IONIZATION OF GASES BY He^+ IONS WITH ENERGY 0.2–1.8 MeV

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Submitted November 28, 1967

Zh. Eksp. Teor. Fiz. 54, 1310–1317 (May, 1968)

The effective cross sections for the production of slow positive ions and free electrons by ionization of the gases H_2, N_2, He, Ne, and Kr with He^+ ions were measured in the energy interval 0.2–1.8. The obtained data are compared with the available experimental data on the ionization of these gases by He^+ ions in the energy region up to 1.0 MeV. Wherever possible, a comparison was also made with the theoretically calculated cross sections. The so-called effective charge was estimated by determining the cross sections for pure ionization and comparing them with the cross sections for ionization by protons.

1. INTRODUCTION

THIS is a continuation of earlier investigations[1] devoted to the study of the processes of ionization of inert and diatomic gases by ions at high energies. We measured the total cross sections σ^+ and σ^- for the production of slow positive ions and electrons, respectively, by ionization of atoms and molecules of the gases H_2, N_2, He, Ae, Ar, and Kr by singly charged helium ions. The ionization of certain gases by helium ions has been the subject of a number of investigations[2-6]. Only Langly et al.[5] made measurements in the energy interval 0.13–1 MeV. All the remaining investigations were performed at lower ion energies.

In the present investigation, the cross sections for the ionization of the gases by helium ions were measured in a wide range of energies, starting from 200 to 1800 keV. A comparison of the experimental results obtained by different investigators for the cross sections for the ionization of gases by protons, and also electrons in the high-velocity region[1] shows that the difference between these data go beyond the systematic measurement errors indicated by these authors. At the same time, in most cases the measurements were performed by the same method, that of gathering slow particles[7].

It should be noted, however, that there were some differences in these investigations, for example a difference in the methods of suppressing secondary electron emission from the measuring plates of the capacitors, a difference in the shapes of the measuring electrode, etc. To ascertain the resultant possible differences in the systematic errors, we undertook in the present investigation certain special methodological studies, the results of which are described briefly in the next section.

2. APPARATUS AND MEASUREMENT PROCEDURE

The singly-charged helium ions were obtained and accelerated with a compact electrostatic accelerator described earlier in[8]. The accelerated-ion energies were measured with accuracy ±1–2%. The beam, leaving the accelerator with initial divergence 2×10^{-4} rad, passed through a collimating slit and a magnetic mass monochromator. From the monochromator the beam passed through a slit which served as the pickup of the stabilization system.

The present investigation was performed with apparatus similar in principle to that used earlier[1]. However, certain differences between this and the earlier setup are of interest from the point of view of the methodology. Therefore Fig. 1 shows without a detailed description a schematic diagram of the apparatus. We note nevertheless that the pressure of the residual gas in the collision chamber, with the bypass valve closed, did not exceed 2×10^{-6} mm Hg.

One of the important problems arising in the measurement of slow-particle currents is the elimination of the distorting influence of the secondary electrons emitted from the plates of the measuring capacitor. To suppress these secondary electrons, different investigators used either an electrostatic or a magnetic field. We used, for comparison, both methods of suppressing the secondary electron emission—the method using a screening grid with large transparency, located ahead of the measuring plate, and the method using a magnetic field produced by Helmholtz coils and directed parallel to the beam of primary ions. Comparison of the results obtained with both methods used independently shows that the cross section σ^+ for the production of slow ions is the same, within the limits of experimental error, for both methods of measuring the currents of the slow positive ions. On the other hand, when the cross sections σ^- for the production of free electrons are measured, a difference is observed between these two methods of suppressing the secondary electrons in light gases (hydrogen and helium). In heavier (Ne, Ar, Kr, and N_2) as shown by control measurements, the differences in the values of the cross sections σ^- for both methods do not go beyond the limits of the measurement errors.

When a magnetic field is used to suppress the secondary electrons, the value of the secondary electron-emission current is determined from the difference of the currents in the measuring plate in the presence and in the absence of a magnetic field. The correction obtained in this manner makes it possible to determine the true value of σ^-. Since these corrections are the results of subtraction of two relatively large quantities, they are subject to large errors. These errors become manifest in the case of hydrogen and helium, for which

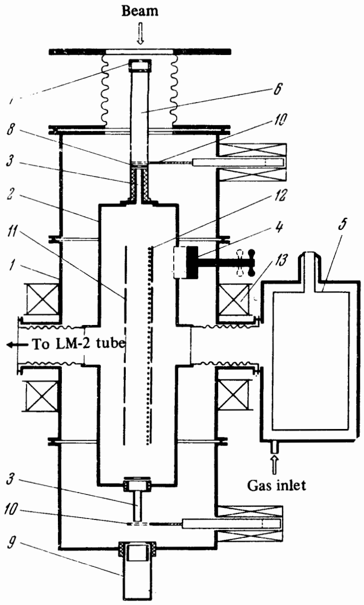

FIG. 1. Schematic diagram of setup: 1—vacuum chamber, 2—collision chamber, 3—capillaries, 4—bypass valve, 5—cooled trap, 6—centering tube, 7—collimating diaphragm, 8—limiting diaphragm, 9—Faraday cylinder, 10—shutters, 11—system of measuring electrodes, 12—guarding screen, 13—Helmholtz coils.

the relative magnitude of the secondary-emission current reaches 15–25%. For heavier gases, the relative magnitude of this kind is of the order of 3–7% and the error in its determination cannot strongly affect the results. Our comparison of the indicated methods of suppressing the secondary electrons has shown that the screening grid provides greater accuracy of determination of the cross sections σ^+ and σ^- than the longitudinal magnetic field. All the results presented below were obtained using a screening grid located ahead of the measuring electrodes.

Inasmuch as the collision chamber employed by us was much longer than the section from which the slow particles were gathered, we estimated the influence of the charge exchange of the He^+ ions on the path from the entrance to the collision chamber to the measuring electrodes. This estimate shows that errors due to charge-exchange processes cannot exceed, in the worst case, 1%. The total error due to the determination of the concentration of the molecules in the collision chamber and to measurement of the currents and the energies did not exceed 10%.

3. MEASUREMENT RESULTS AND DISCUSSION

The results of the present measurements of the total cross sections for the production of slow positive ions, σ^+, and free electrons, σ^-, by ionization of H_2, N_2, He, Ne, Ar and Kr by fast He^+ ions are shown in Figs. 2–5. For comparison, the same figures show the experimental data obtained by other investigators in different regions of the helium-ion energy.

Recently published results of the measurements of the cross sections for gas ionization by He^+ ions, performed by De Heer et al.[6] at energies 10–140 keV, contain a comparison with data obtained by others in approximately the same energy interval, as well as a comparison with data extending to higher energies.

As follows from this comparison, the values of σ^+ and σ^- obtained by De Heer et al.[6] agree in the overwhelming majority of cases with the corresponding measurement data of Fedorenko et al.[2] and Solov'ev et al.[3] The situation is worse when it comes to joining together the data of De Heer et al. with the data of Gilbody et al.[4] and Langly et al.[5] In most gases, the values of σ^+ and σ^- obtained by these authors are much higher in the overlapping energy region than those of De Heer et al.[6] A comparison of our present data with those obtained by Langly et al.[5] shows that in the case of interaction of He^+ with H_2, He, and Ne, the agreement for σ^+ and σ^- is good, and does not go beyond the limits of the measurement errors in the energy interval 400–1,000 keV. In the energy region 200–400 keV, we observe in these cases for our data a more rapid decrease of $\sigma = f(E)$ towards lower energies than for the data of Langly et al.[5]

In the case of interaction between He^+ and N_2 or Ar, our data are systematically lower than those of Langly et al. in the entire overlapping energy interval (200–1000 keV), by an average of 15–20% (without taking into account the corrections for the pressure in[5]). The data of Gilbody et al.[4] at energies 200–300 keV are as a rule higher than our data. On the other hand, at energies above 300 keV, for most investigated gases,

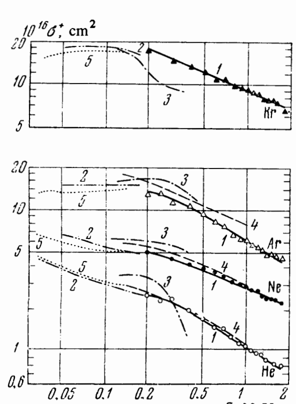

FIG. 2

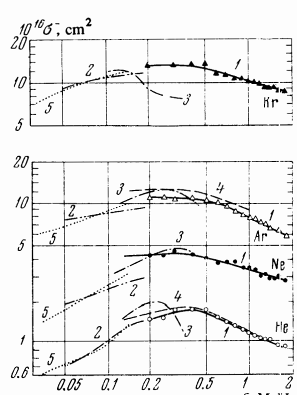

FIG. 3

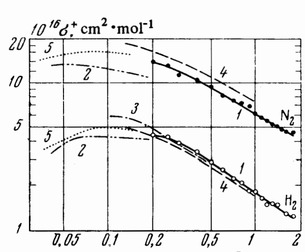

FIG. 4

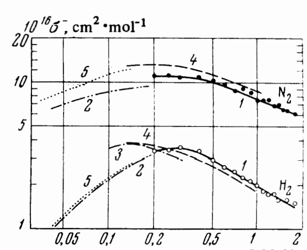

FIG. 5

FIG. 2. Effective cross sections for the production of slow positive ions in He, Ne, Ar, and Kr. Curves 1—data of present work, 2—data of [2], 3—data of [4], 4—data of [5], 5—data of [6].

FIG. 3. Effective cross sections for the production of electrons in He, Ne, Ar, and Kr. Curves 1—present data, 2—data of [2], 3—data of [4], 4—data of [5], 5—data of [6].

FIG. 4. Effective cross section for the production of slow positive ions in H_2 and N_2. Curves 1—present data, 2—data of [3], 3—data of [4], 4—data of [5], 5—data of [6].

FIG. 5. Effective cross section for the production of electrons in H_2 and N_2. Curves 1—present data, 2—data of [3], 3—data of [4], 4—data of [5], 5—data of [6].

the plots of[4] cross our $\sigma = f(E)$ curves and go lower. The data of Gilbody et al. for Kr are much lower than ours in the overlapping energy interval. We call attention to the fact that continuation of our data for σ^+ and σ^- into the low-energy region leads to a fair continuity with the data of[2,3,6] for practically all the investigated gases. It is also of interest to compare the data of the present investigation on the total cross sections σ^+ and σ^- for the production of ions and electrons with the data on the cross sections for the capture and loss of electrons by He^+ ions, σ_{10} and σ_{12}, obtained by analysis of the charge composition of the incoming particles after single collision in gases.

Inasmuch as the positive and negative charges produced upon ionization of the target particles are in balance, the difference between the measured positive and negative currents is due only to capture and loss of electrons by the He^+ ions. Starting from this fact, we can write

$$\sigma^- - \sigma^+ \approx \sigma_{12} - \sigma_{10}. \tag{1}$$

With this, the capture of two electrons by He^+ ions can be regarded as a negligibly slow process in the investigated energy interval[9]. Values of the cross sections σ_{12} and σ_{10} for helium ions, which can be used for a comparison, were obtained in[10] in the energy interval 200—1500 keV. For a comparison at energies above 1500 keV, we have the data of Dmitriev et al.[11] for the electron loss cross sections σ_{12}. Inasmuch as in this energy region σ_{12} is larger than σ_{10} by several dozen times, the difference $\sigma^- - \sigma^+$ can be equated, without great error, to σ_{12}^{12}. Comparison of the differences $(\sigma^- - \sigma^+)$ and $(\sigma_{12} - \sigma_{10})$, for the target gases H_2, He, N_2, Ar, and Kr show that these differences agree with each other within the limits of the errors in the measurement of the ionization cross sections.

Obviously, this agreement of results obtained by entirely different methods can serve as a certain guarantee of the correctness of the obtained data in either case. In addition, this agreement makes it possible to estimate the cross sections of pure ionization in the case when atomic particles are bombarded by He^+ ions, as will be shown subsequently. A least-squares analysis of the results shows that for He^+ ion energies above 600 keV the ionization cross sections follow an energy dependence of the form $E^{-1} \ln E$ for all the investigated gases. Thus, the character of the energy dependence predicted by the theory for ionization of gases by electrons and protons of large velocities remains in force also in the case of ionization by He^+ ions with energies higher than approximately keV.

4. COMPARISON WITH THEORY

For the considered types of interaction, fortunately, there are no corresponding quantum-mechanical theoretical data, with the exception of the calculation of Boyd et al.[12], made in the Born approximation for the case of ionization of atomic hydrogen by He^+ ions. As is well known, the determination of the cross section for the ionization of atoms by ions, in the first Born approximation, if we disregard several simplest cases, entails great difficulty. Interest may therefore attach in many cases to a further simplification of the Born approximation, as proposed by Bethe[13]. It should be noted that for higher ion velocities, calculations in the Bethe-Born approximation agree very well with calculations made in the Born approximation. Martin et al.[14], starting from the foregoing considerations, compared their experimental data for the cross sections of simple ionization of certain gases by helium ions with the corresponding formula obtained in the Bethe-Born approximation. To determine the empirical parameters characterizing each type of atom or molecule of the target, this formula is compared with the experimental data on the cross sections for the ionization of the corresponding gases by protons, obtained by Hooper et al.[15] It turned out that the ratio of the cross sections of simple ionization by He^+ ions to the cross sections for the ionization by protons, at equal velocities, remains practically constant in the energy interval 0.6—1 MeV, and depends little on the nature of the target gas. As follows from the Bethe formula, this ratio can be used to characterize the square of the effective charge of the incoming ion. The effective charge of He^+ estimated in this manner turned out to be approximately 1.2q (q—electron charge). Since the cited authors had at their disposal data on ionization by protons of energy up to 1 MeV, they extrapolated the Bethe formula for the case of helium up to 4 MeV. On the other hand, comparison with the experimental data for He^+, obtained by Langly et al.[5], was possible only up to 1 MeV. The effective charge Z_{eff} remained constant here in the energy interval from 0.6 MeV up to the maximum measured 1 MeV.

The present data allow us to extend the region of energies in which the indicated comparisons with the Bethe formula are possible. It should be noted that comparison with theory is possible for the case of pure ionization, when the incoming ion ionizes only the target atom without changing its charge state.

In the case of target-particle bombardment by He^+ ions, the cross section for pure ionization can be represented by the expression[16]:

$$\sum_n n_{10}\sigma_{1n} = \sigma^+ - \Big(\sum_n n_{10}\sigma_{0n} + \sum_n n_{10}\sigma_{2n} \Big), \tag{2}$$

where n is the ionization multiplicity and $_{10}\sigma_{mn}$ are the effective cross sections of the corresponding processes. It follows from this expression that the corrections to the cross section σ^+ contain the cross sections for the processes of electron capture and stripping by He^+ ions with simultaneous ionization of the target particles.

At the present time, as already indicated, the only data we have in the investigated energy interval are on the cross section σ_{10} and σ_{12} for the capture and loss of an electron by He^+ ions in the gases H_2, N_2, He, Ar, and Kr[10,11]. These cross sections are determined by the expressions

$$\sigma_{10} = \sum_n {}_{10}\sigma_{0n} \text{ and } \sigma_{12} = \sum_n {}_{10}\sigma_{2n}.$$

As seen from a comparison of the expressions for σ_{10} and σ_{12} with the sum of the cross sections determining the correction to formula (2), knowledge of the cross section σ_{10} and σ_{12} still does not suffice for an exact

Cross sections $\sigma_i \times 10^{16}$ cm^2 for the ionization of gases by He^+ ions, and the ratios $\gamma^2 = \sigma_i(He^4)/\sigma_i(H^+)$.

E, MeV	He		Ne		Ar		Kr		H_2		N_2	
	σ_i	γ^2	σ_i	γ^2	σ_i	γ^2	σ_i	γ^2	σ_i	γ^2	σ_i	γ^2
0,8	1	1.38	2,42	1,52	5,15	1.3	8,4	1,43	1,89	1,34	5,85	1,19
1	0.84	1,45	2,38	1,49	4.7	1,3	7,55	1,44	1,64	1,43	4,85	1,24
1,2	0.74	1,54	2,35	1,45	4,35	1,335	6,9	1,44	1,36	1,5	4,3	1,28
1,4	0,7	1.6	1.8	1.46	3,7	1,342	6,2	1,47	1,38	1,53	4	1,33
1,6	0,69	1,65	1,6	1,48	3,85	1,357	6,2	1,55	1,2	1,58	3,7	1,35
1,8	0,7	1,7	1.6	1,38	3,8	1,35	5,65	1,55	1,17	1,63	3,7	1,39

determination of the correction to the cross section σ^+. It is necessary also to know the partial cross sections due to the processes of multielectron ionization of atoms in stripping and capture, and also the cross sections for He^+-ion stripping not accompanied by ionization of the target atoms. However, the lack of these data still does not exclude the possibility of a sufficiently close estimate of the cross sections σ_i for pure ionization.

Indeed, from the data of Fedorenko and Afrosimov on the formation of slow multiply charged ions[17], and also from the measured charge composition of the slow argon ions obtained in[18,19] by ionization by protons, we see that the greatest contribution to the ionization is made by single-electron ionization. This allows us to advance the hypothesis that the loss and capture of an electron by He^+ ions are also accompanied in the main by single-electron ionization processes. The error introduced thereby into the determination of the ionization cross section σ_i actually turns out to be small, if we recognize that at energies above 0.6 MeV the sum of the cross sections $\sigma_{10} + \sigma_{12}$ is at least several times smaller than the cross section σ^+. We can therefore estimate the ionization cross section σ_i, without excessive error, by starting from formula (2) and using the expression

$$\sigma_i \approx \sigma^+ - (\sigma_{10} + \sigma_{12}). \quad (3)$$

Since there are no data on the cross sections σ_{10} and σ_{12} for neon, we start from the assumption that for neon, as well as for the other investigated gases, the relation $\sigma_{10} \ll \sigma_{12}$ holds in the high-energy region[10]. In this case the cross section of pure ionization of neon atoms can be determined by the expression

$$\sigma_i \approx \sigma^+ - \sigma_{12} = 2\sigma^+ - \sigma^-. \quad (4)$$

The cross sections determined from (3) and (4) for pure ionization of gases by He^+ are listed in the table. The same table shows the ratios of the cross sections for ionization by He^+ ions at equal velocities, $\gamma^2 = \sigma_i(He^+)/\sigma_i(H^+)$; as already noted, these ratios can be regarded as the ratios of the squares of the effective charges of the He^+ ions to the H^+ ions. Inasmuch as the probability for the capture of an electron by the H^+ ion at energies higher than 200 keV is very low[9], the effective charge of the He^+ ion is determined numerically by the value of γ, i.e., $Z_{eff} = \gamma q$.

As seen from the table, for all the investigated gases, with the exception of neon, a small but systematic growth of the effective charge of the He^+ ion is observed as the ion energy increases from 0.8 to 1.8 MeV. The absence of such a systematic increase of Z_{eff} in neon is due most likely to the somewhat larger errors, compared with other gases, in the determination of the cross section σ_i (see formula (4)). The increase of the effective charge of the He^+ ion with increasing velocity is due apparently to the somewhat larger contribution of the multi-electron ionization in the case of short-range collisions of the particles, than in the case of the interaction of protons with molecules of these gases. On the average, in the indicated energy interval, the effective charge of He^+ ion equals approximately 1.2q. The effective charge of the He^4 ions obtained in[14], where it was determined in the energy interval 0.6–1 MeV, is of the same magnitude. We must nevertheless point to the need for taking into account the change of Z_{eff} with energy when extrapolating the obtained data into the region of higher energy. Comparison of the obtained results for the cross sections of pure ionization of hydrogen by He^+ ions with the theoretical calculation of Boyd et al.[12] gives good agreement when account is taken not only of the equivalence of the molecule to two atoms, but also of the correspondingly higher ionization potential of the hydrogen molecule compared with the atom.

We have also compared the obtained data with the classical theory of Gryzinski[20]. It turned out that the discrepancy between the experimental and theoretical data in most cases does not exceed 30–35% and in some cases not more than 50%. As a rule, the theoretical data lie for all the investigated gases below the experimental ones. In view of the lack of more rigorously based calculations, such an agreement must be regarded as satisfactory.

In conclusion, we consider it our pleasant duty to thank V. M. Tubaev for taking part in the work and also the accelerator operators K. M. Khurgin and V. G. Rubashkov for help with the measurements.

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Translated by J. G. Adashko
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