SOME PROPERTIES OF He^+ *AND* He^{2+} *ION PRODUCTION CROSS SECTIONS IN* He^{2+}—He *COLLISIONS*

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The cross sections σ_{01} and σ_{02} for the production of slow He^+ and He^{2+} ions in collisions between He^{2+} ions and He atoms are determined experimentally for energies $0.4 \le T \le 8$ keV. In the low-energy region, the function $\sigma_{01}(T)$ has a pronounced structure apparently due to the one-electron charge-exchange processes $He^{2+} + He \rightarrow He^+ + He^+$. It is suggested that the structure of the one-electron charge exchange curve is due to interaction between terms of the $He^{2+} + He(1s^2)$ system and some terms of the $He^+(nl) + He^+(1s)$ and $He^{2+} + He(1s, nl)$ systems.

1. Recent investigations have revealed in certain cases a complicated structure in the dependence of the total effective cross section of inelastic ion-atom collision on the collision energy.

Thus, studies of resonant and nonresonant charge exchange of ions in alkali-metal atoms[1,2] a regular oscillation of the cross sections was observed. It is shown in a theoretical paper[3] that if the difference between the values of the energies of the even and odd states goes through a maximum as a function of the internuclear distance of the quasimolecule, then the dependence of the cross section on the energy should have in the case of resonant single-electron charge exchange an oscillating character similar to that observed in the experiments. From calculations of the Ar^+-Ar charge exchange cross sections, performed in[4] by the impact-parameter method, it also follows that the cross sections oscillate as functions of the energy in the processes of resonant and nonresonant charge exchange if the exchange integral entering in the expression for the electron capture probability has a maximum.

A complicated oscillatory structure of the dependence of the total cross section of excitation of different HeI lines on the collision energy was observed in an investigation of the excitation of the HeI spectrum in He^+-He collisions[5,6]. Starting from the Landau-Zener model of inelastic collisions, Dworetsky et al.[5,6] proposed that such a behavior of the emission cross sections of HeI is the result of interference of the transition amplitudes, due to double passage through the term intersection region in the He^+-He collision.

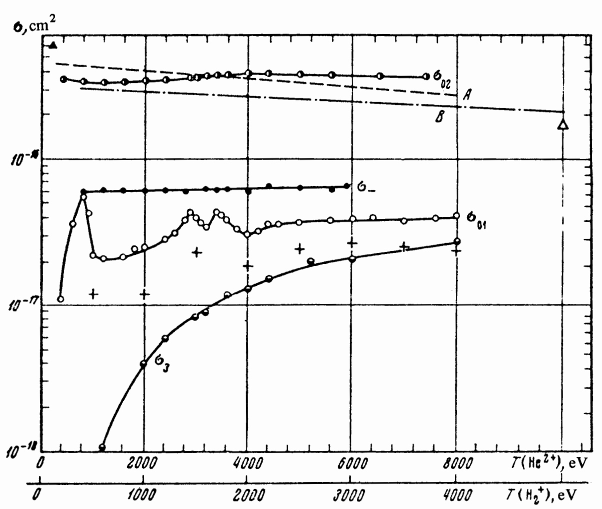
In collisions of two atomic particles, the number of intersecting terms increases with decreasing internuclear distance. Therefore the complicated structure of the dependence of the collision cross section of the energy may be connected with a number of competing processes, which come into play as the system passes through the region of pseudointersection of the terms[7]. The influence of the competing processes on the cross sections of the inelastic processes was demonstrated experimentally in[8], where collisions of slow He^{2+} ions with Ne, Ar, Kr, and Xe atoms were investigated. The energy dependences of the cross sections of the processes are expected to have a simpler structure if a small number of terms intersect in the system. This condition may apparently be satisfied by the slow collisions of light He^{2+} ions and He atoms, leading to formation of He^+ and He^{2+} ions, which are the subject of this paper.

2. In He^{2+}—He collisions, the slow He^+ ions are produced in charge-exchange processes including single-electron charge exchange to the ground and excited states, and in the ionization processes:

$$He^{2+} + He \rightarrow He^+(nl) + He^+(1s), \quad (1)$$

$$He^{2+} + He \rightarrow He^{2+} + He^+ + e. \quad (2)$$

The total cross section $\sigma_{01} = \sigma_{01}^{21} + \sigma_{01}^{22}$ for the production of slow He^+ ions, where σ_{01}^{21} and σ_{01}^{22} are respectively the cross sections of processes (1) and (2), was measured by the method described in[9]. The accuracy of the measurement of the $\sigma_{01}(T)$ dependence characterizes in the relative placement of the experimental points on the $\sigma_{01}(T)$ curves and is estimated at ± 5%; the accuracy of



Effective cross sections for the production of ions on the electrons: ○ – σ_{01}, ◑ – σ_{02}, ● – σ_-, ◒ – cross sections of process (3), dashed line – cross sections (6) from [12], dash-dot line – cross sections (6) from [13], + – cross sections (1) from [11], ▲ – cross sections (6) from [14], △ – cross sections (6) from [15].

the absolute value of σ_{01} amounts to $\pm 25\%$. The figure shows the obtained $\sigma_{01}(T)$ dependence.

To verify that the $\sigma_{01}(T)$ dependence is not distorted by the presence in the He^{2+} beam of a small admixture of H_2^+ ions, we estimated the content of H_2^+ in the He^{2+} beam and measured the total cross section of the processes leading to the formation of He^+ ions in H_2^+-He collisions:

$$H_2^+ + He \rightarrow He^+. \quad (3)$$

In the figure, σ_3 denotes the obtained cross section of the processes (3). Recognizing that $\sigma_3 < \sigma_{01}$ and that the content of H_2^+ in the beam of He^{2+} does not exceed 5%[8], we can conclude that the processes (3) make no appreciable contribution to the cross section σ_{01}.

The $\sigma_{01}(T)$ dependence has a number of peculiarities: a) the $\sigma_{01}(T)$ curve shows clearly three maxima at energies T = 800, 2900, and 3400 eV, and the widths of these maxima at half-height do not exceed $\Delta T \approx 400$ eV; b) the structure of $\sigma_{01}(T)$ is most clearly pronounced in the low-energy region; c) the structure of the $\sigma_{01}(T)$ curve is much simpler than the structure of the energy dependence of the cross section for the excitation of the HeI lines, observed in[5,6].

The role of the processes (1) and (2) in the appearance of the structure on the $\sigma_{01}(T)$ curve was determined by estimating measurements of the cross section σ_- for the production of free electrons in He^{2+}—He collisions. In this case, an important factor is not the accuracy with which the absolute value of the cross section σ_- is determined, but the accuracy with which the dependence $\sigma_-(T)$ is established, particularly in the region in which a structure is observed for the $\sigma_{01}(T)$ curve. Besides the process (2), contributions to σ_- are made by the processes

$$He^{2+} + He \rightarrow He^{2+} + He^{2+} + 2e, \quad (4)$$

$$He^{2+} + He \rightarrow He^+ + He^{2+} + e. \quad (5)$$

If the $\sigma_{01}^{22}(T)$ curve has a structure, we can expect a structure to appear also on the $\sigma_-(T)$ curve. We measured σ_- by a potential method similar to that described in[10]. The accuracy of $\sigma_-(T)$ was $\pm 10\%$, and the accuracy in the determination of the absolute value of σ_- was $\pm 50\%$. Since the $\sigma_-(T)$ curve obtained by us (see the figure) is monotonic, the structure on the $\sigma_{01}(T)$ curve can be connected only with the cross section σ_{01}^{21} of the charge-exchange processes (1).

The cross section of the process (1) was measured in[11] by the Aston-band method in the energy interval $1 \le T \le 8$ keV. The results of these measurements are shown in the figure by crosses. The authors of[11] have drawn through the experimental points a monotonic smooth line, ascribing, apparently, the scatter of the points to the insufficient accuracy of the method. It seems to us that the experimental points of[11] may correspond to the $\sigma_{01}(T)$ dependence obtained in the present paper.

The figure shows also the results of our measurements of the cross section σ_{02}, for the production of slow He^{2+} ions; this cross section is the sum of the cross sections of the processes (4) and (5), and the resonant charge exchange process

$$He^{2+} + He \rightarrow He + He^{2+}. \quad (6)$$

The cross section σ_{02} has been determined with the same accuracy as σ_{01}. The main contribution to the cross section σ_{02} is made by the process (6), as follows from the relation $\sigma_- < \sigma_{02}$ (see the figure). The absolute values of σ_{02} are in satisfactory agreement with the cross sections of the charge exchange (6), calculated in[12] and[13], and represented in the figure by curves A and B, respectively. There are no experimental data on the cross sections of the process (6) and the energy interval investigated by us, and therefore the figure shows the values of the cross sections measured at T = 260 eV[14] and at 10 keV[15]. The $\sigma_{02}(T)$ curve has a relatively weakly pronounced nonmonotonicity. However, as seen from the figure, the correlation between the cross sections $\sigma_{02}(T)$ and $\sigma_{01}(T)$, which was observed in our paper[8], is missing here, and the structure of the curve $\sigma_{01}(T)$ is not reflected on the $\sigma_{02}(T)$ curve.

3. The cross sections of the different channels may correlate with one another, and therefore to ascertain the nature of the structure of the curve $\sigma_{01}(T)$ it would be necessary to consider the cross sections of all the processes in the investigated energy interval. It was shown above that the cross sections of processes (2), (4), (5), and (6) do not correlate with the cross sections of the processes (1). In addition to the considered processes (1), (2), (4), (5), and (6), the He^{2+}—He collisions in the investigated energy interval can also result in processes that include the production of excited particles. The most probable among them are the processes

$$He^{2+} + He \rightarrow He^{2+} + He(1s, nl). \quad (7)$$

We have no information concerning the cross sections of these processes in the considered interval of T.

Unfortunately, there are likewise not enough published data concerning the terms of the $HeHe^{2+}$ system to be able to draw conclusions about the transitions between the terms in the investigated interval of T. By now only the terms of the system $He^+(1s) + He^+(1s)$ (see[16]) and the system $He^{2+} + He(1s^2)$ (see[17]) have been calculated. On the basis of the correlation diagram for the molecular orbitals, which can be constructed with the aid of the levels of Be^{2+} and $HeHe^{2+}$ in analogy with[7], we can expect intersection of the terms of the initial system $He^{2+} + He(1s^2)$ with the terms of the system situated in the right side of the processes (1) and (7). Therefore the structure obtained by us on the $\sigma_{01}(T)$ curve (or on the cross section of the processes (1)) may represent an effect due to the intersection of the terms of the system $He^{2+} + He(1s^2)$ with certain of the terms of the systems $He^+(nl) + He^+(1s)$ and $He^{2+} + He(1s, nl)$.

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