.55	—33.33
4	$\to He^+ + A^{2+} + e$	—8.13	11.05	15.85	21.07
5	$\to He^* + A^{2+*}$	0—16.45	0--35.65	0—40.43	0—45.68
6	$He^{2+} + A \to He^{2+} + A^{3+} + 3e$	—127.83	—84.25	—78.15	—65.43
7	$\to He^+ + A^{3+} + 2e$	—73.43	—29.85	—23.75	—11.03
8	$\to He + A^{3+} + e$	—48.93	—5.35	0.83	13.55
9	$\to He^- + A^{3+}$	~—48.5	~—5.0	~0.45	~13.9

[2)] The atomic-level energies used for the calculation of the quantities were taken from Moore's tables [11].

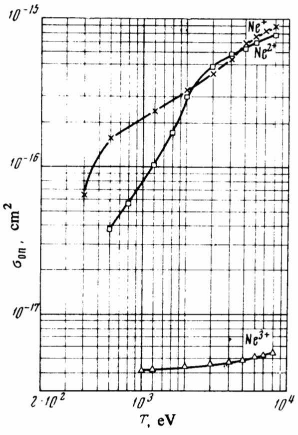

FIG. 1

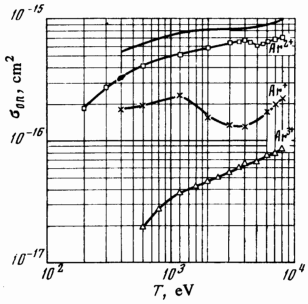

FIG. 2

FIG. 1. Dependence of the cross sections for the production of slow ions σ_{0n}, on the collision energy T for the He^{2+}-Ne pair. Ne^+, Ne^{2+}, and Ne^{3+} denote the cross sections σ_{01}, σ_{02}, and σ_{03}, respectively. A similar notation is used in the remaining figures.

FIG. 2. Cross sections σ_{0n} for the He^{2+}-Ar pair. The upper curve corresponds to the total cross section $\sum_n \sigma_{0n}$.

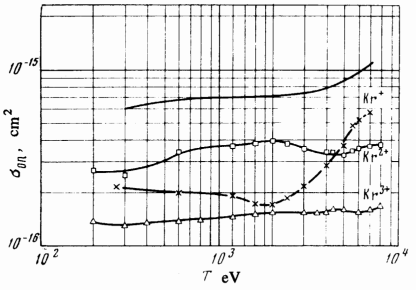

FIG. 3. Cross sections σ_{0n} for the pair He^{2+}-Kr. The upper curve corresponds to the total cross section $\sum_n \sigma_{0n}$.

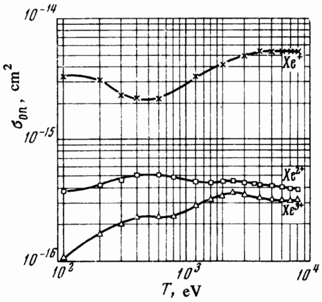

FIG. 4. Cross sections σ_{0n} for the pair He^{2+}-Xe.

ly-excited states, and excitation of He^+ ions is also possible in the case of Xe.

Since the values of the internal-energy defects ΔE_∞ of the processes 2 vary in a wide range, and none of these processes are favored for any reason, the cross sections σ_{01}^{21} in our energy interval will be monotonic functions of T. In the case of Ar and Kr, for which ΔE_∞ is large ($>$ 11 eV), the rising character of the $\sigma_{01}^{21}(T)$ curves follows also from the well known Massey criterion. However, as seen from Figs. 1–4, a monotonic course of the $\sigma_{01}(T)$ curve was obtained only for the He^{2+}–Ne pair. The curves for Ar, Kr, and Xe have a more complicated form and, as will be shown later, this complication can be attributed to the presence of processes that compete with the single-electron charge exchange processes 2.

b) Cross sections for the production of doubly-charged ions. The cross sections σ_{02} for the production of doubly-charged ions Ne^{2+}, Ar^{2+}, Kr^{2+}, and Xe^{2+} receive contributions from the cross sections of the processes of pure ionization 3, of capture with ionization 4, and of two-electron charge exchange 5 (see the table). The cross sections of processes 3 apparently increase monotonically with increasing energy T in our interval of T. The processes 5 are exothermal for all the targets investigated by us, and they can include also two-electron charge exchange with production of one or both particles in different excited states (with the exception of the He^{2+}–Ne pair, for which the excitation of only Ne^{2+} is possible). Just as in the case of single-electron charge exchange, owing to the change of ΔE_∞ in a wide range and owing to the absence of any favored processes, we can assume that the cross sections σ_{02}^{20} of the two-electron charge exchange processes 5 increase monotonically in the investigated interval of T. In the only endothermal process of capture with ionization 4, which leads to the formation of the Ne^{2+} ion, the release of the electron from the shell of the Ne atom is due to the kinetic energy of the He^{2+} ion. On the basis of the results of [6, 7] it can be expected that the cross section of the process 4 in Ne will increase continuously with increasing T. Thus, from an analysis of the behavior of the individual components of the cross section σ_{02} we expect the $\sigma_{02}(T)$ curve to be a monotonic function of T. As seen from Fig. 1, the experimental yield $\sigma_{02}(T)$ of the Ne^{2+} ions agrees with this conclusion.

From the point of view of the results,[9] the exothermal processes 4 of capture with ionization can be realized in the systems He^{2+}–Ar, He^{2+}–Kr, and He^{2+}–Xe either directly in accordance with the scheme 4, or else via intermediate states:

$$He^{2+} + A \begin{array}{l} \nearrow He^+ + A^{+*} \rightarrow He^+ + A^{2+} + e \qquad \text{No. 4a} \\ \searrow He^* + A^{2+*} \rightarrow He^+ + A^{2+} + e \qquad \text{No. 4b} \end{array}$$

The intermediate states in processes 4a and 4b are excited systems that go over into the final state via Penning ionization, and in the case of formation of intermediate $He^+ + Ar^{+*}$ and $He^+ + Kr^{+*}$ systems the transition to the final states is possible via autoionization of the excited Ar^{+*} and Kr^{+*} ions.

The relatively large values of the cross sections σ_{02} and the appearance of a maximum on the $\sigma_{02}(T)$ curves in the case of production of the ions Ar^{2+}, Kr^{2+}, and Xe^{2+} (Figs. 2–4) are apparently connected with the appreciable contribution made to σ_{02} by the cross sections of the exothermal processes of capture with ionization. The results obtained experimentally for these systems indicate also the presence of a definite connection between the cross sections σ_{01} and σ_{02}. Thus, for example, the maximum on the $\sigma_{02}(T)$ curve (Fig. 2) at $T \approx 4000$ eV corresponds to a minimum on the $\sigma_{01}(T)$ curve. In the case of Kr, such a correspondence takes place at $T \approx 2000$ eV (Fig. 3), and in the case of Xe—at $T \approx 600$ eV (Fig. 4). The correspondence between the indicated maxima and the minima is confirmed also by the monotonic variation of the total cross section

$\sum_n \sigma_{0n}(T)$, plotted in Figs. 2 and 3 (upper curves). The noted connection between the cross sections σ_{02} and σ_{01} in Ar, Kr, and Xe makes it possible to ascribe the presence of the maximum on the $\sigma_{02}(T)$ curves to exothermal processes of capture with ionization, realized via the channel 4a. Indeed, exothermal capture with ionization 4a competes with the process of single-electron charge exchange 2 (see the table), which contributes to the cross section σ_{01} for the production of singly-charged ions. It is seen that at definite collision energies between the He^{2+} ions and the Ar, Kr, and Xe atoms there are produced excited quasimolecules $He^+ + Ar^{+*}$, $He^+ + Kr^{+*}$, and $He^+ + Xe^{+*}$, which relax with high probability via electron emission, and not via radiation. Therefore the scheme of these processes can be written, for example for Ar, in the following manner:

$$He^{2+} + Ar \to He^+ + Ar^{+*} \begin{array}{ll} \nearrow He^+ + Ar^+ + h\nu & \quad \text{No. 2} \\ \searrow He^+ + Ar^{2+} + e & \quad \text{No. 4} \end{array}$$

The presence of a definite connection between the cross sections σ_{01} and σ_{02} makes it possible, as will be shown below, to estimate the order of magnitude of the cross sections σ_{02}^{21} of the processes 4.

c) Cross sections for the production of triply-charged ions. Four processes can contribute to the cross sections σ_{03} for the production of the triply-charged ions Ne^{3+}, Ar^{3+}, Kr^{3+}, and Xe^{3+} (see the table). The cross sections of the pure-ionization processes 6, and of the processes of endothermal capture with ionization 7 and 8, in the given interval of energies T, should increase monotonically with increasing T. It is shown in [12] that the cross sections of the processes where the He^+ ions are transformed into He^- ions by collisions with Ne, Ar, and Kr atoms, at energies $T < 60$ keV, are small and decrease with decreasing energy T. At $T \approx 15$ keV, they amount to $\sim 3 \times 10^{-21}$, $\sim 5 \times 10^{-21}$, and $\sim 1 \times 10^{-20}$ cm^2 for Ne, Ar, and Kr, respectively. One can expect the cross sections for the capture of three electrons ($He^{2+} \to He^-$) to be smaller than the cross sections for the capture of two electrons, and since the cross sections σ_{03} measured by us are relatively large, the contribution of the processes 9 to the total cross sections σ_{03} can be neglected. Thus, on the basis of an analysis of the most likely behavior of the components of σ_{03}, we can expect the cross sections σ_{03} for the production of Ne^{3+} and Ar^{3+} ions to be monotonic functions of T, as is indeed confirmed experimentally.

In the systems He^{2+}–Kr and He^{2+}–Xe, exothermal processes of capture with ionization 8 can be realized. The nonmonotonic course of the $\sigma_{03}(T)$ curve for Kr^{3+} ions (Fig. 3) and the presence of a clearly pronounced maximum on the $\sigma_{03}(T)$ curve for Xe^{3+} ions (Fig. 4) are attributed to the contribution made to σ_{03} by the cross sections of the processes of exothermal capture with ionization 8. Since there is no correlation between the cross sections σ_{03} and σ_{02} in the case of Xe, similar to that observed between the cross sections σ_{02} and σ_{01}, it can be assumed that the exothermal capture with ionization 8 is realized for Xe without intermediate competing processes. For Kr, the process 8 is only slightly exothermal ($\Delta E_\infty \sim 0.8$ eV), and this is probably why there is no clearly pronounced maximum on the $\sigma_{03}(T)$ curve (Fig. 3).

4. CONCLUSIONS

A comparison of the results obtained for different targets makes it possible to reveal a number of general features of the processes occurring in collisions between He^{2+} ions and Ne, Ar, Kr, and Xe atoms, and to draw certain conclusions with respect to processes of exothermal capture with ionization.

1. The total cross sections σ_{01} for the production of singly-charged ions receive contributions from the cross sections for ionization and single-electron charge exchange. The cross sections for pure ionization of atoms, as is well known, increase in the sequence Ne, Ar, Kr, Xe. Since the observed character of the $\sigma_{01}(T)$ (Figs. 1–4) differs noticeably from this regularity, we can conclude that an appreciable contribution to σ_{01} is made by processes of single-electron charge exchange 2 with formation of excited particles.

2. The exothermal processes of capture with ionization upon collision between He^{2+} ions with Ar, Kr, and Xe atoms can be realized in different manners. This is due to the presence of a large number of terms in the excited quasimolecule, and the possibility of realizing transitions to different terms as the nuclei come closer together. Thus, for example, exothermal capture with ionization leading to the formation of Xe^{2+} ions can proceed both via channel 4 (see the table), and via channels 4a and 4b.

In [8] we considered three channels through which capture with ionization is possible when an ion B^{n+} collides with an atom A (the particles B^{n+} and A are regarded as Coulomb centers, in the field of which two electrons are situated):

I. Auger ionization, wherein one electron is captured in the ground state of the ion B^{n+}, and the excess energy is transferred to the other electron of the atom A:

$$A + B^{n+} \to A^{2+} + B^{(n-1)+} + e.$$

II. Preliminary single-electron charge exchange with production of an excited ion $B^{(n-1)+*}$ and with subsequent relaxation via Penning ionization:

$$A + B^{n+} \to A^{+} + B^{(n-1)+*} \to A^{2+} + B^{(n-1)+} + e.$$

III. Preliminary two-electron charge exchange in the autoionization state of the ion $B^{(n-2)+**}$ with subsequent Auger effect in it:

$$A + B^{n+} \to A^{2+} + B^{(n-2)+**} \to A^{2+} + B^{(n-1)+} + e.$$

Channels I, II, and III are realizable if $E_k(R) \geq 0$, where E_k is the energy of the released electrons in processes I, II, and III, and R is a quantity of the order of the atomic dimensions. As applied to the systems considered in the present paper, it turns out that channel I is open only to the pair He^{2+}–Xe. The cross section of the process I, according to [8], reaches a maximum at $v \approx 10^8$ cm/sec, which lies outside the interval of the energies T investigated in the present paper. Channel II is energetically impossible for the pairs He^{2+}–Ar and He^{2+}–Kr, since single-electron charge exchange with production of excited He^+ ions is endothermal. Channel III is open for Ar, Kr, and Xe. It should be noted, however, that it is difficult to estimate the extent to which the results obtained within the framework of the model assumed in [8] correspond to reality. One can only note that in multielectron systems there are realized, with a larger probability, processes with excitation of ions made up of the target atoms, such as processes 4a and 4b in Ar, Kr, and Xe, which are considered in the present paper.

3. An analysis of inelastic atomic collisions with allowance for the competing intermediate states yields more information concerning the mechanism of the process than an analysis of only the initial and final states of the system. From this point of view, it was useful in the present investigation to consider simultaneously the $\sigma_{01}(T)$, $\sigma_{02}(T)$, and $\sigma_{03}(T)$ dependences. The previously noted correspondence between the maximum on the $\sigma_{02}(T)$ curve and the minimum on the $\sigma_{01}(T)$ curve in the He^{2+}–Ar, He^{2+}–Kr, and He^{2+}–Xe systems is connected with two competing processes, one of which makes a contribution to σ_{01}, and the other to σ_{02}. The presence of such competing processes points to one of the possible channels of the exothermal capture with ionization.

4. From a comparison of the cross sections σ_{02} and σ_{03} for Ar, Kr, and Xe one can deduce that a definite connection exists between the positions of the maxima of the cross section for exothermal capture with ionization and the values of the internal-energy defect ΔE_∞ or the degree of the exothermal character: the maxima of σ_{02}^{21} and σ_{03}^{20} of processes 4 and 8 shift towards smaller T with increasing ΔE_∞.

5. The presence of exothermal capture with ionization greatly influences the behavior of the curves $\sigma_{01}(T)$, $\sigma_{02}(T)$, and $\sigma_{03}(T)$ in the investigated energy interval. Thus, for example, for the pair He^{2+}–Ne, the processes of exothermal capture with ionization are energetically impossible, and the cross sections for the production of slow ions σ_{0n} increase monotonically with increasing energy T (Fig. 1). In the systems He^{2+}–Ar and He^{2+}–Kr, the exothermal capture with ionization 4 is impossible. As a result, a maximum appears on the $\sigma_{02}(T)$ curves and a minimum on the $\sigma_{01}(T)$ curves (Figs. 2 and 3). For the He^{2+}–Xe pair, exothermal processes of capture with ionization and formation of doubly and triply charged ions are possible. As a result, a minimum is observed on the $\sigma_{01}(T)$ curve, and a maximum on the $\sigma_{02}(T)$ and σ_{03} curves.

6. With decreasing energy T, the probability of the endothermal process decreases strongly, approaching 0 at the energy thresholds. Therefore, in the region of low energies, it becomes possible in some cases to estimate the cross sections of endothermal capture with ionization. Thus, for example, the processes 8 are practically the only exothermal processes for the formation of triply-charged ions Kr^{3+} and Xe^{3+}. It can therefore be assumed that $\sigma_{03}^{20}(Kr) \approx \sigma_{03} \approx 1.4 \times 10^{-16}$ cm^2 at $T \approx 200$ eV, $\sigma_{03}^{20}(Xe) \approx \sigma_{03} \approx 1 \times 10^{-16}$ cm^2 at $T \approx 100$ eV. Apparently, such an estimate is possible for Kr and Xe at even higher values of T.

To estimate the cross section σ_{02}^{21} of processes 4, which lead to the formation of doubly charged Ar^{2+}, Kr^{2+}, and Xe^{2+} ions, we can use the previously established correlation between the cross sections σ_{01} and σ_{02}. Since the appearance of extrema on the $\sigma_{01}(T)$ and $\sigma_{02}(T)$ curves is connected with processes 4, one can take the lower limit of the estimated cross sections σ_{02}^{21} to be the depth of the minimum on the $\sigma_{01}(T)$ curve, reckoned from a smooth curve that can be drawn through the corresponding points, and the upper limit of σ_{02}^{21} to be the values of σ_{02} at the maxima of the curves of Figs. 2–4. Similar estimates yield $1 \times 10^{-16} \lesssim \sigma_{02}^{21} < 6.7 \times 10^{-16}$ cm^2 for Ar and T = 4000 eV, $1 \times 10^{-16} \lesssim \sigma_{02}^{21} < 3.9 \times 10^{-16}$ cm^2 for Kr and T = 2000 eV, and $1 \times 10^{-16} \lesssim \sigma_{02}^{21} < 5 \times 10^{-16}$ cm^2 for Xe at T = 600 eV.

On the basis of the foregoing, we see that exothermal processes of capture with ionization play a predominant role in the formation of multiply charged ions in slow collisions between ions and atoms.

The authors are deeply grateful to Prof. N. V. Fedorenko for useful advice and continuous interest in the work, and to V. V. Afrosimov for a discussion of the results.

---

[1] N. V. Fedorenko, V. V. Afrosimov, and D. M. Kaminker, Zh. Tekh. Fiz. **26**, 1929 (1956) [Sov. Phys.-Tech. Phys. **1**, 1861 (1957)].

[2] N. V. Fedorenko and V. V. Afrosimov, Zh. Tekh. Fiz. **26**, 1929 (1956) [Sov. Phys.-Tech. Phys. **1**, 1861 (1957).

[3] I. P. Flaks, G. N. Ogurtsov, and N. V. Fedorenko, Zh. Eksp. Teor. Fiz. **41**, 1094 (1961) [Sov. Phys.-JETP **14**, 781 (1962)].

[4] I. P. Flaks, G. N. Ogurtsov, and N. V. Fedorenko, Zh. Eksp. Teor. Fiz. **41**, 1438 (1961) [Sov. Phys.-JETP **14**, 1027 (1962)].

[5] V. V. Afrosimov, Yu. A. Mamaev, M. N. Panov, V. Uroshevich, and N. V. Fedorenko, Zh. Tekh. Fiz. **37**, 550 (1967) [Sov. Phys.-Tech. Phys. **12**, 394 (1967)].

[6] V. V. Afrosimov, Yu. A. Mamaev, M. N. Panov, and V. Uroshevich, Zh. Tekh. Fiz. **37**, 717 (1967) [Sov. Phys Phys.-Tech. Phys. **12**, 512 (1967)].

[7] V. V. Afrosimov, Yu. A. Mamaev, M. N. Panov, and N. V. Fedorenko, Zh. Eksp. Teor. Fiz. **55**, 97 (1968) [Sov. Phys.-JETP **28**, 52 (1969)].

[8] L. M. Kishinevskiĭ and É. S. Parilis, Zh. Eksp. Teor. Fiz. **55**, 1932 (1968) [Sov. Phys.-JETP **28**, 1020 (1969)].

[9] I. A. Poluéktov and L. P. Presnyakov, Vth ICPEAC, Leningrad, 1967, Abstracts of papers, p. 71.

[10] Z. Z. Latypov, N. V. Fedorenko, I. P. Flaks, and A. A. Shaporenko, Zh. Eksp. Teor. Fiz. **55**, 847 (1968) [Sov. Phys.-JETP **28**, 439 (1969)].

[11] C. Moore, Atomic Energy Levels (U. S. Government Printing Office) 1 (1949); 2 (1952); 3 (1958).

[12] V. M. Dukel'skiĭ, V. V. Afrosimov, and N. V. Fedorenko, Zh. Eksp. Teor. Fiz. **30**, 792 (1956) [Sov. Phys.-JETP **3**, 764 (1956)].

Translated by J. G. Adashko
8