DISTRIBUTION OF CHARGES IN ION BEAMS AFTER TRAVERSAL OF GASEOUS TARGETS

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We have measured the distributions of charges in nonequilibrium beams of N, Ne, Ar, and Kr ions in passage through gaseous targets of hydrogen, helium, nitrogen, neon, argon, and krypton. We have established that the relative content of equilibrium fractions in the beam does not depend on the ion scattering angle θ, and that the value of the nonequilibrium average charge for angles $\theta \neq 0$ drops with increasing pressure in the collision chamber. For all of the ions studied a noticeable difference has been established in the equilibrium distribution of charges in the different gases. We have obtained empirical formulas for the ratio F_{i+1}/F_i and the mean charge $\bar{i}$ as a function of ion velocity.

1. INTRODUCTION

A number of studies have recently been made of the charge state in beams of fast atomic particles passing through gaseous targets. Systematic measurements of the values of the charge fractions $F_{0\infty}$, $F_{1\infty}$, $F_{2\infty}$ in beams of equilibrium composition have been made by Stier, Barnett, and Evans [1] in the energy range 20—200 keV for ions of hydrogen, helium, nitrogen, neon, and argon interacting with gas molecules. In the high-energy region, beginning with ion velocities of $(2.6-3) \times 10^8$ cm/sec, the distribution of charges in equilibrium beams has been studied for a large group of ions by Nikolaev et al. [2,3] For hydrogen ions Stier and Barnett [4] have investigated the equilibrium fractions at energies up to 1000 keV.

In the intermediate-energy region Allison et al. [5,6] have studied the equilibrium distributions of charges in beams of helium and lithium ions passing through gases. There are no corresponding experimental data for particles with nuclear charge $Z > 3$. Therefore in the present work we have carried out measurements of the distribution of the charge state of ions of nitrogen, neon, argon, and krypton in equilibrium and nonequilibrium beams passing through hydrogen, helium, nitrogen, neon, argon, and krypton. The measurements were made in the ion-energy range 200—1300 keV.

2. APPARATUS AND MEASUREMENT TECHNIQUE

The measurements described below were made with equipment previously used for studying the scattering of ions in the stripping process. [7] To measure the dependence of the relative magnitudes of the charge fractions on the concentration of gas molecules in the collision chamber and on the scattering angle, we used a system of collimating slits similar to that used in our previous work. [7]

For the measurement of charge fractions in equilibrium beams, the design of the collision chamber was changed so as to decrease considerably the flow of gas from the collision chamber into the surrounding volume. This was achieved by installing capillaries 1.5 mm in diameter and 30 mm long at the input and output of the collision chamber. The effective length of the collision chamber was 190 mm. To exclude as far as possible systematic errors due to charge-exchange of ions on the walls of the capillaries, a diaphragm 0.5 mm in diameter and 0.1 mm thick was mounted at the end of the exit capillary, and a diaphragm 1 mm in diameter in front of the entrance capillary. With these dimensions of the capillaries, the pressure in the collision chamber for attainment of the equilibrium charge distribution was higher than the gas pressure in the remaining parts of the apparatus by roughly 2000—5000 times. The above dimensions of the collimating diaphragms determined the diameters of the separated ion beams at the entrance to the detectors (about 5 mm). Since the inside diameters of the detectors are 30 mm, practically complete collection of the particles of each charge by the corresponding detector is guaranteed.

To verify the simultaneous passage and complete collection of the separated beams in the corresponding detectors, we recorded the ion currents

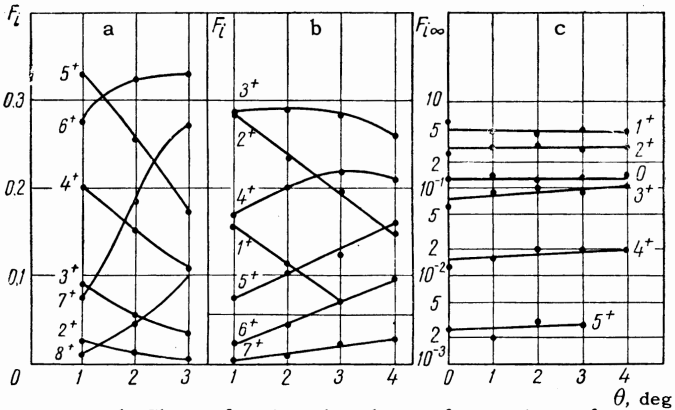

FIG. 1. Charge fractions in a beam of argon ions after passage through argon, as a function of deflection angle θ, at the following pressures: a – $p = 2 \times 10^{-4}$ mm Hg, b – $p = 3 \times 10^{-3}$ mm Hg, c – $p = 4 \times 10^{-2}$ mm Hg ($E = 500$ keV).

E, keV	$\bar{i}$			$\bar{i}_\infty$
	θ=1°	θ=2°	θ=3°	θ=0°
300	4.09	4.45	4.74	1.00
500	4.98	5.57	6.14	1.28
700	5.38	6.15	6.73	1.51
900	5.62	6.83	6.97	1.73
1100	5.99	6.89	—	1.95
1300	6.17	6.73	—	2.15

in the detectors as a function of the magnitude of the deflecting voltage on an electrostatic analyzer. These measurements yielded characteristic curves with broad plateaus corresponding to the internal diameters of the detector Faraday cups. Therefore we were able without great effort to guarantee in all cases simultaneous and complete collection in the detectors of all charged components of the beam, beginning from zero charge and going up to $Z = 8$. Thanks to the high diffusion resistance of the capillaries we were able to produce target thicknesses of the order of $(4-10) \times 10^{16}$ molecules/cm^2.

For each value of primary-ion-beam energy, we verified the establishment of a stationary distribution of the charge groups. This was done by measuring the relative magnitudes of the charge components of the beam as a function of the gas pressure in the collision chamber near the equilibrium state. The random measurement errors were of the order of $\pm(4-5)\%$ for components containing charged particles and $\pm 10\%$ for the neutral component of the beam. The ion energy was measured with an accuracy of $\pm 1.5\%$. However, for accelerator voltages of 200–300 kV, the errors in determination of the ion energies were as high as $\pm 6\%$.

3. EXPERIMENTAL RESULTS AND DISCUSSION

In our previous measurements of the angular and energy dependence of the distribution of the charge fractions in a beam of argon ions for single collisions, we obtained relatively large values of the average charge $\bar{i}$.[7] Therefore in the present work in addition to measurements of the equilibrium fractions, we have also measured the charge fractions as a function of the collision-chamber gas pressure for several values of the deflection angle θ. These measurements were made for argon ions in argon and krypton and for neon ions in argon. Since the nature of the dependence turned out to be roughly the same in all cases studied, we have presented the experimental results only for argon ions in argon.

Figure 1 shows the results of these measurements for 500 keV argon ions. The curves in Fig. 1a correspond to single collisions. The curves in Fig. 1c correspond to the pressure at which an approximate equilibrium distribution of charges in the beam was approached. The curves of Fig. 1b correspond to an intermediate pressure. From comparison of curves a, b, and c in Fig. 1, it is evident that with increasing collision-chamber pressure the relative content of highly charged components in the beam falls rapidly. But the complicated nature of the dependence of the charge fractions on the deflection angle θ for single collisions (Fig. 1a) changes to a simpler variation as the collision multiplicity increases (Fig. 1b). At pressures corresponding to establishment of the equilibrium distribution (Fig. 1c), the charge components already depend very little on the deflection angle θ. This fact is also of interest in connection with the technique of measuring equilibrium charge distributions in ion beams passing, in particular, through gaseous targets. Since the angular scattering in an equilibrium beam is approximately the same for the different charge groups, it is clear that the aperture size should have practically no effect on the measured values of equilibrium charge fractions.[1)]

In the light of this we can begin to understand, in particular, our earlier results[8] in which a change in the diameters of the collision-chamber entrance and exit apertures by 2.6 times did not effect the ratios of the charge components of the beam. As we have already indicated, our earlier

1)We have also observed identical angular distributions for different charge components in the passage of lithium ions through condensed targets.[9]

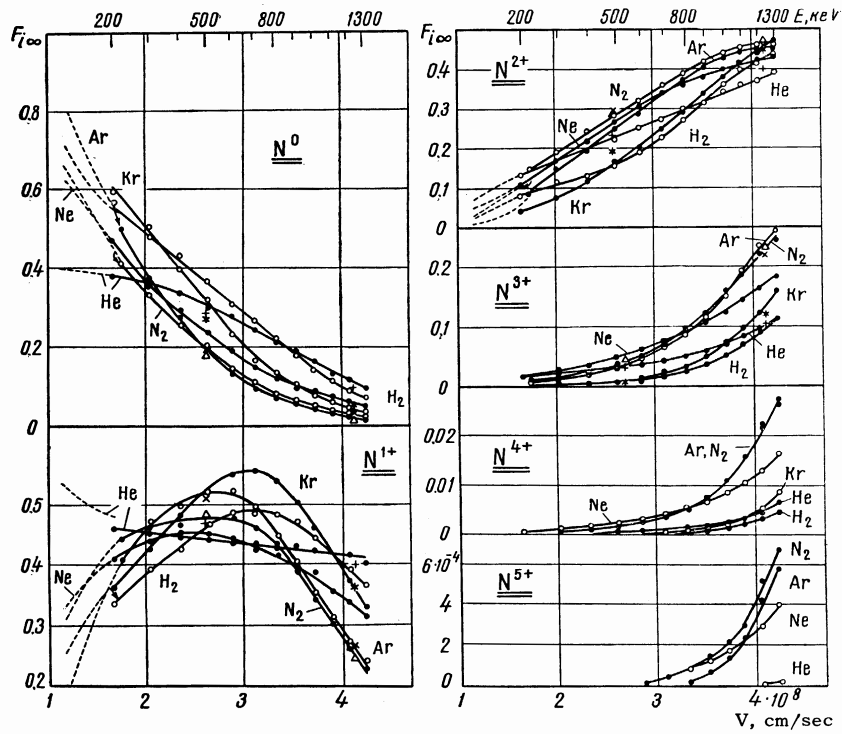

FIG. 2. Charge distribution in an equilibrium beam of nitrogen ions after passing through gaseous targets: o, ● – here and in subsequent figures, data of the present work; + – He, Δ – N_2, × – Ar, * – Kr (data of Nikolaev et al.[3]); dotted lines – data of Stier et al.[1] Here and in the subsequent figures the abscissa represents ion velocity.

values[7] of average charges for single collisions of singly charged ions with atoms turned out to be relatively large. It was therefore of interest to compare these average charges $\bar{i}$ with the average charges of argon ions in argon for the equilibrium distributions obtained in the present work. The corresponding data are listed in the table.

As can be seen from the table, for the entire energy range studied, even at small scattering angles the average charge in single collisions is much higher than the average charge in the equilibrium beams. Since the average charge of ions scattered at a given angle in single collisions of singly charged ions is determined by the scattering and electron-loss cross sections and the average charge in multiple collisions is determined both by electron-loss and electron-capture cross sections, it is evident that the decrease of the average charge $\bar{i}$ with increasing target thickness is explained by the fact that the cross sections for electron capture by multiply charged ions are correspondingly larger than the cross sections for electron loss. As can be seen, for nonequilibrium beams the degree of ionization $\bar{i}/Z$ is already rather large for relatively small ion velocities. This is a consequence of the fact that at ion velocities much less than the orbital velocities of the stripped electrons, ions with correspondingly high multiplicity of ionization are already present in the beams in noticeable quantity.

Figures 2–5 give the results of measurements of the equilibrium charge distribution in beams of nitrogen, neon, argon, and krypton ions after passing through gaseous targets of hydrogen, helium, nitrogen, neon, argon, and krypton. The same figures show for comparison data from the work of Stier et al.[1] for ion energies up to 200 keV and data for several values of ion energy from the work of Nikolaev et al.[2,3]

The distributions obtained by us of the charge components $F_{0\infty}$, $F_{1\infty}$, $F_{2\infty}$ in beams of nitrogen and argon ions satisfactorily match the data of Stier et al.[1] for all targets studied except for nitrogen ions in argon. For neon ions the data do not agree with those of Stier et al.,[1] the discrepancy increasing with the atomic number of the target gas. For nitrogen ions with velocities of 2.6 $\times 10^8$ and 4.1×10^8 cm/sec and for neon ions with a velocity of 2.65×10^8 cm/sec our data agree with those of Nikolaev et at.[2,3]

We can see from Figs. 2–5 that the charge distribution after passage of the ion beam through different targets depends strongly on the nature of the target gas. At the same time the components of beams of different ions with the same multiplicity of ionization have a similar type of velocity dependence. Our attention is drawn to the sharply expressed difference in the distribution of the components $F_{0\infty}$, $F_{1\infty}$, and $F_{2\infty}$ in ion beams which have passed through helium in comparison with other targets, at velocities below 2×10^8 cm/sec. In this velocity region the values

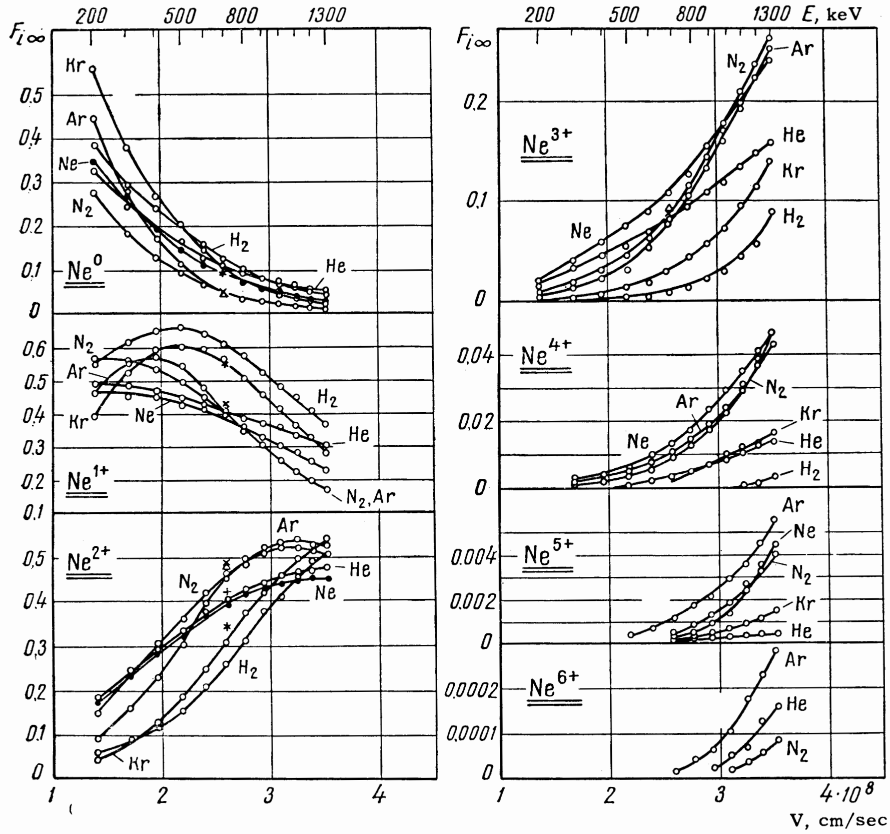

FIG. 3. Charge distribution in an equilibrium beam of neon ions after passing through different gaseous targets: + – He, Δ – N_2, × – Ar, * – Kr (data of Nikolaev et al.[3]).

of $F_{0\infty}$ in helium for beams of nitrogen, argon, and krypton ions are much lower than in other gases. This difference is particularly great for argon and krypton ions. The relative values of $F_{1\infty}$ and $F_{2\infty}$ in helium turn out to be correspondingly higher. These properties of a helium target

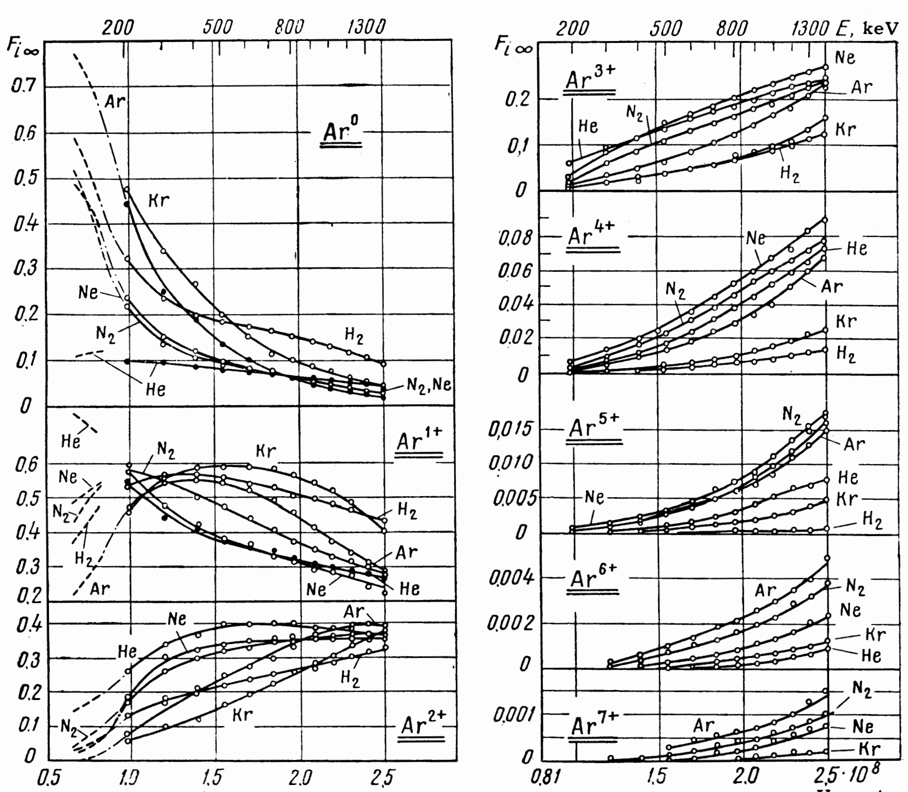

FIG. 4. Charge distribution in an equilibrium beam of argon ions after passing through gaseous targets; the dotted lines are the data of Stier et al.[1]

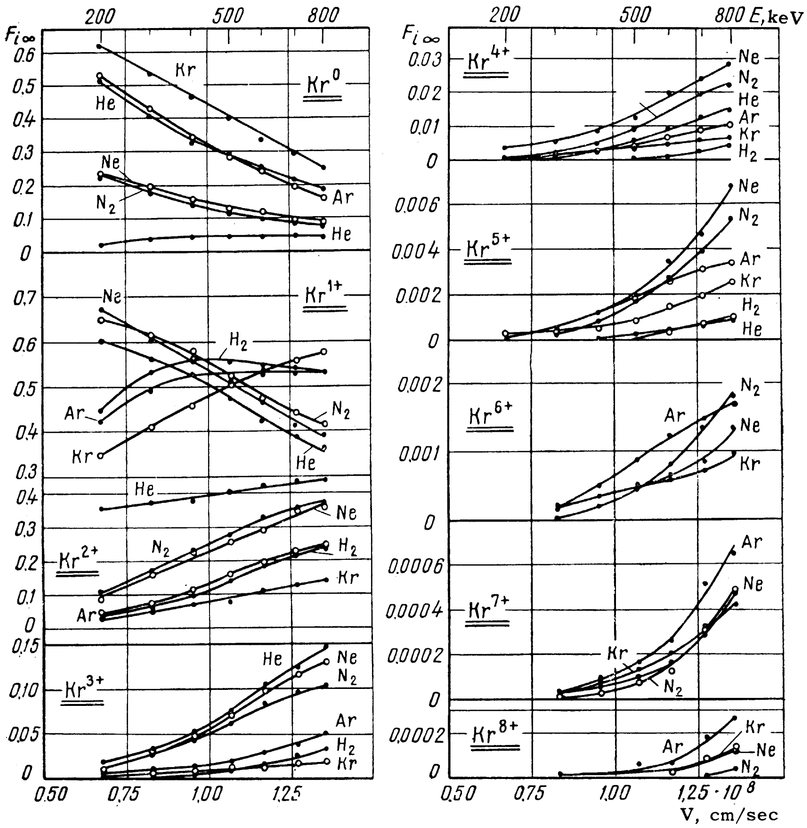

FIG. 5. Charge distribution in an equilibrium beam of krypton ions after passing through gaseous targets.

are interesting also from a practical point of view. In particular, the possibility of the practical application of a helium target for hydrogen and lithium ions in the low-energy region has been studied by Allison and co-workers.[10]

The ratios F_{i+1}/F_i obtained from the data of

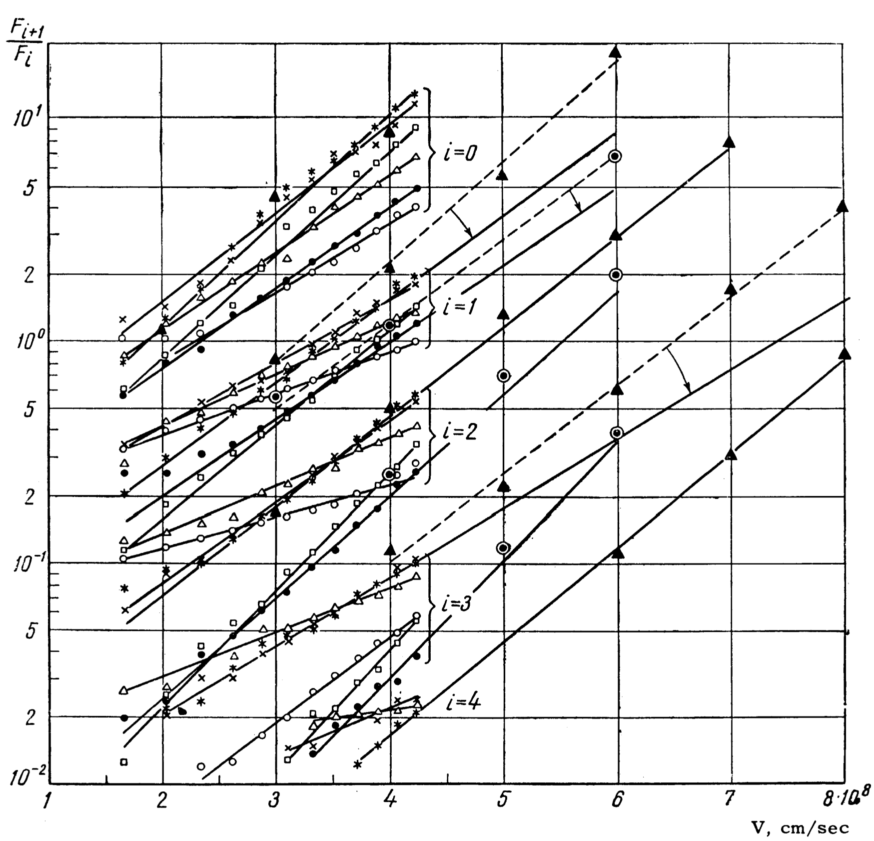

FIG. 6. Variation of the ratio F_{i+1}/F_i with velocity for nitrogen ions passing through the following targets: ● – H_2, ○ – He, × – N_2, Δ – Ne, * – Ar, □ – Kr; ▲ – Ar, ⊙ – H_2 – data of Nikolaev et al.[2]

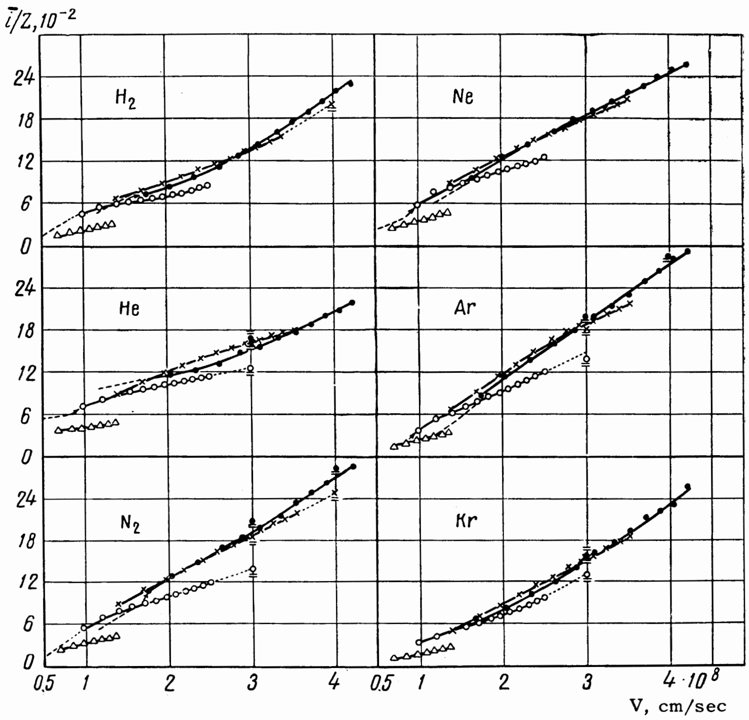

FIG. 7. Degree of ionization $\bar{i}/Z$ as a function of velocity for various ions (passing through gaseous targets): ● – N, × – Ne, ○ – Ar, Δ – Kr, the underscored points are the data of Nikolaev et al.[2]

Fig. 2 are shown in Fig. 6 as a function of nitrogen ion velocity (in different targets). In the overwhelming majority of cases the dependence of $\ln(F_{i+1}/F_i)$ on ion velocity can be represented by straight lines. The deviation of the individual points from a straight line does not exceed 5–10% Thus, the ratio F_{i+1}/F_i has a closely exponential dependence on ion velocity v, and an empirical formula can be represented by the general expression

$$F_{i+1}/F_i = A_i e^{m_i v}, \tag{1}$$

where the coefficients A_i and m_i can be determined from the experimental data. As can be seen from Fig. 6, the constants A_i and m_i are different for different targets.

An approximately exponential dependence of the ratio F_{i+1}/F_i on ion velocity is also observed for Ne, Ar, and Kr ions in the energy regions studied for all targets, at least for the most intense charge groups. Consequently formula (1) can also be used for them.

As an inspection showed, the previously obtained data[2,3] also give an approximately linear dependence of $\ln(F_{i+1}/F_i)$ on the ion velocity v in gaseous targets.[2)] However, it must be noted that the constants A_i and m_i differ in some cases from those obtained in the present work. This circumstance is illustrated in Fig. 6, where the straight-line dependence of $\ln(F_{i+1}/F_i)$ on v for argon and hydrogen targets has been extrapolated to the region of high ion energies. The dashed straight lines have been drawn from points taken from Nikolaev et al.[2] for those cases in which a difference of the coefficients A_i and m_i is observed from those obtained in the present work (the extrapolated straight lines corresponding to our coefficients are indicated by the arrows).

In the present work, just as in that of Nikolaev et al.,[2] the values of $F_{i\infty}$ obtained satisfy a nearly Gaussian distribution as a function of $i - \bar{i}$. In beams of nitrogen and neon ions a normal distribution occurs for the entire energy region studied, and for argon and krypton ions—in the energy range from 200 to 800 keV. The width of the distribution $d^2 = \Sigma(i - \bar{i})^2 F_i$ in the energy range studied increases with velocity for all ions.

For the same ion velocities the value of d in different targets differs at most by 10–20%, the smallest value of d being observed for passage of ions through hydrogen and krypton. For passage of ions through helium, nitrogen, neon, and argon, the difference in the value of d in these gases does not exceed 5–10%. The mean values of d for all targets for nitrogen and neon ions are respectively 0.65 and 0.64 keV at 200 keV and 0.8 and 0.82 at 1300 keV.

The average values of d for argon and krypton

[2)]Choice of the empirical relation for F_{i+1}/F_i in the form of an exponential dependence on velocity allows us to obtain constant values for A_i and m_i, while a power-law dependence of F_{i+1}/F_i on velocity leads to an exponent increasing with velocity.[2]

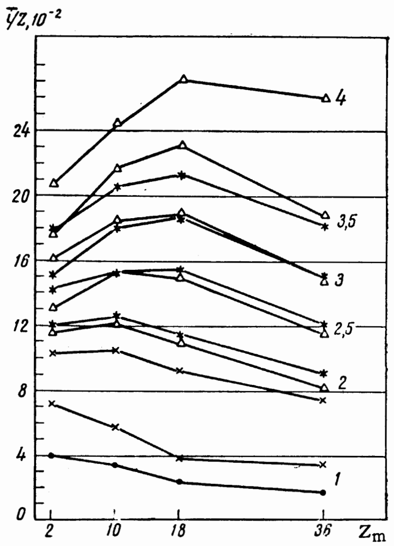

FIG. 8. Degree of ionization $\bar{i}/Z$ as a function of the target-atom charge Z_m, for the following ions: Δ – N, * – Ne, × – Ar, ● – Kr, Values of ion velocity are shown by the numbers on the curves in units of 10^8 cm/sec.

ions are respectively 0.69 and 0.59 at 200 keV and 0.9 and 0.87 at 800 keV. Figure 7 shows the average degree of ionization $\bar{i}/Z$ as a function of velocity for nitrogen, neon, argon, and krypton ions in hydrogen, helium, nitrogen, neon, argon, and krypton.

As the figure shows, in the velocity region studied the degree of ionization $\bar{i}/Z$ is approximately proportional to the ion velocity v, at least for targets of N_2, Ne, Ar, and Kr. The greatest deviation from a straight-line dependence of $\bar{i}/Z$ on velocity is observed in hydrogen; however, the deviation from a straight line in this case does not exceed ~ 15%. The slope of the curve $\bar{i}/Z = f(v)$ decreases with increase of the nuclear charge Z of the ion.

In the low-energy region the values obtained for $\bar{i}/Z$ match the corresponding data of Stier et al.[1] for nitrogen and argon ions. In the higher energy region the values of $\bar{i}/Z$ obtained in the present work for nitrogen and neon ions are in good agreement with the data of Nikolaev et al.,[2,3] and for argon ions extrapolation of our values of $\bar{i}/Z$ to the higher energy region also gives agreement with Nikolaev's data.

The difference between our values of $\bar{i}$ and those of Korsunskiĭ et al.[11] for nitrogen ions in nitrogen systematically decreases with increase of ion energy. The greatest difference occurs for an ion energy of 485 keV and amounts to ~ 20%. Apparently this difference is the result of the fact that Korsunskiĭ et al.[11] did not measure the neutral component of the beam. If appropriate corrections based on the data of the present work are made, good agreement is obtained.

Since the dependence of the average charge $\bar{i}$ on ion velocity is nearly linear, the average charge $\bar{i}$ can be represented by an empirical formula of the form[12]

$$\bar{i} = AZ^{1/2}v, \tag{2}$$

where A is a proportionality coefficient, Z is the atomic number of the ion, and v is the ion velocity. The coefficient A can be determined from the experimental data. For nitrogen ions the average value of A is 18.5×10^{-10} in nitrogen and argon and 16×10^{-10} in neon and krypton (v is in cm/sec). For neon ions the value of A is approximately 19×10^{-10} in nitrogen, neon, and argon, and 17 $\times 10^{-10}$ in krypton. For argon ions the average value of A in neon and argon is 20×10^{-10}, in nitrogen 18×10^{-10}, and in krypton 17×10^{-10}. For krypton ions A is 20×10^{-10} in argon, 18×10^{-10} in nitrogen, and 16×10^{-10} in argon and krypton.

The effect of the atomic number of the gaseous target Z_m on the average charge $\bar{i}$ can be seen from Fig. 8, where $\bar{i}/Z$ is shown as a function of Z_m. At small velocities a decrease of $\bar{i}/Z$ with increasing Z_m is characteristic for the ions studied. However, with increasing ion velocity, the degree of ionization $\bar{i}/Z$ increases with increasing Z_m up to $Z_m = 18$ and then decreases.

This dependence of $\bar{i}$ on Z_m is in contradiction with existing theories[13-15] determining this relation. This fact has been noted by Nikolaev et al.,[3] who measured the dependence of $\bar{i}$ on Z_m for a number of ions in the high-velocity region.

It is a pleasant obligation to express our gratitude to Professor A. K. Val'ter for his attention to this work, and also to the accelerator operators K. M. Khurgin and V. G. Rubashko for assistance in the measurements.

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