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INVESTIGATION, BY THE COINCIDENCE METHOD, OF CHARGE STATE CHANGES OCCURRING IN THE INTERACTION BETWEEN H^+, H^0, *AND* H^- *AND THE XENON ATOM*

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The cross sections for elementary processes of charge-state changes involved in the interaction between hydrogen atoms or negative ions and xenon atoms are measured by simultaneous analysis of the charge state of the two colliding atomic particles and recording them by a coincidence method. The cross sections for the production of xenon ions with charges between 1 and 4 and of fast hydrogen particles in charge states +1, 0, −1 are measured for H^0 and H^- energies ranging from 5 to 50 keV. The measured cross sections are compared with the cross sections for similar processes involving protons, obtained by the coincidence method in an earlier investigation[2] in the same energy range. It is found that cross sections for the production of xenon ions with various charges are larger for protons than for H^0 atoms or H^- ions. This is partly due to electron capture by protons with simultaneous ionization of the Xe atom, and partly to the large value of the proton cross sections for pure ionization of the Xe atom. The largest contribution to the production of xenon ions of any charge, in collisions between Xe atoms and H^+ atoms and H^+, H^0 or H^-, is made by those elementary processes which lead to the formation of fast H^0 atoms, irrespective of the initial charge state of the fast particles. Elementary processes with proton production make a smaller contribution, and those with H^--ion production make an insignificant contribution. The probability distribution of various finite charge states of fast hydrogen particles (+1, 0 and −1) in single collisions involving the production of xenon ions depends weakly on the initial charge state of the xenon ions. This permits an arbitrary division of the collision between a light hydrogen particle and a multielectron atom into two stages. In the first, when the nuclear particles approach each other, the target atom is excited and subsequently autoionization transitions and production of a slow ion occurs. In the second stage, when the particles fly apart, the interaction between the fast particle and the weakly-bound external electrons of the atom results in a probability distribution of its final charge states that is determined by the velocity of the fast particle, but depends only weakly on its initial charge state and on the total excitation energy of the atom.

INTRODUCTION

DIRECT measurement of the cross sections of elementary processes in ion-atom collisions, using a simultaneous analysis of the charge states and with registration of both particles by the coincidence method, was first undertaken in[1,2]. These investigations yielded information on the role of different types of elementary changes of the charge states following collision of photons with atoms of inert gases in the energy range 5–50 keV. In collisions between protons and gas atoms, the main types of elementary processes are pure capture of one or two electrons by a proton (or simple and so-called "double" charge exchange), pure ionization of the atom, and capture of the electrons by a proton with simultaneous ionization of the atom. The latter process, as shown in[1,2], plays the principal role in the formation of multiply charged slow ions. In collisions between atoms and negative hydrogen ions with gas atoms, another system of elementary changes in the charge states should take place, namely pure ionization of the target atom, pure ionization of the fast particle (stripping), and simultaneous ionization of both particles (ionization with stripping). In atom-atom collisions, a certain role can be played also by processes connected with the capture of an electron by the atom and formation of a fast negative ion H^-.

The cross sections for the measurement of the charge state of each of the particles separately—fast or slow—were measured in a large number of investigations for the case of collisions of protons, atoms, and negative ions of hydrogen with gas atoms. However, a detailed analysis and a comparison of the cross sections of the elementary processes of variation of the charge states for ion-atom and atom-atom collisions are possible only when the coincidence method is used, inasmuch as the usual methods of analysis of the charge state of one of the particles do not make it possible to separate such processes, particularly when multiply charged slow ions are produced.

In this paper we have measured, by the coincidence method, the cross sections of the elementary processes of variation of the charge states in collision of atoms and negative ions of hydrogen with atoms of xenon, in the incoming-particle energy interval 5–50 keV. The cross sections of the elementary processes obtained for the H^0-Xe and H^--Xe pairs are compared with analogous cross sections for the H^+-Xe pair, which were measured in our preceding investigation[2]. Xenon atoms were chosen as the target in connection with the greatest variety of elementary processes of variation of the charge states occurring in this case. Compared with other noble gases, xenon is characterized by the largest contribution of processes in which several electrons are removed in single collisions, and by the presence of maxima in the cross sections of elementary processes at incoming-particle velocities close to the velocities of external atomic electrons[2], corresponding to the interval investigated in the present paper.

The experimental setup, the procedure, and the choice of conditions necessary for the measurement of the cross sections of the elementary processes by the coincidence method were described by us earlier[3]. In the present investigations, beams of negative ions of hydrogen, as well as beams of protons, were produced by acceleration and mass-monochromatization of ions extracted directly from the ion source. The hydrogen-atom beams were produced with the aid of charge exchange of a monokinetic beam of protons in an auxiliary chamber filled with gas and installed passed the mass monochromator. To eliminate from the beam the ions which were not charge exchange, as well as impurities of atoms that are in long-lived highly-excited states, the beam was made to pass through a capacitor with an electrostatic field of 40 kV/cm. Such a field ensures disintegration of the atoms that are in excited states with principal quantum numbers $n \geq 12$[4]. The excited atoms with $n = 2-7$, in view of their short lifetime[5], had time to go over to the ground state on the path from the charge-exchange chamber to the collision chamber. Thus, the admixture of excited hydrogen atoms in the beam did not exceed 0.1%.

CROSS SECTION MEASUREMENT RESULTS

The elementary processes involving changes in the charge states upon collision of fast hydrogen particles with xenon atoms, namely $H^{k+}Xe^0 \rightarrow H^{m+} + Xe^{n+} + (m + n - k)e$ (where k and 0 are the initial charge states of the particles and m and n the final states), are denoted by us, as usual, by the four numbers k0mn. The abbreviated symbol for the elementary-process cross section is σ_{0n}^{km}.

I. Charge Composition of Slow Xenon Ions

One of the main tasks of the investigation was to compare the cross sections of the processes connected with formation of slow xenon ions for different incoming particles: $H^+(k = +1)$, $H^0(k = 0)$, and $H^-(k = -1)$. In view of the large number of elementary processes for the cases under consideration, we first measured the total cross section σ_{0n} for the production of xenon ions with a definite charge n by the method of analysis of the composition of only the slow ions produced in the gas[6], without using coincidences, for each of the incoming particles ($k = +1, 0, -1$). Such cross sections characterize the total yield of the n-charged slow ions in interactions between fast particles in a definite charge state k and atoms of xenon $H^{k+}-Xe$, but independently of the final charge states m of the fast particles: $\sigma_{0n} = \sum\limits_m \sigma_{0n}^{km}$.

An analysis of the charge composition of the slow ions of xenon was carried out heretofore only for the H^--Xe pair[7]. Therefore Fig. 1 shows data on the total cross sections σ_{0n} for the production of slow ions with different charges, for all three pairs of particles H^+-Xe, H^0-Xe, and H^--Xe. The cross sections σ_{0n} for the H^--Xe pair, obtained in the present paper, are in good agreement with those given in[7]. A comparison of the cross section σ_{0n} for different incoming particles shows that the values of the cross sections are largest for protons at all values of n. One of the obvious causes of this circumstance is the presence of the processes of capture and capture with ionization for protons. The cross sections σ_{0n} for atoms and negative ions of hydrogen are close to each other, especially upon production of multiply charged slow ions. A small excess of the cross sections for negative ions H^-, compared with the cross sections for the atoms H^0, is observed only in the region of large energies. The greatest differences between the cross sections for the production of slow ions for protons and the cross sections for atoms and negative ions of hydrogen are observed in the initial part of the investigated energy interval. With increasing energy T_0, the difference between the cross sections for the production of slow ions σ_{0n} decreases for these incoming particles.

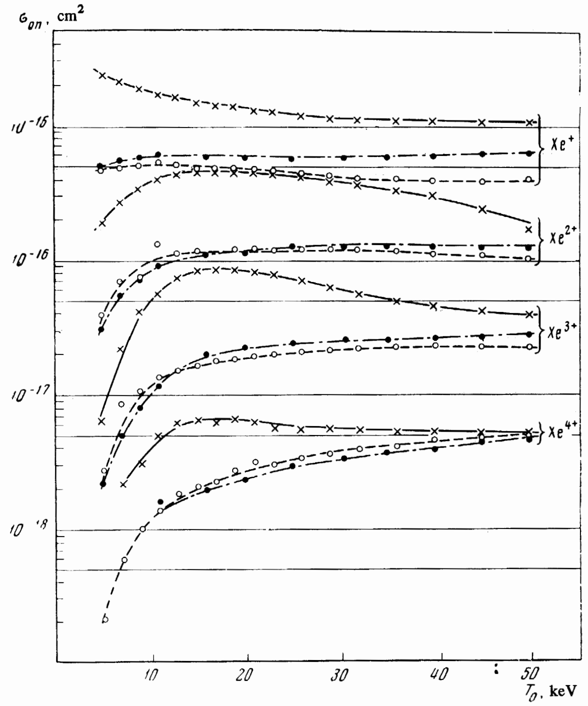

FIG. 1. Total cross section σ_{0n} for the production of xenon ions with different degrees of charge upon collision of protons, atoms, and negative ions of hydrogen with xenon atoms. Continuous curves – for protons (k = +1), dashed – for hydrogen atoms (k = 0), dash-dot – negative hydrogen ions (k = –1). The charge states of the slow ions are indicated.

For protons, the plots of the cross sections for the production of multiply charged xenon ions have a maximum in the investigated energy interval. The cross section for the production of singly charged ions σ_{01} decreases continuously with increasing energy, since it has a maximum already in the region of the lowest energies $T_0 < 5$ keV. For atoms and negative ions, the cross sections σ_{01} and σ_{02} for the production of singly- and doubly-charged slow ions also have a broad maximum in the investigated energy interval. The cross section for the production of triply- and quadruply-

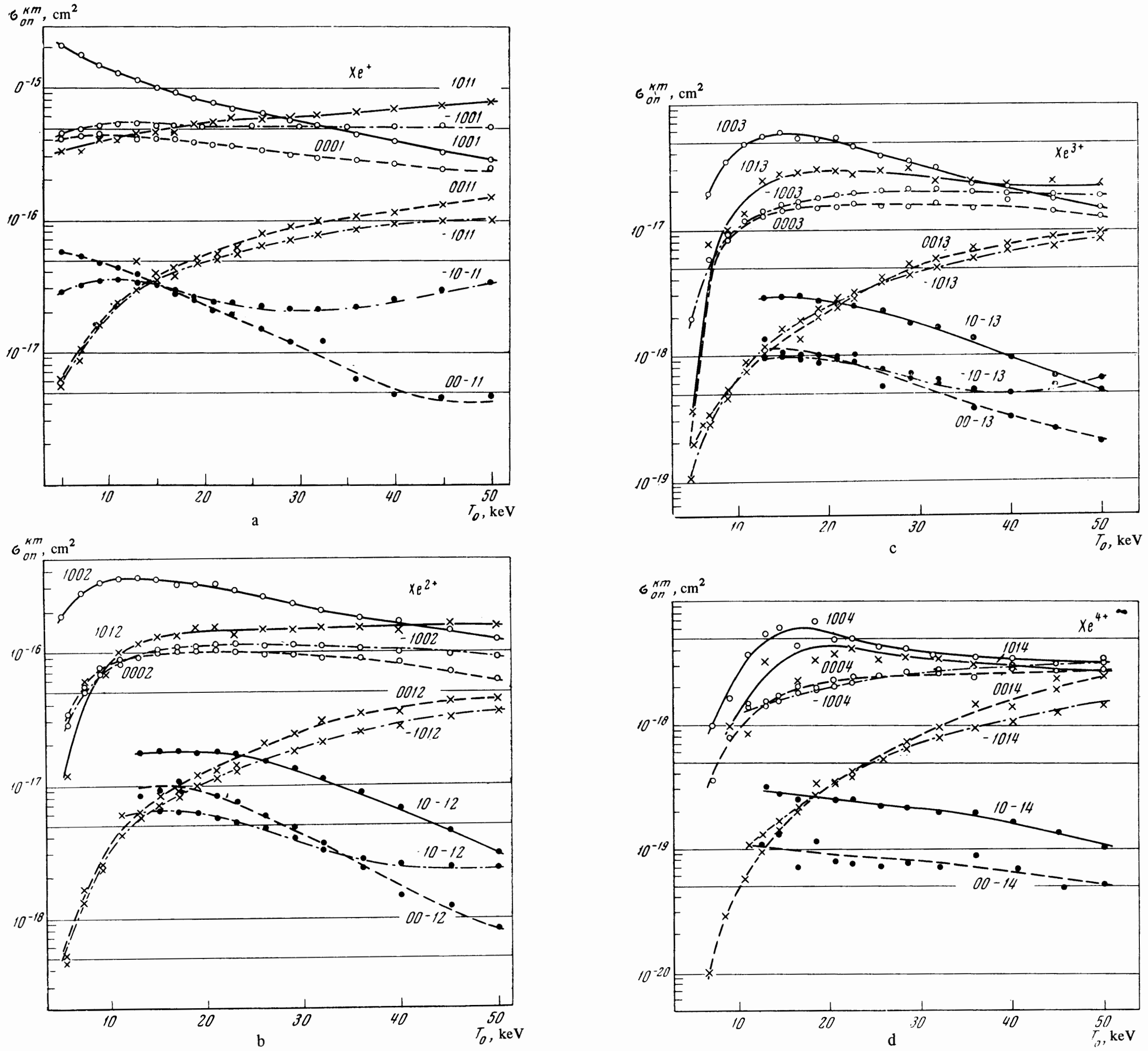

FIG. 2. Cross section $\sigma_{0n}{}^{km}$ of the elementary processes in which the charge states kOmn are changed upon production of xenon ions: a – singly-charged (n = 1), b – doubly-charged (n = 2), c – triply-charged (n = 3), d – quadrup quadruply charged (n = 4). The initial charge states of the fast hydrogen particles (prior to the collisions) are: k = +1 (continuous curves) k = 0 (dashed curves), k = –1 (dash-dot curves); the final states (after collision) are: m = +1 (χ), m = 0 (○), m = –1 (●). The elementary processes involving the change of the charge states are indicated on the corresponding curves.

charged slow ions, σ_{03} and σ_{04}, do not reach a maximum, but their growth, starting with an energy $T_0 \approx 20-25$ keV, is strongly decelerated.

II. Elementary Processes in Which the Charge States are Changed

The cross sections of the elementary processes kOmn, measured by the coincidence method, are shown in Fig. 2. On each of the figures are shown the cross sections of the processes for all the initial (k = +1, 0, –1) and all the possible final charge states (m = +1, 0, –1) of the fast particles, but for one charge state n of the slow xenon ions. It is therefore natural that, for any pair of colliding H^{k+}—Xe particles, each curve of the total cross section σ_{on} for the production of an n-charged slow ion in Fig. 1 corresponds as a rule to three curves of Fig. 2 for the cross sections of the elementary processes σ_{on}^{km}, which are components of the cross section σ_{on} and are connected with different fast-particle final states with m equal to +1, 0, and –1. It should be noted here that owing to the use of ion-electron converters as individual-particle detectors[3], in which the particles strike a target that has an appreciable negative potential, the fast negative hydrogen ions could be registered at energies $P_0 \geq 13$ keV. Therefore the cross sections of processes of the type k0—1n, connected with the registration of fast ions H^-, were measured in the interval 13—50 keV.

Comparison of Figs. 2a–d shows that the absolute values of the cross sections of the elementary processes decrease strongly with increasing charge of the slow ion. However, the sequence of the cross sections of processes of different types in each of these figures remains the same in first approximation. Therefore it is advantageous to consider the data shown in Figs. 2a–d simultaneously.

1. **Comparison of processes for fast incoming protons with processes for fast incoming atoms and negative ions of hydrogen.** The data presented in Fig. 2 make it possible to explain what processes cause the protons ($k = +1$) to have larger cross sections for slow-ion production than the atoms and the negative ions ($k = 0, -1$). First, as expected, such processes are the capture of one electron by the incoming photon with ionization of the atom, 100n. However, as shown in Fig. 2, processes of pure proton ionization, 101n, also have a larger cross section than for atoms and negative ions. With this, the cross sections for pure ionization by protons exceed not only the cross sections of those target-atom ionization processes that require a considerable energy for their implementation and are connected with simultaneous stripping of the fast particle (001n and –101n), but also the cross sections of such processes of ionization by H^0 atoms and H^- ions, which consume practically the same energy, namely pure ionization by atoms 000n and ionization by ions H^- with detachment of the weakly-coupled electron –100n. Indeed, the processes 101n, 000n, and –100n require approximately the same energy, $\Delta E \approx -12$ eV at a slow-ion charge $n = 1$, $\Delta E \approx -33$ eV at $n = 2$, $\Delta E \approx -0.65$ eV at $n = 3$, and $\Delta E \approx -111$ eV at $n = 4$. The only exception for the group of processes 101n, 000n, and –100n is the incoming-particle energy interval $T_0 < 10–15$ keV for n equal to 1 and 2, where the cross section for the protons (101n) is somewhat smaller than the cross sections for the atoms and negative ions (000n and –100n).

2. **Comparison of processes for fast incoming atoms and negative hydrogen ions.** If we compare the cross sections for different xenon ionization processes by H^0 atoms and by negative H^- ions, then such cross sections turn out to be as a rule quite close in value if the charges of the produced slow ions are equal. The main cause of this fact is apparently the large value of the cross section for the detachment of the weakly coupled electron from the H^- ion, as a result of which the H^-–Xe interaction, which leads to ionization of the xenon atom, reduces in first approximation to the H^0–Xe interaction. However, the existing insignificant differences in the cross sections of the ionization processes for H^0 and H^- have a systematic character and can therefore be discerned.

Processes of ionization of an atom by a negative ion with detachment of a weakly-coupled electron, –100n, have somewhat larger cross sections than the processes 000n of pure ionization by atoms. This difference is most strongly manifest in the formation of singly-charged slow ions (the processes –1001 and 0001) in the region of high energies. Differences between the ionization cross sections for H^0 and H^{-1} could be expected precisely in the case of formation of singly-charged slow ions, since, starting with a velocity corresponding to the energy of the H^- ions $T^0 = 21.2$ keV, additional ionization of the xenon atoms becomes possible, with removal of one electron by the weakly-coupled electron of the incoming particle. Of course, we cannot regard the cross sections of the processes –100n simply as sums of the cross sections of the independent processes of ionization of the xenon atom by the fast hydrogen atom and electron impact. It is seen from Fig. 2 that in the case of simultaneous ionization of the atom and "stripping" of all the electrons of the incoming particle ($H^0 \rightarrow H^+$, $H^- \rightarrow H^+$), the cross sections for the processes for the fast atoms 001 turn out, in contrast to the processes –100n and 000n, to be somewhat higher than for the fast negative ions, –101n.

3. **Processes with formation of fast negative hydrogen ions in the final charge state.** The elementary processes in which the charge states change and which cause the fast particle to end up in the state H^- ($m = -1$) form a separate group. At a given charge n of the slow ion, the cross sections of these processes are smaller, in the greater part of the investigated energy interval, than the cross sections of all the other processes corresponding to the final charge states of the fast particles $m = +1$ and $m = 0$. Comparison of the processes with $m = -1$ for different incoming particles ($k = +1$, 0, and -1) shows that the greatest cross section in this group is possessed by processes of pure double capture and double capture with ionization for protons 10–1n. This is seen from the data for all the multiply charged ions (Figs. 2b, c, d); (the process of double capture is impossible in the production of singly-charged at slow ions ($n = 1$)). Thus, the process 10–1n connected with the capture of two electrons turns out to be more probable than processes of pure ionization (in this case –10–1n) and the capture of an electron with ionization (00–1n). One of the causes of this fact is apparently the energy consumed in the implementation of the process 10–1n, which is approximately 14 eV lower than for the processes –10–1n and 00–1n. However, the insignificant magnitude of the cross sections for all the processes with $m = -1$ compared with the processes with $m = +1$ and $m = 0$ is not at all connected with the energy consumed in their implementation, but with the small relative probability of the production of negative hydrogen ions as a result of collisions of fast hydrogen particles with xenon atoms. The question of the distribution of the probability of the final charge states of fast particles will be considered in greater detail in Sec. 6 below.

As to the ratio of the cross sections of the processes –10–1n and 00–1n, the cross section for capture with ionization 00–1n exceeds somewhat the cross section of pure ionization –10–1n in the energy region $T_0 < 20–25$ keV. When $T_0 > 25$ keV, conversely, the cross sections of the process –10–1n can greatly exceed the cross sections of the process 00–1n.

4. **Dependence of the cross sections on the energy of the incoming particles.** Figure 2 shows that the majority of $\sigma_{on}^{km}(T_0)$ curves for the processes connected with production of slow xenon ions with different charge states have a maximum in the investigated energy range. The only exothermal process of pure capture of one electron (charge exchange) for protons, 1001, with an energy defect $\Delta E = +1.5$ eV, and certain processes with production of fast negative ions in the final state have maxima at energies that lie below the investigated interval. It

was noted in our paper[2] that in collisions between protons and multi-electron atoms of Xe, not only processes of capture with ionization, but also processes of pure ionization, leading to the formation of multiply charged ions, have cross-section maxima in the proton energy region T_0 = 15–30 keV. These energies correspond to incoming-particle velocities close to the velocity of the external electrons of the atoms. It is seen from Fig. 2 that an analogous conclusion can be drawn for the majority of processes of pure ionization by atoms (000n) and processes of ionization by negative ions of hydrogen with splitting of the weakly-coupled electron (−100n). To the contrary, processes of ionization of xenon atoms with simultaneous stripping of all the electrons of the incoming particles (001n and −101n) have cross sections that increase with increasing energy T_0 in the entire investigated interval. It should be noted that the main factor influencing the form of the $\sigma^{k1}_{0n}(T_0)$ curves is precisely the simultaneous ionization of the target and stripping of the fast particle. Indeed, processes connected with removal of the same total number of electrons but from one particle, and requiring even a greater energy consumption, have a cross-section maximum in the region $T_0 < 50$ keV. This can be seen from a comparison of the $\sigma^{km}_{0n}(T_0)$ curves for processes with removal of two electrons: 0011 (E = −25.7 eV) and 0002 (ΔE = −33.3 eV), and also with removal of three electrons: 0012 (ΔE = −46.9 eV), and 0003 (ΔE = −65.4 eV). Judging from the form of the curves, the process with removal of four electrons from the atom, 0004 (ΔE = −111 eV), should also have a maximum at a lower energy of the incoming particles than the process 0013 (ΔE = −79 eV).

The behavior of the cross sections of pure ionization by negative ions (−10−1n) is somewhat unexpected. The cross sections of these processes go through a maximum in the initial part of the investigated energy interval and reveal a new growth in the region of large energies.

5. Competition between the processes of ionization and "stripping" with removal of one electron. In the investigation of collisions of hydrogen particles with multi-electron atoms, it is best to compare the probabilities of the electron loss by the fast particle and by the target particle by comparing the cross sections of the process of pure stripping of the hydrogen atom 0010 and the process of pure ionization of the atom 0001 with removal of one electron. The binding energies of the electron in the hydrogen atom and in the outer shell of the xenon atom are close to each other. To compare the elementary processes in which atoms and negative ions of hydrogen take part in the initial charge state, it is of interest to compare also the cross sections of pure stripping of these particles with the removal of one electron 0010 and −1000. The coincidence procedure used in the present paper makes it possible to study different elementary processes connected with the formation of slow ions. However, the presence of data on the total cross sections for the loss of one electron by atoms and negative ions of hydrogen σ^{01} and σ^{-10}, measured in[8-10], and on the cross sections of the elementary processes measured in the present paper, make it possible to determine the cross sections of the processes which are not accompanied by formation of slow ions and are connected only with changes of the charge of the fast particle (0010 and −1000). Indeed,

$$\sigma_{00}{}^{01} = \sigma^{01} - \sum_{n\geqslant1}\sigma_{0n}{}^{01} \text{ and } \sigma_{00}{}^{-10} = \sigma^{-10} - \sum_{n\geqslant1}\sigma_{0n}{}^{-10}.$$

The cross sections of these processes are shown in Fig. 3, which shows for comparison also the cross section of the process of pure ionization of the xenon atom 0001, measured directly in the present investigation. It is seen from Fig. 3 that the cross section of the pure stripping process −1000, in which only the weakly-coupled electron of the negative ion is removed in the H^-–Xe collisions, greatly exceeds the cross sections of all other processes in which the charge states of these particles change. As to the loss of one electron by the hydrogen and xenon atoms, in spite of the small difference between the binding energies of the electrons, it is most probable that the electron is removed from the xenon atom ($\sigma^{00}_{01} > \sigma^{01}_{00}$), particularly at low energies. This is to be expected from the ratio of the statistical weights of the states H^0–Xe^+ and H^+–Xe of the H^0–Xe system that is produced during the collisions. With increasing energy of the colliding atoms, the difference between the cross sections of pure ionization and pure stripping decreases.

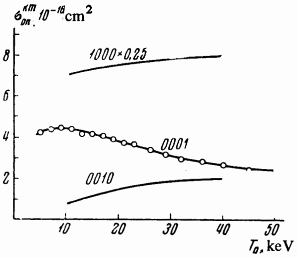

FIG. 3. Cross sections of elementary processes in which the charge states are changed and one electron is removed in atom-atom collisions H^0–Xe: pure ionization of the xenon atom 0001 and pure stripping of the hydrogen atom 0010; −1000 – cross section of the process of pure stripping of negative hydrogen ions in H^-–Xe collisions.

6. Distribution of probability of the final charge states of fast hydrogen particles. The elementary processes occurring in single collisions between fast hydrogen particles and xenon atoms, investigated in the present study, are accompanied by formation of slow ions with charges from n = 1 to n = 4, and require different energy consumption for their implementation, from a release of +1.5 eV in charge exchange 1001 to a loss −124 eV in ionization with stripping 0014. It would be natural to assume that the distribution with respect to the final state of one of the particles should depend on the final charge state of the second particle. By way of illustration, Fig. 4 shows data on the relative probability P_m of different final charge states of the fast particle (m equal to +1, 0, and −1) for different values of the charge of the produced slow ions of xenon in H^0–Xe collisions (i.e., at an initial charge state k = 0 of the fast particle). For this case we have

$$P_m = \sigma_{0n}^{0m} \Big/ \sum_m \sigma_{0n}^{0m}.$$

At fast-particle energies $T_0 < 13$ keV, where the cross sections of the processes k0−1n (i.e., with m = −1) were not measured, the relative probabilities for m = −1 were not determined, and for m = +1 and m = 0 they were calculated from the formula

$$P_m = \frac{\sigma_{0n}{}^{0m}}{(\sigma_{0n}{}^{01} + \sigma_{0n}{}^{00})\left[1 + \sigma^{0-1} \Big/ \sum_n (\sigma_{0n}{}^{01} + \sigma_{0n}{}^{00})\right]}.$$

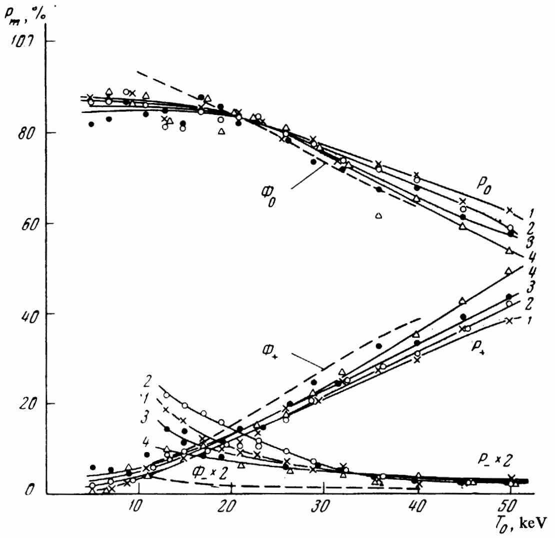

FIG. 4. Relative probabilities P_m of different final charge states m = +1, 0, −1 of a fast hydrogen particle for single collisions H^0–Xe, accompanied by production of xenon ions of different charge. The charge states of the slow ions n = 1, 2, 3, 4 are indicated by the numbers on the corresponding curves. Φ_+, Φ_0, and Φ_- – equilibrium fractions of the protons, atoms, and negative hydrogen ions in multiple collisions with the Xe atoms of fast hydrogen particles passing through a thick xenon target.

In this formula the total cross section for the capture of the electron by the fast hydrogen atom σ^{0-1} is taken from the paper of Fogel' et al.[10] Therefore the cross section σ^{0-1} is much smaller than the total cross section $\sum_n (\sigma^{01}_{on} + \sigma^{00}_{on})$, and the values of P_m calculated from the two formulas differ in the region $T_0 \geq 13$ keV by less than 1%. This shows that the latter formula can be used with sufficient accuracy to determine P_+ and P_0 in the fast-particle energy region $T_0 < 13$ keV.

It is seen from Fig. 4 that the charge composition of the fast particles after collision depends only little on the charge of the slow ion. The relative proton-production probability P_+ increases somewhat with increasing charge of the slow ions. The distribution of the fast particle with respect to the charge, after single collisions with xenon atoms, agree qualitatively with the equilibrium distribution (shown in the same Fig. 4) established as a result of multiple collisions after the hydrogen particles pass through a thick xenon target. Similar results follow from an analysis of the distributions of the final charge states of the fast particle P_m for the pairs H^+–Xe and H^-–Xe (k equal to +1 and −1).

In single collisions, it would be natural to expect also the initial charge state of the fast particles to influence the distribution of the probability of their final charge states. Figure 5 shows the relative probabilities of the final charge states of the fast hydrogen particles, P_+, P_0, and P_-, upon production of doubly-charged slow ions (n = 2), for different initial charge states of the fast particles k = +1, 0, and −1. It is seen from Fig. 5 that the distribution of the final charge states depends little on the initial charge state of the fast particles. As expected, the probability of retaining the electrons in the fast-particle shell after collision is maximal for the initial charge state k = −1, and decreases successively for k = 0 and k = +1. An analysis of the experimental data for processes in which ions with other values of the charge are produced shows that the connection between the initial and final charge states of the fast particle decreases with increasing charge of the slow ions and is even weaker at n = 3 and n = 4.

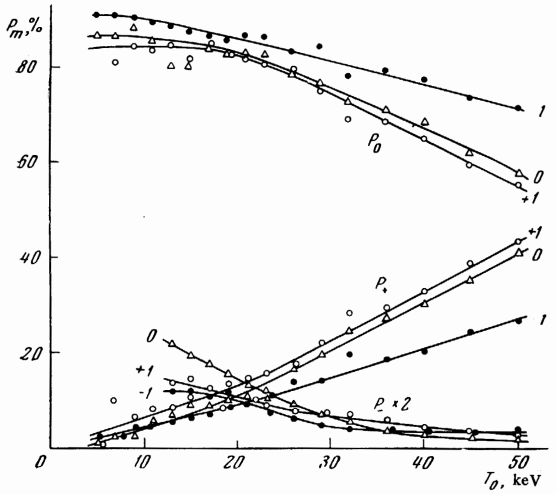

FIG. 5. Relative probabilities P_m of different final charge states m = +1, 0, −1 of a fast hydrogen particle, for single collisions H^+–Xe, H^0–Xe, and H^-–Xe, accompanied by production of doubly-charged xenon ions (n = 2). The initial charge states of the fast hydrogen particles k = +1, 0, −1 are indicated by the figures on the corresponding curves.

III. Concluding Remarks

Thus, in collisions of fast hydrogen particles with multi-electron atoms of xenon at energies $T_0 \leq 50$ keV, the greatest contribution to the production of the xenon ions, regardless of the initial charge of the fast particles, is made by processes in which hydrogen atoms are produced. A smaller contribution is made by processes accompanied by production of protons, and only a negligible contribution is made by processes in which negative hydrogen ions are produced. The role of the processes in which protons are produced increases with increasing energy of the incoming particles T_0. The connection between the initial and final charge states of the fast particles turns out to be weak, particularly in the energy region T_0 from 15 to 25 keV, which corresponds to a colliding-particle velocity v close to the velocities of the external atomic electrons ($v = v_e = e^2/\hbar$).

In collisions of different hydrogen particles with xenon atoms, the absolute values of the cross sections of the elementary processes, leading to the formation of slow ions, turn out to be largest for protons and somewhat smaller, but as a rule close to each other, for atoms and negative ions of hydrogen. In the velocity region $v \approx v_e$ the cross sections of most processes connected with the production of multiply charged slow ions have a maximum. The presence of maxima in the cross sections of the elementary processes with production of multiply charged slow ions in the velocity region $v \approx v_e$ confirms the conclusion made in our paper[2] that in this region there is in operation a mechanism of inelastic interaction of atomic particles, which is characterized by participation of many electrons and leads to a considerable probability of multiple ionization of the atom.

The weak dependence of the charge composition of the fast particles following the collision on their initial charge state and on the charge of the produced slow ions gives grounds for arbitrarily subdividing the implementation of the elementary processes into two stages. During the first stage, when the nuclei of the particles come closer together, the fast hydrogen particle crosses the shells of the multi-electron atom and excites this atom. In the second stage, when the particles move apart, the fast particle passes through the outer shells of the atom, where it interacts with the weakly-coupled electrons. This stage apparently determines the distribution of the probability of the final charge states of the fast particle, which turns out to depend on the particle velocity, but is weakly connected with the charge state prior to the collision and with the total energy of excitation of the target nucleus. The excited state of the atom can decay via removal of various numbers of electrons and production of slow ions with different degrees of charge. The described rough scheme of a "two-stage" inelastic interaction between a light atomic particle and a multi-electron atom should be most probable for collisions in which the particle nuclei come very close together, accompanied by removal of several electrons. The latter assumption is in satisfactory agreement with the experimental data reported in Sec. 6.

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

[2] V. V. Afrosimov, Yu. A. Mamaev, M. N. Panov, and N. V. Fedorenko, ibid. in press.

[3] V. V. Afrosimov, Yu. A. Mamaev, M. N. Panov, V. Uroshevich, and N. V. Fedorenko, ibid. **37**, 550 (1967) [**12**, 394 (1967)].

[4] A. S. Riviere and D. R. Sweetman, Comptes Rendus de la VI Conference Internationale sur les Phenomenes d'Ionisation dans les Gaz (Paris, 1963), 1, SERMA, Paris, (1964), p. 105.

[5] J. R. Hiskes, C. B. Tarter, and D. A. Moody, Phys. Rev. **133**, A427 (1964).

[6] N. V. Fedorenko and V. V. Afrosimov, Zh. Tekh. Fiz. **26**, 1941 (1956) [Sov. Phys.-Tech. Phys. **1**, 1872 (1957)].

[7] Ya. M. Fogel', A. G. Koval', Yu. Z. Levchenko, and A. F. Khodyachikh, Zh. Eksp. Teor. Fiz. **39**, 548 (1960) [Sov. Phys.-JETP **12**, 384 (1961)].

[8] J. B. Stedeford and J. B. Hasted, Proc. Roy. Soc. **A227**, 466 (1955).

[9] Ya. M. Fogel', V. A. Ankudinov, and R. P. Slabospitskiĭ, Zh. Eksp. Teor. Fiz. **32**, 453 (1957) [Sov. Phys.-JETP **5**, 382 (1957)].

[10] Ya. M. Fogel', V. A. Ankudinov, D. V. Pilipenko, and N. V. Topolya, ibid. **34**, 579 (1958) [**7**, 400 (1958)].

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