ELECTRON LOSS AND CAPTURE BY 200 – 1500 kev HELIUM IONS IN VARIOUS GASES

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The cross sections for electron loss σ_{12} and electron capture σ_{10} by singly charged helium ions in single collisions in gases have been measured. The relative amounts of He^0, He^+, and He^{2+} ions in beams of equilibrium composition traversing the gases have also been measured. The cross section for electron capture by doubly charged helium ions σ_{21} and the cross section for electron loss by helium atoms σ_{01} are estimated from the ratios of these components. The gas targets consisted of helium, nitrogen, argon, and krypton. The measurements were performed for ion energies between 200 and 1500 kev.

1. INTRODUCTION

A number of studies have been devoted to charge-exchange processes involving helium atoms and ions in collisions with gas molecules. A summary of the basic experimental results is given in the review article of Allison.[1] This review article gives the results of experimental investigations on the loss and capture of electrons by helium ions and atoms in collisions with molecules of H_2, N_2, O_2, He, Ne, Ar, Kr, and Xe in the 0.2 – 200 kev interval and with molecules of H_2, He, and air up to an energy of 450 kev. The article also gives separate data for the charge exchange of α particles in air obtained at high energies by Rutherford.

Extension of the investigations in the direction of higher energies is of interest from the viewpoint of further development of the theory of atomic collisions.

In the present article, we describe the results of measurements of the effective cross section for the loss and capture of an electron by helium ions and also the results of measurements of collisions between helium particle beams of equilibrium composition and H_2 and N_2 molecules and He, Ar, and Kr atoms in the 200 – 1500 kev interval.

2. APPARATUS AND EXPERIMENTAL METHOD

In this experiment, we used the arrangement employed by us earlier[2] for the measurement of the cross sections for the dissociation of molecular ions of hydrogen. The method of measurement was basically the same.

The primary beam of single charged helium ions produced by an electrostatic accelerator was separated by a mass monochromator and passed through the collision chamber. The He^+ and He^{2+} components which were formed were separated by an electrostatic analyzer and entered Faraday cups. The currents were measured by ÉMU-3 vacuum-tube electrometers. The intensity of the beam of neutral He^0 particles was recorded with a detector which measured the secondary electron emission current arising from the bombardment of copper foil by the fast helium atoms.

The basic design of this detector is the same as that described by Stier, Barnett, and Evans.[3] The detector was calibrated with an auxiliary detector consisting of a thin copper foil and a copper-constantan thermocouple mounted at the center of the foil (on the rear side). This foil too was bombarded by the He^0 beam. Since the difference in temperature at the ends of the thermocouple did not exceed 0.1° C during the measurements, the thermal emf was proportional to the intensity of the beam of particles bombarding the foil. The size of the secondary electron emission current was measured with an ÉMU-3 vacuum-tube electrometer.

The beam component currents were measured simultaneously, which made it possible to decrease the error caused by oscillations in the primary ion beam intensity. The measurements of the cross sections for electron capture σ_{10} and electron loss σ_{12} by singly charged helium ions were made by the mass-spectrographic method.

The cross sections were calculated from the formulas

$$\sigma_{10}=\left\{d\left[\frac{N^0}{N^0+N^++N^{2+}}-\left(\frac{N^0}{N^+}\right)_b\right]/d\,(nL)\right\}_{nL\to 0}, \qquad (1)$$

$$\sigma_{12}=\left\{d\left[\frac{N^{2+}}{N^0+N^++N^{2+}}-\left(\frac{N^{2+}}{N^+}\right)_b\right]/d\,(nL)\right\}_{nL\to 0}, \qquad (2)$$

where N^0, N^+, and N^{2+} are the amounts of neutral atoms, singly charged ions, and doubly charged ions of helium in the beam traversing the collision chamber; n is the concentration of the gas atoms in the chamber; L is the effective length of the chamber; the subscript b indicates background. For each case, we plotted the ratio of the number of secondary particles to the number of primary particles as a function of nL. We determined the cross sections σ_{10} and σ_{12} from the linear part of these curves.

In all cases, we checked the influence of the difference in the scattering of secondary and primary beam particles by means of diaphragms at the exit channel of the collision chamber. Under the geometrical conditions of our experiment (beam diameter 2 mm and channel diameter 6.5 mm), the scattering had no influence on the size of the measured cross sections, within the limits of experimental error. The cross sections σ_{10} and σ_{12} were calculated as the mean of two or three independent measurements. The random errors of measurement did not exceed ± 12% for the cross sections σ_{12} and ± 18% for the cross sections σ_{10}. The primary ion beam energy was determined to an accuracy of ± 2%.

For the measurements of the equilibrium components of the beam, entrance and exit channels, each of diameter 2.5 mm and length 80 mm, were mounted in the collision chamber, which had an over-all length of 400 mm. The beam entered the collision chamber through a diaphragm 1.6 mm in diameter mounted in front of the entrance channel. The large diffusion resistances of the channels made it possible to use target thicknesses of about $(3-5)\times 10^{17}$ molecules per cm^2. At each value of the primary ion beam energy, a check was made to establish whether the charge distribution of the beam had attained a stationary value. To do this, we investigated the dependence of the size of the He^0, He^+, and He^{2+} components of the beam on the gas pressure in the collision chamber close to the equilibrium composition.

In the ion energy region studied by us, we could neglect the influence of the process of formation of negative helium ions [4] and assume that the above-mentioned three components were present in the 200 to 500 — 700 kev energy interval and that effectively only two components, He^+ and He^{2+}, were present in the 500 — 700 to 1500 kev interval, since at 500 — 700 kev the He^0 is already present in the beam in quantities no greater than 6% of the total number of particles, and its content drops very quickly with an increase in energy. If we also neglect the influence of the two-electron loss and capture processes, then we can estimate the electron capture cross section σ_{21} and electron loss cross section σ_{01} from the following relations: [1]

$$\sigma_{21}=\sigma_{12}F_{1\infty}/F_{2\infty}, \qquad \sigma_{01}=\sigma_{10}F_{1\infty}/F_{0\infty}, \qquad (3)$$

where σ_{12} and σ_{10} are the cross sections for electron loss and capture by singly charged helium ions; $F_{0\infty}$, $F_{1\infty}$, and $F_{2\infty}$ are the relative contents of the He^0, He^+, and He^{2+} components in a beam of equilibrium composition.

In order to check whether differences in the scattering of the beam components affect their size, we changed the collision chamber channels. It turned out that, when the 6.5-mm diam channels were replaced by 2.5-mm diam channels, the ratios of the beam components remained unchanged within the limits of experimental error. The random errors in the measurement of the equilibrium composition were about ± 5% for the $F_{1\infty}$ and $F_{2\infty}$ components and ± 11% for the $F_{0\infty}$ component.

3. RESULTS OF MEASUREMENTS AND DISCUSSION

In this experiment, we measured the cross sections for electron capture and loss by singly charged helium ions in collisions with H_2, N_2 molecules and He, Ar, and Kr atoms. We used the following gases as targets: hydrogen admitted through a palladium filter, helium with impurities not exceeding 0.1%, nitrogen with 0.03% impurities, and argon and krypton with 0.1% impurities.

The results of the measurements of equilibrium compositions in the helium beam are shown in the table. The equilibrium components of the helium beam in some gases have been measured and calculated by other authors in the 8- to 450-kev interval. The data of the present experiment are in satisfactory agreement with the data calculated by Allison [1] for hydrogen, helium, and air and with the measurements of Snitzer [5] in argon. At 200 kev, our data fit together with the data of Barnett and Stier [6] for hydrogen, helium, nitrogen, and argon.

Owing to the small cross sections for electron capture by He^+ and He^{2+} ions, the neutral component of the beam $F_{0\infty}$ did not attain equilibrium for the target thicknesses used at energies above 800 — 1000 kev (above 600 kev in the case of hydrogen and above 900 kev for the $F_{1\infty}$ component).

Energy, kev	$F_{0\infty}$	$F_{1\infty}$	$F_{2\infty}$	$F_{0\infty}$	$F_{1\infty}$	$F_{2\infty}$	$F_{0\infty}$	$F_{1\infty}$	$F_{2\infty}$
	Hydrogen			**Helium**			**Nitrogen**		
200	0.43	0.556	0.014	0.495	0.485	0.02	0.335	0.628	0.037
300	0.24	0.696	0.064	0.307	0.637	0.056	0.23	0.66	0.11
400	0.128	0.712	0.16	0.204	0.666	0.13	0.13	0.685	0.185
500	0.07	0.67	0.26	0.125	0.67	0.205	0.086	0.63	0.284
600	0.045	0.57	0.385	0.08	0.63	0.29	0.05	0.55	0.4
700	(0.02)	0.43	0.55	0.06	0.58	0.36	0.03	0.47	0.5
800	(0.010)	0.35	0.64	0.045	0.525	0.43	0.02	0.41	0.57
900	(0.006)	0.264	0.73	(0.03)	0.47	0.5	0.012	0.35	0.64
1000	(0.004)	(0.22)	0.776	(0.02)	0.42	0.56	0.008	0.3	0.700
1100	(0.0025)	(0.17)	0.828	(0.013)	0.37	0.617	(0.006)	0.224	0.77
1200	(0.0015)	(0.125)	0.874	(0.01)	0.31	0.68	(0.0037)	0.19	0.806
1300	(0.0012)	(0.105)	0.894	(0.007)	0.26	0.733	(0.003)	0.165	0.832
1400	(0.001)	(0.09)	0.909	(0.005)	0.215	0.78	(0.002)	0.145	0.853
1500	—	(0.07)	0.93	(0.0035)	0.187	0.81	—	0.123	0.877
	Argon			**Krypton**					
200	0.36	0.615	0.025	0.5	0.49	0.01			
300	0.19	0.72	0.09	0.258	0.697	0.045			
400	0.102	0.7	0.198	0.170	0.725	0.105			
500	0.056	0.604	0.34	0.09	0.68	0.23			
600	0.03	0.48	0.49	0.05	0.55	0.4			
700	0.017	0.383	0.6	0.025	0.46	0.515			
800	0.009	0.281	0.71	0.015	0.35	0.635			
900	0.006	0.224	0.77	0.01	0.266	0.724			
1000	0.003	0.178	0.819	(0.006)	0.214	0.78			
1100	(0.0023)	0.146	0.852	(0.0045)	0.18	0.815			
1200	(0.002)	0.119	0.879	(0.003)	0.162	0.835			
1300	(0.0015)	0.099	0.9	(0.002)	0.15	0.848			
1400	(0.0012)	0.084	0.915	(0.0016)	0.135	0.863			
1500	(0.001)	0.073	0.926	(0.0014)	0.122	0.877			

The corresponding values of $F_{0\infty}$ and $F_{1\infty}$ are therefore shown in parentheses in the table.

The results of the measurements of the cross sections for electron loss σ_{12} and electron capture σ_{10} as a function of the He^{+} ion energy are shown in Figs. 1 — 5. Also shown in these figures are the values of the cross sections for electron capture and loss σ_{21} and σ_{01} calculated from formula (3). Wherever possible, we give for comparison the data of Allison et al,[1] who measured the corresponding cross sections in the 100 — 450-kev interval in hydrogen, helium, and air. Our values are in satisfactory agreement with their data.

As seen from the figures, the cross sections for electron loss σ_{12} and σ_{01} for all the gases studied by us increase with energy, attain a broad maximum, and then slowly decrease with a further increase in the energy of the He^{+} ions. The cross sections for electron capture σ_{10} and σ_{21} rapidly decrease monotonically with an increase in energy over the entire investigated interval. The values of the cross sections depend on the kind of target gas and increase with the atomic number of the target substance.

Also shown in Fig. 1 are the values of the cross sections for electron capture by doubly charged helium ions in hydrogen as calculated by Schiff.[7]

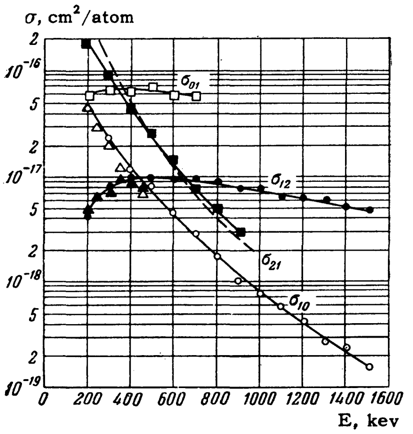

FIG. 1. Cross section for electron loss and capture by helium ions in hydrogen. △ – values of σ_{10} from reference 1, ▲ – values of σ_{12} from reference 1; dotted curve – according to data of reference 7.

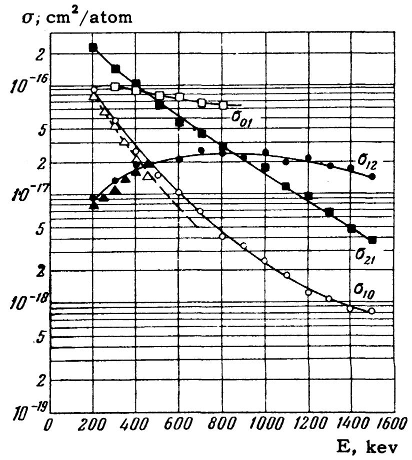

FIG. 2. Cross section for electron loss and capture by helium ions in helium △ – values of σ_{10} from reference 1, ▲ – values of σ_{12} from reference 1; dotted curve – according to data of reference 7.

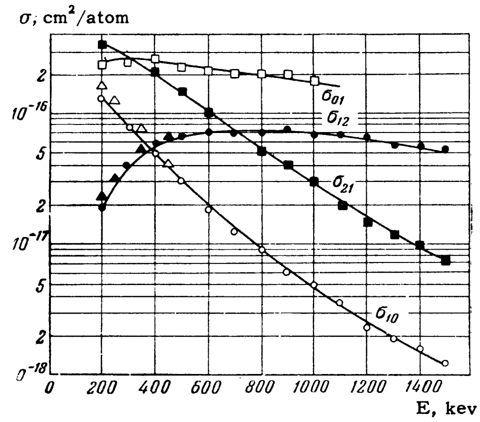

FIG. 3. Cross section for electron loss and capture by helium ions in nitrogen. △ – data from reference 1 for σ_{10} in air, ▲ – data from reference 1 for σ_{12} in air.

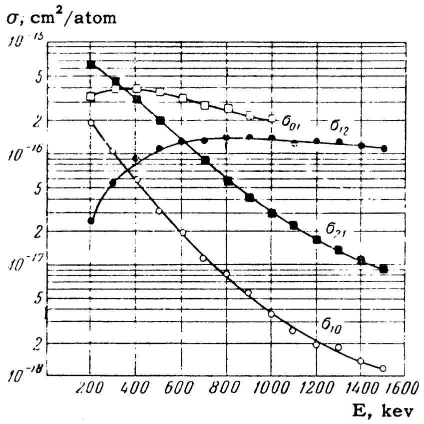

FIG. 4. Cross section for electron loss and capture by helium ions in argon.

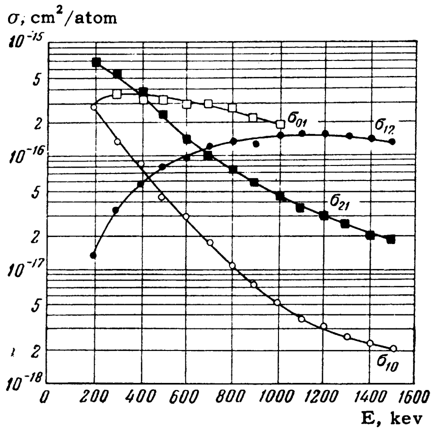

FIG. 5. Cross section for electron loss and capture by helium ions in krypton.

The theoretical and experimental curves in the 400 – 900 kev interval are in good agreement. It should be kept in mind, however, that such close agreement can be more or less accidental, if only because the experimental values of σ_{21} are given with a large error — this includes both the error of measurement of σ_{12} and the error of measurement of the equilibrium components $F_{1\infty}$ and $F_{2\infty}$.

Schiff[7] also calculated the cross sections for electron capture σ_{10} by He^+ ions in helium by means of the Born approximation. The corresponding values of σ_{10} are shown in Fig. 2 by the dotted curve. The theoretical curve systematically lies 20 – 40% below the experimental curve; the difference between them increases with energy. We note that this position of the theoretical curve with respect to the experimental curve of Fig. 2 was predicted by Schiff for ion velocities $v > v_0$ $(v_0 = q^2/\hbar)$, which occurs in this case.

Since we measured the cross sections for ion velocities up to $v \approx 4v_0$, it is of interest to compare the data obtained in the velocity interval between $v \sim 3v_0$ and $v \sim 4v_0$ with the qualitative results obtained by Bohr for σ_{12} and σ_{21} in the case of light ions at velocities $v \gg v_0$.[8]

Assuming that the nucleus and the electron of the target atom act independently on the ion, Bohr obtained the following expression for light atoms:

$$\sigma_{12} \sim (v_0/v)^2. \tag{4}$$

For substances of larger atomic number $(Z_1 \leq Z_2^{1/3})$, where the electrons and nucleus of the target atom do not act independently,

$$\sigma_{12} \sim v_0/v. \tag{5}$$

For electron capture by an α particle in the case of atoms that are not very light, Bohr obtained the expression

$$\sigma_{21} \sim (v_0/v)^6. \tag{6}$$

The experimental results do not strictly follow these functions of the ion velocity, but for H_2 and He the decrease in the cross sections for electron loss σ_{12} takes place more rapidly than for N_2, Ar, and Kr, which is in qualitative agreement with Bohr's conclusions.

The dependence of σ_{21} on the ion velocity obtained in this experiment for N_2, Ar, and Kr differs from expression (6) in the value of the exponent. The corresponding expressions can be written as follows: for nitrogen, $\sigma_{21} \sim (v_0/v)^{6.9}$; for argon, $\sigma_{21} \sim (v_0/v)^{6.7}$; and for krypton, $\sigma_{21} \sim (v_0/v)^{4.7}$. We note that Barnett and Reynolds[9] obtained similar results for hydrogen ion energies up to 1000 kev. For nitrogen, the exponent turned out to be ~ 6.5 and for argon 3.7.

In conclusion, the authors consider it their duty to express their gratitude to Academician A. K. Val'ter for his interest in and attention to this work.

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