IONIZATION IN THE COLLISIONS OF Ne^{n+} *WITH* Xe *ATOMS AND OF* Xe^{n+} *WITH* Ne *ATOMS* ($n = 0, 1, 2, 3, 4$)

I. P. FLAKS, G. N. OGURTSOV, and N. V. FEDORENKO

Leningrad Physico-Technical Institute

Submitted to JETP editor June 9, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 1438-1442 (November, 1961)

The total cross sections for the production of free electrons, i.e., the total ionization cross sections (σ_-) for single collisions between fast Ne^{n+} particles and Xe atoms and between fast Xe^{n+} particles and Ne atoms, have been measured. The fast ions had charges from 0 to 4 and were accelerated by a potential which varied from 3 to 30 kv. With increasing charge n of the fast particle, the cross section σ_- was found to increase for the Ne^{n+}—Xe pair and to decrease for the Xe^{n+}—Ne pair. An analysis of the elementary processes in which electrons are liberated from the shells of each of the colliding particles indicates that a behavior of this type could be expected. The increase of the cross section σ_- with the fast particle charge is due to the possibility of exothermal ionization processes involving capture. An opposite type of dependence occurs when the capture ionization is an endothermal process, so that the main contribution to the cross section σ_- is due to the "stripping" of the fast particle.

1. INTRODUCTION

ACCORDING to our views on collision ionization in the kev range of energies, the ionization cross sections for the collisions of particles with medium mass should be very small. Large cross sections in this energy range are due to a so-called "strong-interaction mechanism," which is connected with the perturbation of many electrons and with autoionization.[1,2] To investigate this mechanism, it is important to explain the variation of the ionization cross section with the relative velocity, the structure of the electron shells, and the charge of the fast ionizing particle. From general considerations, we should assume that, in the velocity range $v < e^2/\hbar$, the ionization cross section should increase with increasing velocity and with an increasing number of electrons in the shells of the colliding particles.[2]

As far as the influence of the charge is concerned, the investigations carried out by us in an earlier experiment[3] for singly, doubly, and triply charged ions of several inert gases showed that the charge dependence is weak and irregular. In order to explain more fully the influence of the charge of the ionizing atomic particles on the production of free electrons in the present experiment, we have measured the total ionization cross section σ_- for two groups of colliding particles strongly differing in the binding energy of the electrons in the shells of the ionizing particle and of the target atoms. In one case, the neutral atoms or ions of neon served as fast particles and the xenon atoms (the Ne^{n+}—Xe pairs) as the target, while in the second case the neon atoms were ionized by fast atoms or ions of xenon (the Xe^{n+}—Ne pairs).

The investigation was carried out using an experimental arrangement described earlier.[3-5] The determination of the total ionization cross section σ_- was based on the detection of the total number of electrons liberated from the shells of both colliding particles as a result of their decomposition or change of structure. As before,[3,4] the cross section σ_- was measured by the condenser

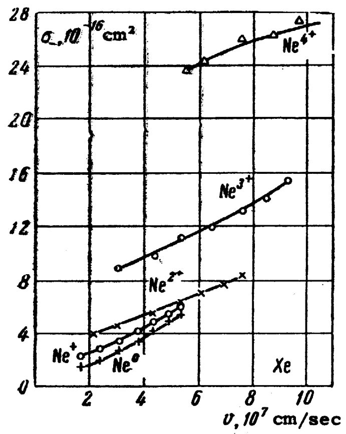

FIG. 1. Variation of the total ionization cross section σ_- of the Xe atoms with the velocity v of fast Ne^{n+} particles.

method for single collisions. The accelerating voltage varied from 3 to 30 kv. It was possible to obtain fast ion beams with a charge of 0 to 4. The multiply charged ions were identified by studying the isotopic composition, and also by analysis of the secondary spectrum produced in the capture of electrons by primary ions.[3] The total error in the determination of the cross section was not greater than 15%, for ions with charge n = 1, 2, 3, and 20% for fast neutral atoms and quadruply charged ions.

2. RESULTS OF THE MEASUREMENTS

Figure 1 shows the variation of the total ionization cross section σ_- with velocity v of fast ionizing particles Ne^0, Ne^+, Ne^{2+}, Ne^{3+}, Ne^{4+} in the passage through xenon. Fig. 2 shows the same for the fast particles Xe^0, Xe^+, Xe^{2+}, Xe^{3+}, Xe^{4+} in their passage through neon.

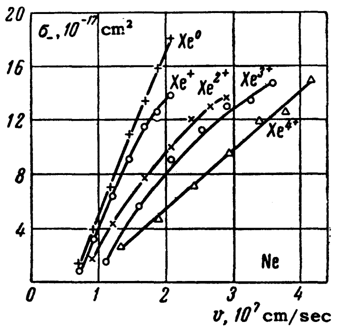

FIG. 2. Variation of the total ionization cross section σ_- of Ne atoms with the velocity v of Xe^{n+} particles.

The main experimental result of the work is that for the Ne^{n+}—Xe pairs the total ionization cross section increases with increasing charge of the fast Ne^{n+} particles, while for the Xe^{n+}—Ne pairs the cross section decreases for increasing charge of the fast Xe^{n+} particles. It can also be seen from Fig. 1 that for the Ne^{n+}—Xe pairs a sharp increase in the σ_- cross section occurs starting with n = 3. Thus, e.g., for v = 5.4 $\times 10^7$ cm/sec (particle energy T = 30 kev), the cross section σ_- equals 5.5×10^{-16} cm² for the Ne^0—Xe pairs, 6×10^{-16} cm² for Ne^+—Xe, 6.2 $\times 10^{-16}$ cm² for Ne^{2+}—Xe, 11.2×10^{-16} cm² for Ne^{3+}—Xe, and $\sim 24 \times 10^{-16}$ cm² for Ne^{4+}—Xe. The decrease of the σ_- cross section with increasing n for the Xe^{n+}—Ne pairs is smoother. For v = 2.1×10^7 cm/sec (T = 30 kev), the cross section σ_- equals 1.8×10^{-16} cm² for the Xe^0—Ne pairs, 1.4×10^{-16} cm² for Xe^+—Ne, 1×10^{-16} cm² for Xe^{2+}—Ne, 0.9×10^{-16} cm² for Xe^{3+}—Ne, and 0.6×10^{-16} cm² for Xe^{4+}—Ne. It can also be noted that, for the same velocity, the total ionization cross section σ_- is practically identical for the Ne^0—Xe and Xe^0—Ne pairs, and therefore these pairs are completely equivalent with respect to the production of free electrons.

All cross sections increase continuously with increasing velocity v. However, for the Ne^{n+}—Xe pairs, a slower rise of σ_- with velocity is observed than for the Xe^{n+}— Ne pairs, and the behavior of the curve $\sigma_-(v)$ depends little on the charge. For the Xe^{n+}—Ne pairs, the curvature of the curve $\sigma_-(v)$ increases with decreasing charge.

3. DISCUSSION OF RESULTS

In the collision of a fast particle I^0 with atoms of the gas A, the electrons are freed either as the result of pure ionization

$$I^0 + A \rightarrow I^0 + A^{k+} + ke, \tag{1}$$

as a result of stripping of the fast particle

$$I^0 + A \rightarrow I^{m+} + A + me, \tag{2}$$

or else through a combination of ionization and stripping

$$I^0 + A \rightarrow I^{m+} + A^{k+} + (m + k)\, e. \tag{3}$$

If the fast particle is an ion I^{n+}, then, in addition, we can have processes of capture ionization*

$$I^{n+} + A \rightarrow I^{m+} + A^{k+} + (m + k - n)\, e, \tag{4}$$

in which some of the electrons removed from the atomic shell are captured by the shell of the ion and some are freed.

The relative role of any process is determined primarily by the energy ε necessary for its occurrence. Thus, for instance, it is clear that for the Ne^{n+}—Xe pairs the ionization of the Xe atoms should predominate over the stripping of the fast Ne^{n+} particles, which calls for a much higher energy. The stripping can probably contribute appreciably to the total ionization cross section σ_- only for the Ne^0—Xe pair. For the Ne^+—Xe pair, the cross section $\sigma_-(Ne^+)$ is somewhat greater then the cross section $\sigma_-(Ne^0)$ (see Fig. 1), for in this case ε = 11.7 ev, and the following combined ionization and capture is possible

$$Ne^+ + Xe \rightarrow Ne^0 + Xe^{2+} + e. \tag{5}$$

Although the process (5) is endothermic, it needs less energy than the stripping process $Ne^0 \rightarrow Ne^+$.

The role of ionization with capture is evidently greater for highly ionized fast neon particles

*We consider only the atoms and ions of inert gases, and capture of the electron by fast atoms is therefore excluded.

where these processes become exothermic. For the Ne^{2+}—Xe pair, the energy $\varepsilon \approx -29$ ev liberated in a single-electron charge exchange

$$Ne^{2+} + Xe \rightarrow Ne^{+} + Xe^{+}, \qquad (6)$$

is sufficient for the removal of a second electron from the Xe atom

$$Ne^{2+} + Xe \rightarrow Ne^{+} + Xe^{2+} + e \qquad (\varepsilon = -7.75\,\text{ev}). \qquad (7)$$

The liberated energy may be carried away by the free electron or used up for optical excitation.

For the Ne^{3+}—Xe pair in the single-electron and two-electron charge exchange

$$Ne^{3+} + Xe \rightarrow Ne^{2+} + Xe^{+} \qquad (\varepsilon \approx -51\,\text{ev}), \qquad (8)$$

$$Ne^{3+} + Xe \rightarrow Ne^{+} + Xe^{2+} \qquad (\varepsilon \approx -71\,\text{ev}) \qquad (9)$$

an energy $|\varepsilon| > 50$ ev is liberated, and for the Ne^{4+}—Xe pair, the charge exchange processes are even more exothermic:

$$Ne^{4+} + Xe \rightarrow Ne^{3+} + Xe^{+} \qquad (\varepsilon \approx -85\,\text{ev}), \qquad (10)$$

$$Ne^{4+} + Xe \rightarrow Ne^{2+} + Xe^{2+} \qquad (\varepsilon \approx -127\,\text{ev}), \qquad (11)$$

$$Ne^{4+} + Xe \rightarrow Ne^{+} + Xe^{3+} \qquad (\varepsilon \approx -136\,\text{ev}) \qquad (12)$$

and the energy liberated in these processes is sufficient for the removal of the next two electrons from the Xe atom, e.g.,

$$Ne^{4+} + Xe \rightarrow Ne^{3+} + Xe^{2+} + e \qquad (\varepsilon \approx -64\,\text{ev}), \qquad (13)$$

$$Ne^{4+} + Xe \rightarrow Ne^{3+} + Xe^{3+} + 2e \qquad (\varepsilon \approx -32\,\text{ev}) \qquad (14)$$

etc.*

It is clear that, at relatively large distances of approach of the nuclei in the case of multiply charged ions,[7] the liberation of electrons from the shells of colliding particles may not only be due to the kinetic energy of the relative motion (ionization mechanism discussed in[2]), but may also be a result of the excitation of the system due to the internal energy liberated in strongly exothermic charge-exchange processes. This explanation of the observed increase of the cross section σ_- with increasing charge is favored by the fact that the curves $\sigma_-(v)$ for the Ne^{2+}—Xe, Ne^{3+}—Xe, and Ne^{4+}—Xe pairs (see Fig. 1) are practically parallel, so that this ionization depends little on the relative velocity v. It is also interesting to note that the ionization due to the internal energy is similar to the field extraction of electrons from metals by ions of different charge as studied by us,[8] and may be regarded as a field ionization.

Whereas, the field ionization is the determining factor for the Ne^{n+}—Xe pairs when $n \geq 3$, for the opposite Xe^{n+}—Ne pair ionization of this type cannot occur even when $n \leq 5$. The charge exchange of Xe^{n+} ions in Ne is endothermic when $n \leq 3$, and when $n \leq 5$ the energy freed in exothermic charge-exchange processes is not sufficient to free the second electron from the Ne atom. For the Xe^0—Ne pair, the cross section σ_- is undoubtedly determined by the stripping of the fast atom of Xe^0, and the relative contribution of the pure ionization process of the Ne atoms is relatively small.

From indirect data* we can also establish that for the Xe^+—Ne pair the main role in the production of free electrons is also played by the stripping process, although the energy $\varepsilon = 21.2$ ev necessary for the stripping reaction

$$Xe^{+} + Ne \rightarrow Xe^{2+} + Ne + e, \qquad (15)$$

is close to the ionization energy of neon ($\varepsilon = 21.56$ ev). Apparently, this is due to the excitation of a larger number of electrons in the outer shell of Xe than in Ne. The stripping with a higher degree of ionization of the fast Xe particles needs a relatively larger energy loss, and the total cross ionization σ_- therefore decreases with increasing charge. However, the fact that the σ_- cross section decreases continuously right up to the Xe^{4+}—Ne pair testifies to the considerable contribution of the stripping processes to the σ_- cross section also for the Xe^{2+}—Ne and Xe^{3+}—Ne pairs.

Thus, the results of the present experiment permit us to explain to a certain degree the influence of the charge of the fast particle when the relative velocity is $v < e^2/\hbar$.

The production of free electrons is connected with the probability of occurrence of various inelastic processes, and the character of the variation of the total ionization cross section σ_- with the charge n is determined by the relative role of the particular process. This is well illustrated by the data obtained for two groups of particles (Ne^{n+}—Xe, Xe^{n+}—Ne) which differ strongly in the binding energy of the electrons in the ionizing par-

*We do not consider here the charge exchange with total neutralization of the charge for the Ne^{3+} and Ne^{4+} ions, since it is known[6] that the charge-exchange cross section decreases strongly with an increasing number of captured electrons. Apparently, the main role in the further ionization of the Xe atoms is played by the processes of single-electron charge exchange (8) and (10).

*For the pairs Xe^+—Ne, the ionization cross section Ne practically coincides with the total production cross section of slow ions (σ_+), and the stripping cross section of Xe^+ can be determined from the difference between the cross sections ($\sigma_- - \sigma_+$).[4]

ticle and in the gas atom. In this case, where the ionization processes with capture are exothermic, they can contribute greatly to the total ionization cross section σ_-, and an increase in σ_- with increasing charge is observed (Ne^{n+}—Xe pairs). On the contrary, for the pairs Xe^{n+}—Ne, the predominant role in the production of free electrons is due to the stripping processes, and the cross section σ_- decreases with increasing charge. When there is no sharp difference in the binding energy of the electrons in the shells of colliding atomic particles, there may be no regular variation of the cross section σ_- with the charge n.[3]

In the future, it would be of interest to carry out similar investigations with ions having larger charges and in the range of lower velocities, which might enable us to separate the field ionization in pure form (without the superposition of kinetic ionization). It would also be of basic interest to measure the energy of electrons produced in the ionization of the gas by ions with different charge.

In conclusion, the authors express their deep gratitude to Prof. V. M. Dukel'skii for valuable advice in discussing the results of the experiment.

[1] N. V. Fedorenko, Usp. Fiz. Nauk **58**, 481 (1959).

[2] O. B. Firsov, JETP **36**, 1517 (1959), Soviet Phys. JETP **9**, 1076 (1959).

[3] Fedorenko, Flaks, Filippenko, JETP **38**, 719 (1960), Soviet Phys. JETP **11**, 519 (1960).

[4] I. P. Flaks, ZhTF **31**, 367 (1961), Soviet Phys.-Tech. Phys. **6**, 263 (1961).

[5] Flaks, Ogurtsov, and Fedorenko, JETP **41**, 1094 (1961), Soviet Phys. JETP.

[6] I. P. Flaks and L. G. Filippenko, ZhTF **29**, 1100 (1959), Soviet Phys. Tech. Phys. **4**, 1005 (1960).

[7] Fedorenko, Filippenko, and Flaks, ZhTF **30**, 49 (1960), Soviet Phys. Tech. Phys. **5**, 45 (1960).

[8] I. P. Flaks, ZhTF **25**, 2463 (1955).

Translated by H. Kasha
246