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EXPERIMENTAL INVESTIGATION OF ELECTRON CAPTURE BY MULTIPLY CHARGED IONS

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The electron capture cross sections $\sigma_{i,i-1}$ of multiply charged light ions having charge i and atomic numbers Z from 2 to 18 were determined for ions moving with velocities $v = (2.6-12) \times 10^8$ cm/sec in helium, nitrogen, argon, and krypton. Approximately the same dependence of $\sigma_{i,i-1}$ on v was found for all ions in a given gas. A correlation was found between the cross sections in different gases and the numbers of electrons in specified shells of the gas atoms. Minima in the dependence of $\sigma_{i,i-1}$ on Z were found for low-charge ions.

1. INTRODUCTION

ELECTRON capture by fast ions passing through matter has so far been studied mainly for protons and helium ions.[1] Heavier ions have been studied principally at velocities under 10^8 cm/sec.[2,3] Data obtained at higher velocities were available only for nitrogen[4] and oxygen ions.[5] The theoretical papers are also concerned with the passage of hydrogen and helium ions through matter;[6,7] only estimates of the cross sections are available for other ions.[5,8,9]

The present paper reports an experimental investigation of single-electron capture by ions of light elements with $Z \geq 2$ passing through helium, nitrogen, argon, and krypton. Measurements for He, Li, B, and N ions were obtained in the velocity range $(2.6-4) \times 10^8$ to $\sim 12 \times 10^8$ cm/sec, for Ne ions at $(2.6-6) \times 10^8$ cm/sec, and for P and Ar ions at 2.6 and 4.1×10^8 cm/sec. For the purpose of determining the dependence of the cross sections on Z, measurements were also obtained for Be, C, and O ions in helium and nitrogen at $v = 8 \times 10^8$ cm/sec, and for Na, Mg, Al, and Kr ions in helium, nitrogen, and krypton at $v = 2.6 \times 10^8$ cm/sec.

2. PROCEDURE

Cross sections for the capture of a single electron were measured along with cross sections for other electron capture and loss processes, using the experimental setup represented in Fig. 1. Multiply charged ions were accelerated in the 72-cm cyclotron and were focused at a point 8 m from the cyclotron chamber.[10] Near the focus the beam was defined by two 1-cm slits (1 and 3). A thin ($\sim 2 \mu g/cm^2$) celluloid film 2 was placed behind slit 1; after traversing this film the beam contained ions with different charges. The first analyzing magnet H_1 directed ions with a specified charge i into the charge-exchange (collision) chamber B, consisting of a cylinder 8 cm in diameter and 38 cm long with inlet and exit channels (4 and 5) 0.5 cm high, 0.2 cm wide, and 2.6 cm long. Gas was admitted to the chamber continuously; the pressure was measured with 3 — 5% accuracy by ionization gauges calibrated for the different gases against an oil compression gauge.

The helium, nitrogen, and argon target gases contained less than 0.5% impurities; the krypton contained 7% xenon. The pressure in the collision chamber varied from $(1-2) \times 10^{-5}$ mm Hg (re-

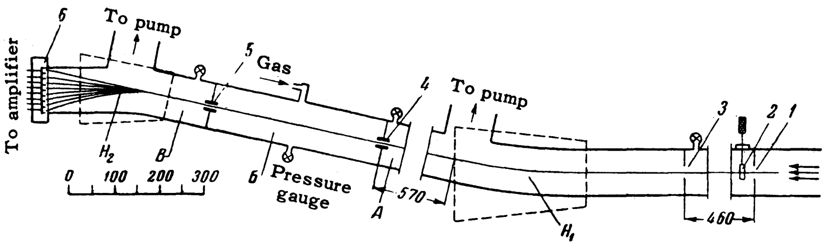

FIG. 1. Diagram of apparatus. Scale in mm.

sidual pressure) to 7×10^{-3} mm for helium and 10^{-3} mm for the other gases. The pressure was $(0.5-2) \times 10^{-5}$ mm in the chambers traversed by the ions before (A) and after (C) the collision chamber.

When a beam of ions with the initial charge i traversed a gas, ions with charges $k \neq i$ resulted from electron capture or loss. The charge distribution in the beam was determined by a second analyzing magnet H_2 and a system (6) of eight proportional counters, each of which registered ions with a single specified charge. The first counter registered neutral particles, while the last counter registered septuply charged ions. The counters were separated from the high-vacuum portion of the apparatus by a slit 0.08 mm high and 100 mm long, sealed with a $\sim 20 \mu g/cm^2$ celluloid film. The entrance window of each counter was 10 mm wide. The field of the second analyzing magnet was adjusted to cause most ions to impinge on the middle of each appropriate counter. This adjustment was monitored by placing before each counter a screen, with a 2-mm slit, which could be moved across the counter entrance window. The counters exhibited practically 100% efficiency in registering particles that passed through their entrance windows.

The fraction Φ_{ik} of ions with a given charge k ($\Sigma_k \Phi_{ik} = 1$) was calculated from the simultaneous readings of all counters. Φ_{ik} was determined for different initial ion charges i at several gas pressures in the target chamber including the residual pressure. The maximum pressures at which Φ_{ik} was measured were such that the intensity reduction of the primary beam as a result of charge exchange amounted to about 20 to 30%, i.e. $\Phi_{ii} \approx 0.7-0.8$. The charge distribution at each pressure was measured three to six times; in each instance the counters registered a total of at least 10^4 particles. The individual measurements usually did not differ by more than the statistical error, which was of the order 2 — 3% for the most intense ion groups produced by charge exchange. The possible error in Φ_{ik} resulting from varying height of the counter entrance slits did not exceed 2 — 3%.

Since the charge distribution of the beam was measured at relatively low pressures, with most ion charges remaining unchanged after traversal of the gas, the ratio of ions with charges i + 1 and i − 1 was determined mainly by the cross sections for single-electron capture and loss. The experimental values of $\Phi_{i,i\pm 2}$ made it possible to determine the cross sections for two-electron capture and loss, values of $\Phi_{i,i\pm 3}$ led to the cross sections for three-electron capture and loss etc. The cross sections were calculated by solving the charge exchange equation

$$d\Phi_{ik}(t)/dt = \sum_j \Phi_{ij}(t)\sigma_{jk}, \qquad (1)$$

where t is the number of gas atoms in a volume with 1-cm^2 cross section along the ion path ($t = \int N dl$, where N is the number of gas atoms per cm^3 and dl is an ion path element in the gas), σ_{jk} with $j \neq k$ is the cross section for the process which changes the ion charge from the initial value j to k, and

$$\sigma_{kk} = -\sum_j{}' \sigma_{kj}$$

(the primed summation indicating $j \neq k$).

The calculation of cross sections from experimental results was usually confined to the first approximation

$$\Phi_{ik} = \sigma_{ik} t \qquad (k \neq i) \qquad (2)$$

at pressures where Φ_{ik} is proportional to t (i.e. to the pressure). However, for $\Phi_{ii} \sim 0.7-0.8$ the single-electron capture and loss cross sections, $\sigma_{i,i+1}$ and $\sigma_{i,i-1}$, calculated from this formula incur an error of 20 — 30%, which could only be reduced by higher approximations. A more exact relationship between Φ_{ik} and σ_{ik} is also required in calculating cross sections for the capture and loss of two or more electrons; the possibility must be allowed that even at the residual pressure a considerable fraction of the ions would be formed by successive single-electron captures or losses. We know that in this case the cross section cannot be determined from the slope of the curve representing Φ_{ik} as a function of the admitted target gas pressure. In the present work we used a practically exact solution of Eq. (1) (for $\Phi_{ii} \sim 0.6 - 0.7$) in order to achieve complete elimination of errors in calculating cross sections from the experimental values Φ_{ik}.

Since charge exchange took place in a mixture of admitted and residual gases, the cross sections σ_{jk} were replaced in (1) by $\sigma_{jk}\alpha + \sigma'_{jk}\alpha'$, where σ_{jk} pertains to the admitted gas and σ'_{jk} to the residual gas, and α and α' are the relative concentrations ($\alpha + \alpha' = 1$). In the solution α was taken as constant for each of the chambers A, B, and C along the ion path (Fig. 1). The initial conditions for A were $\Phi_{ik} = \delta_{ik}$, where $\delta_{ik} = 0$ for $k \neq i$ and $\delta_{ii} = 1$. The values of Φ_{ik} at the boundary between chambers A and B, obtained by solving (1), were taken as initial conditions in solving the equation for chamber B etc. The final expression for Φ_{ik}, obtained after integrating (1) and used to calculate cross sections, is

$$\Phi_{ik} = \delta_{ik} + g_{ik} + \frac{1}{2}\sum_{p}(g_{ip}g_{pk} + \gamma g'_{ip}g_{pk} - \gamma g_{ip}g'_{pk})$$
$$+ \frac{1}{6}\sum_{p,q}(g_{ip}g_{pq}g_{qk} + 2\gamma g'_{ip}g_{pq}g_{qk} - \gamma g_{ip}g'_{pq}g_{qk}$$
$$- \gamma g_{ip}g_{pq}g'_{qk}) + \frac{1}{24}\sum_{p,q,r} g_{ip}g_{pq}g_{qr}g_{rk}$$
$$+ \frac{1}{120}\sum_{p,q,r,s} g_{ip}g_{pq}g_{qr}g_{rs}g_{sk}, \tag{3}$$

where

$$g_{js} = \sigma_{js}t + \sigma'_{js}t', \quad g'_{js} = \sigma'_{js}t', \quad \gamma = (\beta'_1 - \beta'_3) - (\beta_1 - \beta_3),$$

and β_m is the fraction of gas molecules in the m-th chamber along the ion path ($\beta_1 + \beta_2 + \beta_3 = 1$); σ, t, and β pertain to the admitted gas and σ', t', and β' to the residual gas.

β_1 and β_3 were determined experimentally from the ratios between pressures in different portions of the apparatus, taking into account the ion path length in each portion; the values were small for the admitted gas. The largest values were found in the work with helium ($\beta_1 = 0.05$ and $\beta_3 = 0.035$), and were 2.5 — 3 times larger than for the other gases. For the residual gas $\beta'_1 = 0.45$ and $\beta'_3 \approx 0.07$, so that γ was close to 0.4.

Φ'_{ik} for the residual gas and Φ_{ik} for specified pressures of the admitted gas were known experimentally. Solving the system (3) of algebraic equations with these data, we first obtained g'_{ik} for the residual gas and then σ_{ik}, the charge-exchange cross section for the investigated gas. The equations were solved on the "Strela" computer of Moscow State University.

The accuracy of the cross sections depended on the errors in the largest terms of Eq. (3). The errors in the cross sections for capture and loss of a single electron depended on the errors of $\Phi_{i,i\pm1}$ and pressure in the first-approximation formula. In calculating the cross sections for capture or loss of several electrons the terms representing successive captures or losses were sometimes large; the errors in the cross sections then depended on errors in $\Phi_{i,i\pm1}$, $\Phi_{i\pm1,i\pm2}$ etc. as well as errors in $\Phi_{i,i\pm2}$ or $\Phi_{i,i\pm3}$. The cross sections calculated from experimental values Φ_{ik} obtained at different pressures agreed within the limits of error.

In collisions between ions and gas atoms, besides electron captures and losses, ion scattering took place with the result that some ions with changed charge did not emerge from the collision chamber. Therefore from a rigorous point of view the cross sections obtained in the described experiments represent only electron capture or loss accompanied by ion scattering at angles $\theta \leq \theta_m$, where θ_m is the maximum scattering angle of particles emerging from the collision chamber. The mean value of θ_m was $\sim \Delta/l = 0.005$ rad (l is the length of the collision chamber B and Δ is the width of the entrance channel 5). However, there are grounds for believing that at the given ion energies only a small fraction of each cross section, not exceeding the limits of error, is associated with scattering at larger angles.

In all our cases, the scattering at angles $\theta \geq \theta_m$ can be treated classically. For the total scattering cross section at angles $\theta \geq \theta_m$ we can therefore take $\sigma_p(\theta_m) = \pi p^2(\theta_m)$, where $p(\theta)$ is the impact parameter for scattering at the angle θ. If we obtain $p(\theta)$ by using the calculations of Everhart et al.,[11] which agree well with experiment[12] in our required region of p values, then $\sigma_p(\Delta/l)$ is not greater than 1 — 3% of the total value obtained for the charge-exchange cross section $\sigma_i = \Sigma'_k\sigma_{jk}$, and reaches 5 — 10% only for singly charged ions with minimum velocity in argon and krypton.

From experiments[12] on the charge distribution of scattered particles, at somewhat lower velocities than in the present work, it is known that the largest fraction of scattered ions having a specified charge does not exceed one-half the total number of scattered particles and is practically independent of the velocity. Since there is no reason to assume that this fraction can be larger in our velocity range, for each given process of electron capture or loss we can take $\frac{1}{2}\sigma_p(\theta_m)$ as the maximum possible cross section for scattering at $\theta > \theta_m$. In most instances $\frac{1}{2}\sigma_p(\Delta/l)$ did not exceed the random errors of the derived cross sections.

There is experimental confirmation of the conclusion that the fraction of the cross section associated with scattering at angles $\theta > \theta_m$ is within the limits of the indicated random errors. Particles scattered at angles from 1.5 to 2.5 Δ/l in the last third of the ion path within the target chamber entered the counters close to the edges of the entrance windows. The number of these particles was measured by means of a slotted screen placed in front of the counter entrance window. It was found that the few particles scattered at the given angles, did not exceed the background of accidental pulses ($\sim$ 1 pulse per minute in each counter) while the usual registered beam intensity was $(1-2) \times 10^2$ particles per sec.

3. EXPERIMENTAL RESULTS

Figure 2 shows the cross sections for single-electron capture by He, Li, B, and N ions. Figures 3, 4, and 5 show the cross sections for the other ions. The cross sections were calculated per atom. In order to give an idea of the maximum possible cross sections for scattering at $\theta > \theta_m$, Figure 2 shows $\frac{1}{2}\sigma_p(\Delta/l)$ for singly charged nitrogen ions. The scattering cross section depends only slightly on the ionic nuclear charge Z. For helium ions $\sigma_p(\Delta/l)$ is about 5% larger than for nitrogen ions, while for argon ions in nitrogen, argon, and krypton it is 5 — 12% smaller, and in helium it is 30% smaller, than for nitrogen ions. For ions with charge $i = Z$ the scattering cross section exceeds $\sigma_p(\Delta/l)$ for singly charged nitrogen ions by not more than 40% at $v = 2.6 \times 10^8$ cm/sec and by not more than 25% at $v \geq 6 \times 10^8$ cm/sec.

Figure 2 also shows the values of σ_{10} and σ_{21} for helium ions, taken from Allison's review article.[1] In helium at $v \approx 4 \times 10^8$ cm/sec the values of σ_{10} from reference 1 agree with our work, but the values of σ_{21} are 40% under ours. A reasonable interpolation can be made between our values of σ_{10} in nitrogen and argon for $v \gtrsim 4 \times 10^8$ cm/sec and those in reference 1 for $v \lesssim 3 \times 10^8$ cm/sec. It should be noted that the values of σ_{10} given in reference 1 for helium ions in air are about 30% larger than in nitrogen, according to both our own data and reference 1. σ_{21} in air as given in reference 1 agrees with our results in nitrogen at $v \sim (4-5) \times 10^8$ cm/sec, but at $v \approx (6-8) \times 10^8$ cm/sec it is smaller by the factor 1.5 than the results given below.

Our earlier[4] cross sections for electron capture by nitrogen ions in nitrogen and argon, with θ_m larger by the factor 1.5, agree with the present measurements within the limits of error.

The experimental values of σ_{43} and σ_{54}, given in reference 5, for oxygen ions in argon at $v \sim 10^9$ cm/sec agree well with our present results, since the ratios of these cross sections to the corresponding cross sections for nitrogen ions in the present work agree with our ratios of these cross sections at $v = 8 \times 10^8$ cm/sec. σ_{65} in reference 5 is 1.5 times larger than could be expected from our present results.

The following regularities are derived from the experimental results.

a) <u>Dependence of $\sigma_{i,i-1}$ on v</u>. Figure 2 (a—d) shows that the relationship between cross sections and velocity, which can be represented by $q = -d \log \sigma_{i,i-1}/d \log v$, depends mainly on ion velocity and the medium, while depending only slightly on the charge i of the ion and Z of its nucleus. As v increases in helium and nitrogen, q increases monotonically from $\sim 1-2$ at $v = (2.6-4) \times 10^8$ cm/sec to $\sim 5-7$ at $v \sim 10^9$ cm/sec. A decrease of q is observed in argon and krypton for $v > 8 \times 10^8$ cm/sec. The maximum of q, at $v = (6-8) \times 10^8$ cm/sec, is ~ 6 in argon and ~ 7 in krypton. At $v \sim 10^9$ cm/sec we have $q \sim 4$ in argon and $q \sim 3$ in krypton.

The general character of the dependence of $\sigma_{i,i-1}$ on v for the investigated ions agrees with that of σ_{10} for protons.[13] However, q for protons is larger by ~ 2 than for the other ions.

b) <u>Dependence of $\sigma_{i,i-1}$ on Z</u>. Figures 3 and 4 show that this is determined by the ion charge i. For ions with small i minima are observed in the region of Z where a transition occurs from the filling of one electron shell to another. As i increases the minima become shallower, and at sufficiently large values of i the cross section depends only slightly on Z. In all cases the cross section minimum corresponds to the capture of the first L or M electron. The minimum is found at larger Z only for σ_{10} in helium and nitrogen.

c) <u>Dependence of $\sigma_{i,i-1}$ on i</u>. For ions of a given element $\sigma_{i,i-1}$ can be represented approximately by the power function i^m. As a rule, m is somewhat smaller in helium than in other gases. There appears to be a general tendency toward stronger dependence of $\sigma_{i,i-1}$ on i as v increases. For example, as the velocity of nitrogen ions increases within the range $(2.6-8) \times 10^8$ cm/sec, m increases from ~ 1.5 to ~ 3.

In accordance with the foregoing properties of $\sigma_{i,i-1}$ as a function of Z, m varies greatly for different ions and attains maximum values for Z = 3, 11, and 12 (Fig. 6). A similar dependence

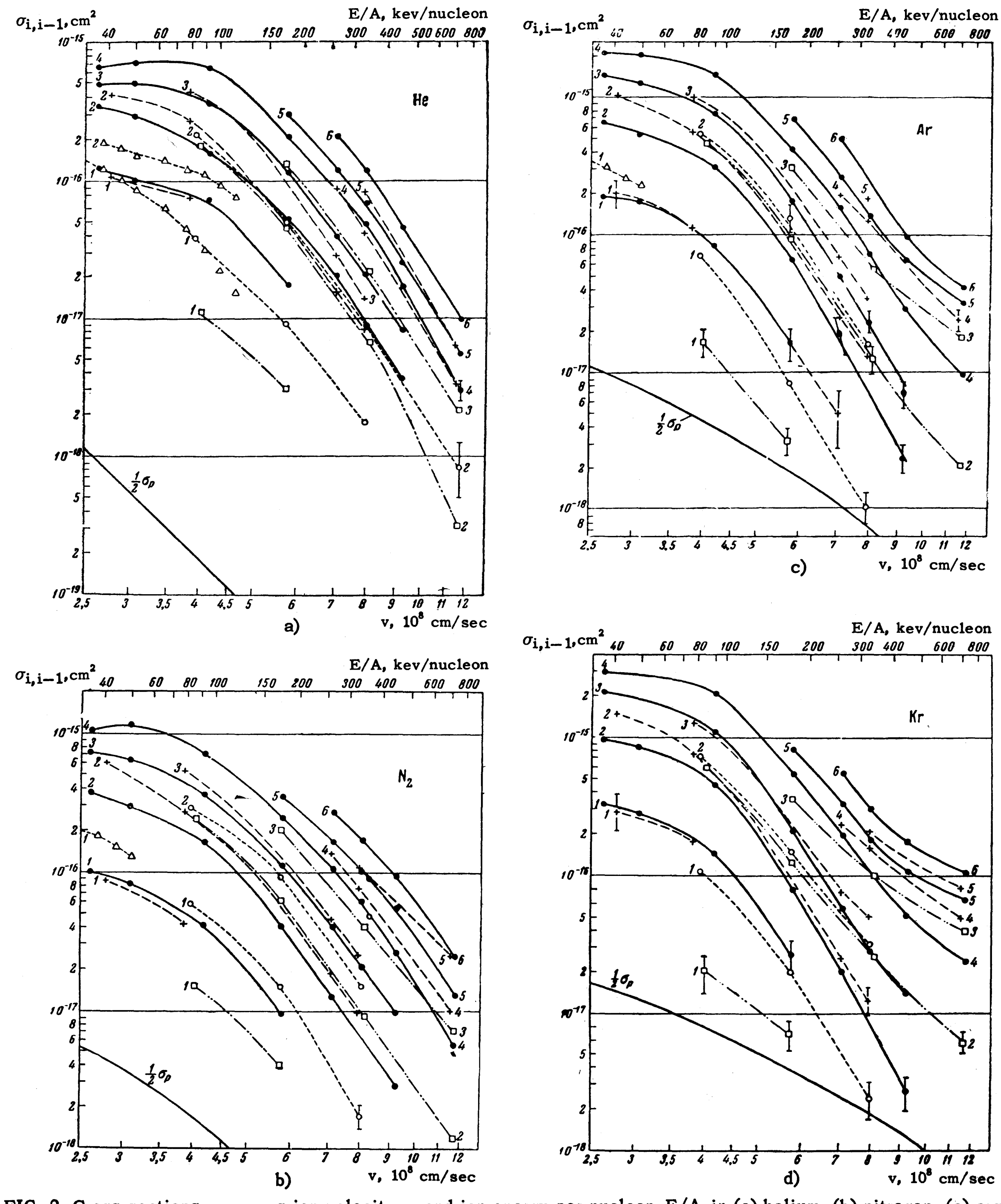

FIG. 2. Cross sections $\sigma_{i,i-1}$ vs ion velocity v and ion energy per nucleon E/A in (a) helium, (b) nitrogen, (c) argon, and (d) krypton, for ions of: o – He, □ – Li, + – B and • – N. Δ represents cross sections for He ions taken from Allison's review article.[1] The value of i is indicated at the ends of the curves. Only errors above 10% are indicated.

on Z − i (the number of electrons) is exhibited by the exponent m′ in the dependence of $\sigma_{i,i-1}$ on i for different ions with identical values of Z − i.

d) Dependence of $\sigma_{i,i-1}$ on the medium. The cross section for electron capture by a given ion usually increases with the atomic number Z_m of the gaseous medium (Fig. 5). The ratios of cross sections in different gases depend generally on all the parameters (i, v, Z, and Z_m). However, as Z_m increases the dependence of the ratios on i and Z becomes weaker. For example, the ratios of the cross sections in argon and krypton differ on the whole by not more than 20% for ions with different i and Z.

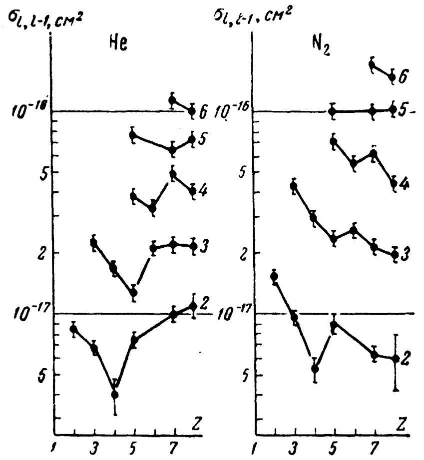

FIG. 3. $\sigma_{i,\,i-1}$ vs Z of ions at v = 8 × 10^8 cm/sec in helium and nitrogen. The initial ion charge i is indicated at the end of each curve.

For v < 8 × 10^8 cm/sec the cross section ratio usually depends only slightly on v. In this case cross sections in helium and nitrogen are close, and cross sections in krypton are on the average only about three times as large. For v > 8 × 10^8 cm/sec the cross section ratio begins to change rapidly with increasing velocity, leading to a stronger dependence of $\sigma_{i,i-1}$ on Z_m. For v ~ 12 × 10^8 cm/sec the cross sections in helium are smaller by a factor 2.5 — 4 than in nitrogen, and by a factor 10 — 20 than in krypton. Cross sections for electron capture by protons exhibit approximately the same behavior.[13]

4. DISCUSSION OF RESULTS

Numerical values of electron capture cross sections based on quantum mechanical calculations are available for only the simplest cases.[5,6] Therefore experimental values can be compared

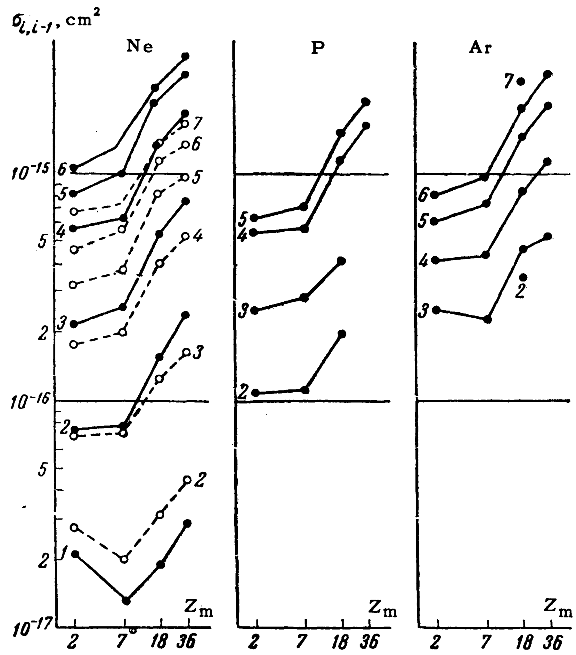

FIG. 5. Cross sections $\sigma_{i,i-1}$ for electron capture by Ne, P, and Ar ions in gases with atomic numbers Z_m. The black circles correspond to v = 4.1 × 10^8 cm/sec; open circles correspond to v = 5.6 × 10^8 cm/sec. The value of i is indicated at the end of each curve.

directly with calculations only for electron capture by singly charged helium ions in helium at (4 — 6) × 10^8 cm/sec. At v ≈ 4 × 10^8 cm/sec the calculated values of σ_{10} agree with experimental results; at v ≈ 6 × 10^8 cm/sec the experimental values are greater by the factor 1.7. The calculations did not take into account the increased effective ion charge in close collisions; the calculated

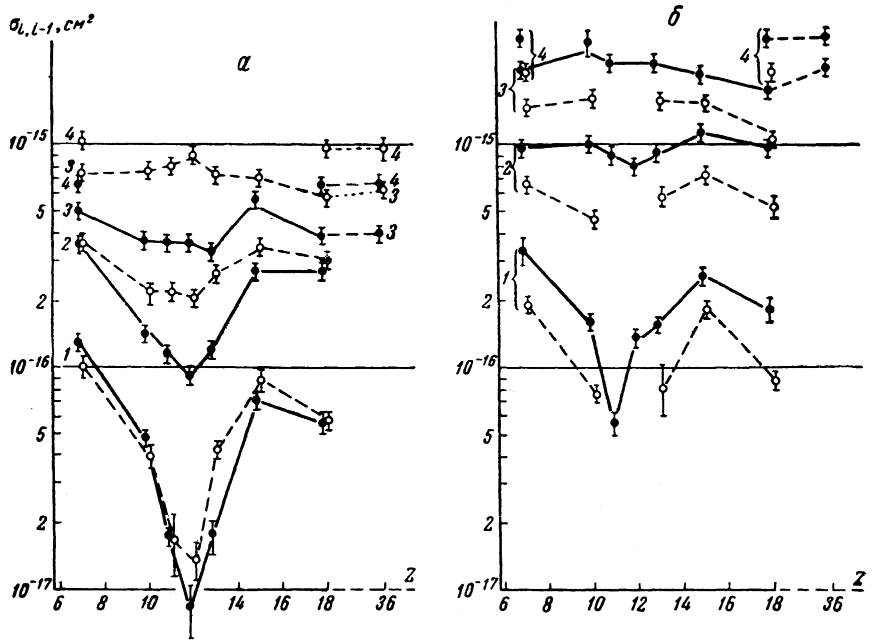

FIG. 4. $\sigma_{i,i-1}$ vs Z of ions at v = 2.6 × 10^8 cm/sec in: a — helium (●) and nitrogen (○), b — krypton (●) and argon (○). The ion charge i is indicated at the end of each curve.

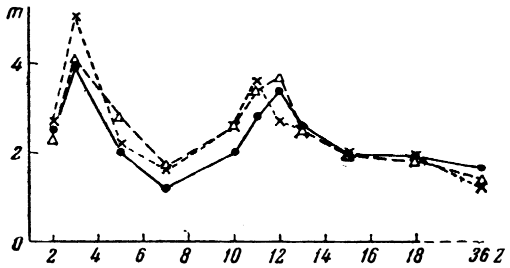

FIG. 6. The exponent $m = \Delta \log \sigma_{i,i-1}/\Delta \log i$ in helium (●), nitrogen (Δ), and krypton (×) for different ions. For helium and lithium ions $v = 4 \times 10^8$ cm/sec; otherwise, $v = 2.6 \times 10^8$ cm/sec.

cross sections can therefore be too small at high velocities.

Because of the great difficulties encountered in quantum mechanical calculations of electron capture by multiply charged ions, it is very important to develop approximation methods for estimating the cross sections. In the attempted method the electron capture cross section is represented by the product $\sigma' fn$, where σ' is the cross section for an ion-electron collision in which energy of the order $\mu v^2/2$ is transferred to the electron (μ is the electron mass), f is the probability of electron capture after the collision, and n is the number of gas-atom electrons effectively participating in the capture.

When this method was first used to obtain cross sections for the capture of an electron by a fast α particle, Bohr[14] obtained values of σ_{21} close to the experimental values. According to Bohr's formula the cross section $\sigma_{Z,Z-1}$ for electron capture by bare nuclei would be proportional to Z^5 (that is, $m' = 5$), since σ' is proportional to Z^2 and $f \approx (Zv_0/v)^3$, where $v_0 = e^2/\hbar = 2.19 \times 10^8$ cm/sec. Our present experimental data in conjunction with results obtained by Barnett and Reynolds[13] at $v \sim 10^9$ cm/sec give $m' = 4-5$ for $Z = 1$ and 2 and $m' = 2-2.5$ for Z from 3 to 5. This not unexpected result shows that when $Zv_0/v \gtrsim 1$ the electron capture probability f ceases to depend on Z, as a result of which m' is determined only by the dependence of σ' on Z and approaches the value 2.

Satisfactory agreement with the available experimental data was obtained when this method was used to evaluate cross sections for electron capture by nitrogen ions.[9] It was shown that when i is small $\sigma_{i,i-1}$ must depend on ion size and the electron binding energy after capture, which fluctuate considerably with Z, while for sufficiently large values of i the cross section is dependent only on i and v, but is independent of Z.

Our experimental results confirm the foregoing conclusion. The minimum of the curve representing the dependence of $\sigma_{i,i-1}$ on Z agrees in most cases with the given theory. However, such effects as the reduction of $\sigma_{i,i-1}$ with increasing Z in the capture of the last K and L electrons (with continuous increase of the ionization potential) and the shift of the minimum in the dependence of σ_{10} on Z in light elements cannot be accounted for solely on the basis of the hypotheses in reference 9. The smaller cross sections for the capture of the last K and L electrons can be attributed reasonably to reduced capture probability f when the respective shells are filled. The shift of the minimum of σ_{10} can evidently be accounted for by loss of the weakly bound first M electron. It remains unclear why electron loss is important only in light gases.

The theoretical dependences of the electron capture cross section on the target gas and ion velocity are based to a considerable extent on a statistical atomic model and do not represent many experimental facts. Specifically, the statistical model cannot account for the observed decrease of q in argon and krypton for $v > 8 \times 10^8$ cm/sec. However, this effect agrees with the idea of the preferential capture of electrons with orbital velocity close to the ion velocity, and can be associated with the fact that atoms of these gases contain a large number of electrons with orbital velocities of the order 1.5×10^9 cm/sec. The reduction of q is not observed in nitrogen, the atoms of which contain only two electrons with this velocity. The highest value of q is reached in helium, the atoms of which have no such electrons.

The hypothesis of preferential capture of electrons with orbital velocity near the ion velocity is confirmed by the dependence of the cross sections on the target gas. Electrons in the outer shells of helium, nitrogen, argon, and krypton atoms have velocities in the range $\sim (3-6) \times 10^8$ cm/sec, the numbers of these electrons in the gas atoms being 2, 5, 8, and 8, respectively. The next shell contains electrons with velocities $\sim (1-2) \times 10^9$ cm/sec, the numbers of electrons being 0, 2, 8, and 18, respectively. The cross section ratio in these gases averaged over all ions at $v = (4-8) \times 10^8$ cm/sec is 4 : 5 : 8 : 10; at $v \sim 12 \times 10^8$ cm/sec the ratio is 1 : 4 : 8 : 20. These ratios are approximately the same as the ratios of the numbers of electrons in the corresponding shells of the gas atoms. The cross sections are twice as large only in the case of electron capture from the K shell, at $v = (4-8) \times 10^8$ cm/sec in helium and $v \sim 1.2 \times 10^9$ cm/sec in nitrogen.

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