Formation of autoionizing metastable lithium-like particles in collisions of fast ions with argon atoms

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Experiments have been carried out to measure the relative number $\alpha_\nu(T)$ of ions in the $(1s2s2p)^4P_{5/2}$ autoionization state in beams of fast lithium-like particles formed as ions of light elements, with atomic numbers $Z = 4$–8, with velocities $v = (4$–$12)\cdot 10^8$ cm/s, and with $\nu = 1, 2$, and 3 electrons pass through an argon target of thickness T. The autoionizing particles are detected from the spontaneous increase in ion charge in the collision chamber. The probabilities for the formation of metastable ions in the capture of one or two electrons have been determined. The limiting values of α for the passage of fast particles through thick targets have also been determined. The basic aspects of the behavior $\alpha_\nu(T)$ are discussed. The difference between the measured average cross sections for the loss and capture of one and two electrons due to the presence of metastable particles in the ion beams is estimated.

1. INTRODUCTION

A small fraction (0.3–7%) of the lithium-like particles in beams of fast ions of light elements which have passed through a solid target are in the $(1s2s2p)^4P_{5/2}$ long-lived autoionization state.[1–4] The excited particles in the beam affect the characteristics of inelastic collision processes and should be taken into consideration in studies of the passage of ions through matter. Since the probability for the formation of excited ions depends on the method by which the beam is formed,[5] we have studied the number of metastable lithium-like particles formed in collisions of hydrogen-like, helium-like, and lithium-like ions with atomic numbers Z from 4 to 8 at ion velocities $v = 4\cdot 10^8$, $8\cdot 10^8$, and $12\cdot 10^8$ cm/s with argon atoms.

2. EXPERIMENTAL PROCEDURE AND CONDITIONS

Fast ions with various charges were produced by passing particles extracted from a 72-cm cyclotron through a thin celluloid film *1* or by means of charge exchange with the residual gas as the ions moved from the accelerator to a magnetic analyzer *2* (Fig. 1). In some of the experiments, this magnet directed the particles with charges $i = Z-1, Z-2$, or $Z-3$ into a flowing gas target *3* formed in a channel with a cross-sectional area of 0.5×10 mm^2 and a length of 70 mm. In other experiments, the magnet directed the particles to a thin celluloid target *4*. The magnetic analyzer *5* then selected lithium-like ions with a charge $i = Z-3$ from the ion beam and sent them into the collision chamber *6*. The relative number Φ of lithium-like ions which have lost an electron through autoionization or in collisions with gas atoms over the path length $r_c = 75$ cm between the analyzers *5* and *7* was determined by the magnetic analyzer *7* and a system of proportional counters, *8* (Refs. 1 and 6).

The relative number α of autoionizing metastable particles which formed among the lithium-like ions which passed through the gas or solid target is related to the values of Φ found at low gas pressures in the collision chamber by

$$\alpha=[\Phi(t)-Dt]/\{C-CB+B[\Phi(t)-Dt]\}, \tag{1}$$

where B and C are the fractions of the metastable ions which have undergone autoionization on the path from their formation point to analyzer *5* and on path r_c, respectively, Dt is the fraction of lithium-like ions which have lost an electron in collisions with gas atoms, and t (atoms per square centimeter) is the thickness of the gas layer in region r_c. Assuming that the α values are proportional to the number of argon atoms in channel *3* (T_g, in atoms per square centimeter) and to the number of residual gas atoms between analyzers *2* and *5* (T_0, in atoms per square centimeter), we have the following expression for experiments involving the formation of metastable ions in the target *3*:

$$B_g=1-\frac{2v\tau}{T}\left[\frac{T_g}{r_1}\operatorname{sh}\left(\frac{r_1}{2v\tau}\right)\exp\left(-\frac{r_g}{v\tau}\right)+\frac{T_0}{r_0}\operatorname{sh}\left(\frac{r_0}{2v\tau}\right)\exp\left(-\frac{r_0}{2v\tau}\right)\right] \tag{2}$$

where $T = T_0 + T_g$, τ is the lifetime of the metastable ions, $r_1 = 7$ cm is the length of channel *3*, $r_g = 33$ cm is the distance between the center of channel *3* and the center of analyzer *5*, and $r_0 = 540$ cm is the length of the ion duct between the analyzers *2* and *5*. For $T > 3\cdot 10^{15}$ atoms/cm^2 with $T \gg T_0 \approx 8\cdot 10^{14}$ atoms/cm^2, the quantity B_g depends only weakly on T and can be described to within 20% by

$$B_g=1-\exp\left(-\frac{r_g}{v\tau}\right). \tag{2a}$$

For the experiments with solid film *4* we have

$$B_s=1-\exp\left(-\frac{r_s}{v\tau}\right), \tag{3}$$

where $r_s = 14$ cm is the distance from the target *4* to the center of the analyzer *5*. (Here and below, the subscript g corresponds to the gaseous target, and s to the solid target.) For the other quantities in (1) we have

$$C=1-\exp\left(-\frac{r_c}{v\tau}\right), \tag{4}$$

$$\Phi(t)-Dt=\lim_{t\to 0}\Phi(t)\equiv\Phi(0),$$

$$D=(1+h)\sigma_{Z-3,Z-2},$$

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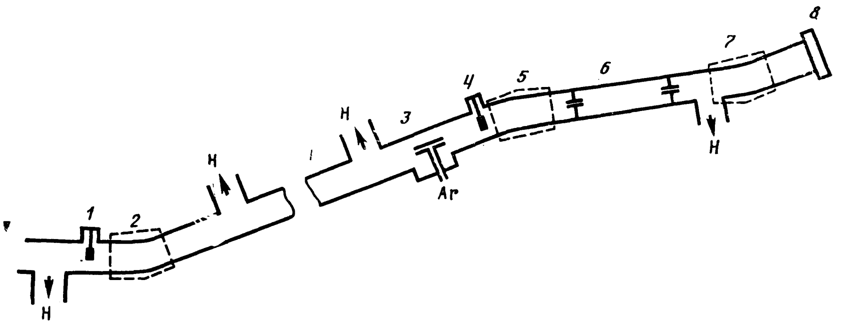

FIG. 1. Experimental layout. 1,4—Solid charge-exchange targets; 3—flowing gas target; 2,5,7—magnetic analyzers; 6—collision chamber; 8—system of proportional counters; H—diffusion pumps.

$$h=\Phi(t)\Big/\left[C(1-C)\frac{\sigma_{z-3,z-2}}{\sigma_{z-3,z-2}}-1\right],$$

where $\sigma_{z-3,z-2}$ and $\sigma^*_{z-3,z-2}$ are the cross sections for the loss of an electron by an unexcited ion and by a metastable ion, respectively. In all these experiments, the relations $\Phi(0)\leqslant 0.15C$ and $|h|\lesssim 0.1$ held.

Measurements of α_s for ion beams which passed through the solid target *4* were carried out with $t\sim 10^{14}$ atoms/cm^2. In this case the relation $\Phi_s(t)\gg Dt$ holds, so the values of $\Phi_s(0)$ can be determined accurately by extrapolating the experimental values of $\Phi_s(t)$ to $t=0$ (Ref. 1). From the values of $\Phi_s(0)$ found as a result and from the values of τ from Ref. 1, we find the values of α_s from Eqs. (1), (3), and (4). The thickness of the solid target, $T_s\sim 10^{17}$ atoms/cm^2, was sufficient to give essentially equilibrium values of α_s, i.e., values which were independent of T_s and of the charge of the ions directed to the target. The values of α_s agreed to within the experimental errors with those found in Ref. 1. The values of α_s for the O^{5+} ions which passed through the celluloid target at $v=8\cdot 10^8$ cm/s according to the present measurements and according to Ref. 1 are $\sim 20\%$ lower than the values of α_s for the same ions which passed through a carbon target.[2] (We determined the latter from the values of $\alpha_s\Phi_s$ found in Ref. 2 through the detection of autoionization electrons.)

For the ions which passed through the argon target *3*, the values of α_ν ($\nu=Z-i=1,2$, or 3 is the number of electrons in the ions directed to the target 3) were determined from the values of Φ_ν and Eqs. (1), (2), and (4) with $h=0$. As a result, a relative error less than 1–2% was introduced in the values of α_ν. The statistical error, on the other hand, in the determination of the values of Φ_ν and α_ν was $\sim 10\%$, because the particles of a certain charge were selected from the ion beams twice (by the analyzers *2* and *5*), and the beam intensity was low in the collision chamber.

Figure 2 shows some typical experimental results: the values of Φ_ν and α_ν for N^{4+} ions at $v=8\cdot 10^8$ cm/s as a function of $T=T_g+T_0$. Also shown here are the results of some control measurements of Φ_s and α_s with film *4* in the beam path, for various values of T. For $T<0.2\cdot 10^{16}$ atoms/cm^2, the values of Φ_ν are low because these lithium-like ions are formed primarily in collisions of fast particles with residual gas molecules far from the analyzer *5* when the argon target, *3*, is thin; a significant fraction of these ions undergo autoionization without reaching the analyzer. For this reason, the values of $\alpha_1(0)$ and $\alpha_2(0)$ for the extremely thin argon target were found by extrapolating to $T=0$ the experimental T dependence of α_ν in the region $T>0.2\cdot 10^{16}$ atoms/cm^2. The error in these values reached 20–30%. The minimum values of α_3 found in our experiments were on the order of $(1-3)\cdot 10^{-3}$.

To determine the values of α_1 and α_2, the hydrogen-like and helium-like ions which were sent to the target *3* were formed by passing an ion beam through a celluloid film 1 with a thickness $T_s\sim 2$–$3\,\mu$g/cm$^2\sim 10^{17}$ atoms/cm^2. In this case, the beams of helium-like ions contained an equilibrium number β_s of metastable particles in $(1s2s)^{1,3}S$ states. The value of β_s ranged from 8% to 50%, depending on the charge and velocity of the ions,[7] so we have $\alpha_2=\alpha_2(T,\beta_s)$. For boron ions at $v=8\cdot 10^8$ cm/s, we also determined the values of $\alpha_2(T,\beta_3)$ in experiments in which helium-like B^{3+} ions were formed by ionizing B^{2+} ions (with $\nu=3$) extract-

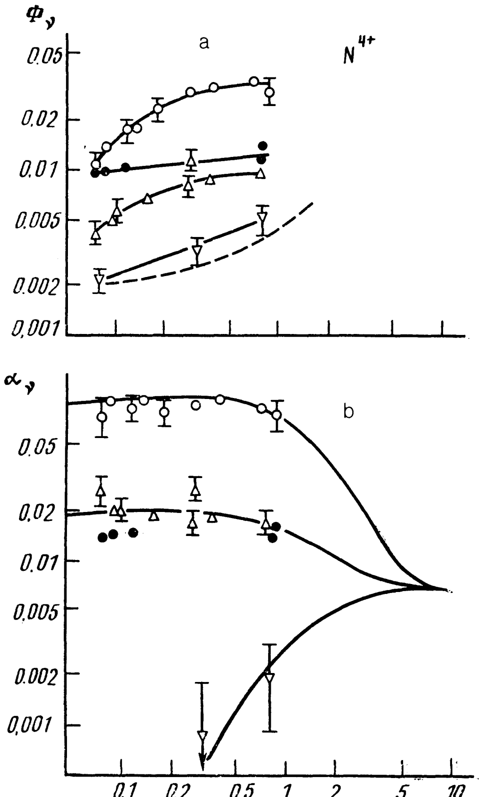

FIG. 2. T dependence of (a) Φ_ν and Φ_s and (b) α_ν and α_s for N^{4+} ions at $v=8\cdot 10^8$ cm/s. a: ●—Φ_s; ○—Φ_1; Δ—Φ_2; ∇—Φ_3. The experimental points have been connected by solid lines to aid the eye. The dashed line shows values of Dt. b: ●—α_s; ○—α_1; Δ—α_2; ∇—α_3. The solid lines are a solution of the system of balance equations in (5).

ed from the accelerator in collisions with residual gas molecules. In this case, the relative number of metastable particles ($\beta_3 \approx 12\%$) was lower by a factor of three than in the case of formation in a solid target ($\beta_4 \approx 34\%$) (Ref. 7). In the determination of the values of $\alpha_3(T)$, the film 1 was not in the beam path, so there were essentially no metastable particles in the beams of lithium-like ions which were directed to target 3 (Ref. 7).

3. EXPERIMENTAL RESULTS

In all the cases we studied, the relations $\alpha_1(T) \gtrsim \alpha_2(T,\beta_s) > \alpha_3(T)$ held. The values of α_1 and α_2 were less than 10–12%. As T increased from 10^{15} to 10^{16} atoms/cm^2, they decreased by respective factors of 1.2–1.5 and 1.3–5. The values of α_3 was less than 0.1% at $T \lesssim 10^{15}$ atoms/cm^2; they increased to 0.3–2% at $T \gtrsim 10^{16}$ atoms/cm^2. It can thus be assumed that the equilibrium values $\alpha_g \equiv \alpha_v(\infty)$ (i.e., the values which do not depend on v or T) lie between the values of α_2 and α_3 corresponding to the maximum thickness T (Fig. 2).

The values of $\alpha_1(0)$, $\alpha_2(0,\beta)$, and also α_s and α_g are shown in Fig. 3. The largest relative numbers of autoionizing particles in the ${}^4P_{5/2}$ state were observed at $v = 8 \cdot 10^8$ cm/s in beams of lithium-like ions formed through the capture of two electrons by hydrogen-like particles in single collisions with argon atoms: $\alpha_1(0) = 6$–12%.

The values of $\alpha_2(0,\beta_s)$ depend only weakly on v; as Z is increased from 4 to 8, they decrease from $\sim 10\%$ to 2%. The decrease by a factor ~ 3 in the relative number of metastable helium-like particles in the beam of B^{2+} ions leads to essentially the same decrease in the values of $\alpha_2(0,\beta)$ [Fig. 3(a)]. A similar result was found in Ref. 8, where metastable lithium-like ions N^{4+} were detected by virtue of their vacuum-UV spectrum in a beam of helium-like N^{5+} ions with a velocity $v = 1.4 \cdot 10^8$ cm/s which passed through a gas. Lines of autoionizing N^{4+} particles were observed only when the initial helium-like N^{5+} ions were formed through the capture of an electron by hydrogen-like N^{6+} ions in a thin gas target. Consequently, the formation of a significant number of autoionizing N^{4+} ions in a beam of helium-like ions requires the presence of particles in metastable states, and the greatest number of such particles forms in the case of one-electron capture.[3] In the charge exchange of unexcited helium-like ions, the formation of autoionizing N^{4+} particles is unlikely since it would require the excitation of one of the K electrons and a flip of its spin.

At $v = 8 \cdot 10^8$ cm/s, the values of α_g decrease with increasing Z, from $\sim 3\%$ to $\sim 0.8\%$; at $v = 4 \cdot 10^8$ cm/s their values are lower by a factor of 2–4. The values of α_s, in contrast, depend only weakly on v; as Z is reduced, they decrease from $\sim 7\%$ to 1%. The ratios α_g/α_s, $\alpha_2(0,\beta_s)/\alpha_s$ and $\alpha_1(0)/\alpha_s$ are determined to a large extent by the reduced ion velocity $V_z = v/Zv_0$, with $v_0 = 2.19 \cdot 10^8$ cm/s (Table I). As V_z increases, the values of α found for the lithium-like ions by the various methods become more nearly the same.

4. DISCUSSION OF RESULTS

1. In view of these experimental results, one might suggest that lithium-like ions form in significant numbers in the quartet state ${}^4P_{5/2}$ in collisions of fast ions with argon atoms only in processes which conserve the electron spin orientation. The values of $\alpha_v(T)$ are determined by the processes by which the various ions are formed and destroyed as fast particles pass through a target. These processes can be described by the balance equations for the relative numbers $N_{\bar\nu}$ and N_ν of ions with ν electrons of which respectively one and two are in the K shell:

$$\frac{dN_{\bar\nu}}{dT} = -N_{\bar\nu}\sigma^{\bar\nu} + \sum_{\mu\neq\nu} N_\mu \sigma^{\mu\nu}(1 - A_{\mu\nu} - R_{\mu\bar\nu}) + \sum_{\mu} \sigma^{\bar\mu\bar\nu}(1 - A_{\bar\mu\bar\nu} - R_{\bar\mu\bar\nu}),$$

$$\frac{dN_\nu}{dT} = -N_\nu\sigma^\nu + \sum_{\bar\mu} \sigma^{\mu\nu} + \sum_{\mu} N_{\bar\mu}\sigma^{\bar\mu\nu} + \sum_{\mu\neq\nu} N_\mu \sigma^{\mu\bar\nu}(A_{\mu\bar\nu} + R_{\mu\bar\nu})$$

$$+ \sum_{\bar\mu} N_{\bar\mu}\sigma^{\bar\mu\bar\nu}(A_{\bar\mu\bar\nu} + R_{\bar\mu\bar\nu}), \qquad (5)$$

Here $\sigma^{\nu\mu}$ is the cross section for the $\nu \to \mu$ collisional transition,

$$\sigma^\nu = \sum_\mu (\sigma^{\nu\mu} + \sigma^{\nu\bar\mu})$$

is the total cross section for a change in the charge of ions with ν electrons, $A_{\mu\bar\nu}$ and $R_{\mu\bar\nu}$ are the relative numbers of excited ions formed in the process $\mu \to \bar\nu$ which undergo auto-

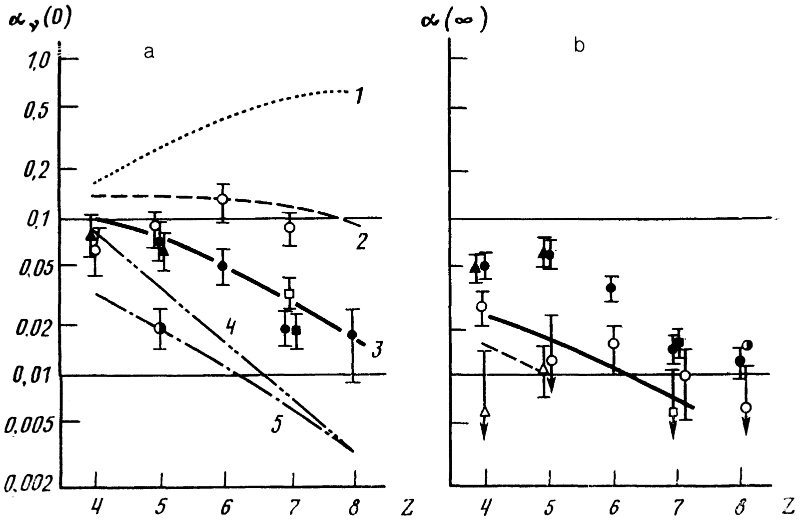

FIG. 3. Z dependence of $\alpha_v(0)$, α_g, and α_s. The points are experimental values of α for $v = 4 \cdot 10^8$ cm/s (triangles), $v = 8 \cdot 10^8$ cm/s (circles), and $v = 12 \cdot 10^8$ cm/s (squares). a: Thin target. ○, □—$\alpha_1(0)$; ▲, ●, ■ — $\alpha_2(0,\beta_s)$; ◑ — $\alpha_2(0,\beta_3)$. The lines show values of $\alpha_2(0,\beta)$ for $v = 8 \cdot 10^8$ cm/s according to (8) with $\beta = 1$ (curve 1), $\beta = \beta_1$ (curve 2), $\beta = \beta_s$ (curve 3), $\beta = \beta_g$ (curve 4), and $\beta = \beta_3$ (curve 5). b: Thick target. ∇,○,□—α_g; ▲,●,■ — α_s from the present study; ◑—α_s for O^{5+} ions in carbon, from Ref. 2. The dashed and solid lines show values of α_g found through a solution of system (5) with $v = 4 \cdot 10^8$ and $8 \cdot 10^8$ cm/s, respectively.

TABLE I. Values of α/α_s, $p_{\bar{1}3}$, and p_{23}.

Ion	ν, 10^8 cm/s	v_Z	$\alpha_1(0)/\alpha_s$	$\alpha_2(0,\beta_s)/\alpha_s$	α_g/α_s	$p_{\bar{1}3}$	p_{23}
Be^+	4	0,46	–	1,6±0,5	0,1±0,1	–	1,2±0,6
B^{2+}	4	0.37	–	0,9±0,3	0,16±0,06	–	1,0±0,7
Be^+	8	0,91	1,3±0.5	–	0,6±0,2	0,27±0,10	–
B^{2+}	8	0,73	4,5±0,5	1,2±0,3	0,2±0,2	0,4±0,2	0,8±0,3
C^{3+}	8	0.61	3.5±1,0	1,4±0,5	0,4±0,2	0,6±0,3	1,1±0,5
N^{4+}	8	0,52	6±2	1,3±0,3	0,7±0,4	0,35±0,10	0,6±0,2
O^{5+}	8	0.46	–	1,5±0,5	0,5±0,5	–	1,0±0,5
N^{4+}	12	0,78	2,0±0,5	1,2±0,2	0,4±0,4	0,15±0,05	0,5±0,3

ionization and which decay in a subsequent collision of the ion with a target atom, respectively. For $Z \leqslant 8$, according to Ref. 9, radiative transitions can be ignored in comparison with autoionization transitions for metastable ions with a K vacancy and with $\bar{\nu} \geqslant 3$, so one can set $R_{\mu\bar{\nu}} = 0$ for $\mu \neq 1$. The quantity $R_{\bar{1}\bar{2}}$ does not exceed the statistical weight of the doublet states formed in the process $\bar{1} \to \bar{2}$, i.e., 1/4.

In a gaseous target, nonmetastable lithium-like ions with a K vacancy which are in doublet states undergo autoionization over the time between collisions, $\tau \sim 10^{-8}$–10^{-9}s. For ions with $Z \geqslant 7$, the metastable ions in $^4P_{1/2,3/2}$ states do the same, to a large extent. (The lifetimes of these states, $\tau_{1/2}$ and $\tau_{3/2}$, which were calculated in Refs. 10 and 11 are given in Ref. 1.) Over times close to $\tau_{1/2}$ and $\tau_{3/2}$, the electrons of lithium-like ions in states with principal quantum numbers $n = 3$ and 4 generally are able to undergo transitions to states with $n = 2$, so the excitation of these ions to these states can be ignored in a first approximation.

It follows from statistical considerations that among the lithium-like ions which are formed in the most important processes, $\bar{1} \to \bar{2} \to \bar{3}$, $\bar{1} \to \bar{3}$, $3 \to \bar{2} \to \bar{3}$, and $3 \to 4 \to \bar{3}$, half the particles are in doublet states, a quarter are in $^4P_{1/2,3/2}$ states, and another quarter are in the $^4P_{5/2}$ state. For ions with $Z = 4$ we thus have $A_{\bar{2}\bar{3}} \approx A_{4\bar{3}} \approx A_{\bar{1}3} \approx 1/2$, while for $Z \geqslant 7$ we have $A_{\bar{2}\bar{3}} \approx A_{4\bar{3}} \approx A_{\bar{1}3} \approx 3/4$. For the less important processes, $\bar{3} \to 4$ and $\bar{4} \to \bar{3}$, we find $A_{\bar{3}4} \approx 3/8$ and $A_{4\bar{3}} = 0$ for $Z = 4$ and $A_{\bar{3}4} \approx 0.65$ and $A_{4\bar{3}} = 1/4$ for $Z \geqslant 7$.

It follows that the quantities $\sigma^{\nu,\nu+1}$ and $\sigma^{\bar{\nu},\nu+1}$ in (5) are the cross sections for the capture of an electron to all states with principal quantum numbers $n \geqslant 2, \sigma^{\nu,\nu+1}$ are the cross sections for the capture of an electron to 1s states, $\sigma^{\nu,\nu-1}$ are the cross sections for the loss of a K electron, and $\sigma^{\nu,\nu-1}$ and $\sigma^{\bar{\nu},\nu-1}$ are the cross sections for the loss of an L electron by unexcited and metastable ions.

Since the change in N_3 due to the autoionization of ions with $\bar{\nu} = 4$ can be ignored in the cases of interest here,[1] we have the following expression for the relative number α of particles in the $^4P_{5/2}$ state:[1]

$$\alpha = N_{\bar{3}}/[N_{\bar{3}} + 4(1 - A_{\bar{2}\bar{3}}) N_3]. \tag{6}$$

2. For the cases in which ions pass through thin gas targets, we find from (5) and (6) the following expressions for $\alpha_\nu(0) = \lim_{T\to 0} \alpha_\nu(T)$ for $\nu = 1$ and 2 and for $\alpha_3(T)$:

$$\alpha_1(0) = \frac{1}{4}\frac{\sigma^{\bar{1}\bar{3}}}{\sigma^{\bar{1}3}} \Big/ \left[1 + \frac{1}{4}\frac{\sigma^{\bar{1}\bar{3}}}{\sigma^{\bar{1}3}}\right], \tag{7}$$

$$\alpha_2(0, \beta) = \frac{1}{4}\frac{\sigma^{\bar{2}\bar{3}}}{\sigma^{23}} \Big/ \left[\frac{1-\beta}{\beta} + \frac{\sigma^{\bar{2}3}}{\sigma^{23}} + \frac{1}{4}\frac{\sigma^{\bar{2}\bar{3}}}{\sigma^{23}}\right], \tag{8}$$

$$\alpha_3(T) = \frac{1}{8}(\sigma^{3\bar{2}}\sigma^{\bar{2}\bar{3}} + \sigma^{34}\sigma^{4\bar{3}})\, T^2, \tag{9}$$

where $\beta = N_{\bar{2}}/(N_{\bar{2}} + N_2)$ is the relative number of metastable particles in $(1s2s)\,^{1,3}S$ states among the helium-like ions. The values of $\alpha_2(0,\beta)$ and $\alpha_1(0)$ are the probabilities for the formation of lithium-like particles in the $^4P_{5/2}$ state in the capture of respectively one and two electrons in single collisions of ions with argon atoms, and $\alpha_3(T)$ is the population of these states in the beam of lithium-like particles as a result of the multistep processes $3 \to \bar{2} \to \bar{3}$ and $3 \to 4 \to \bar{3}$.

Expressions (7)–(9) allow us to use the experimental values of $\alpha_\nu(T)$ at $T \leqslant 0.4 \cdot 10^{16}$ atoms/cm^2 to determine the cross-section ratios $p_{\bar{1}3} = \sigma^{\bar{1}\bar{3}}/\sigma^{\bar{1}3}$ and $p_{23} = \sigma^{\bar{2}\bar{3}}/\sigma^{23}$ and the average cross sections for the loss of a K electron for ions with $\nu = 3$ and 4:

$$\langle \sigma^{\nu, \overline{\nu-1}} \rangle_{3,4} = \frac{(\sigma^{3\bar{2}}\sigma^{\bar{2}\bar{3}} + \sigma^{34}\sigma^{4\bar{3}})}{(\sigma^{\bar{2}\bar{3}} + \sigma^{34})}.$$

For the ratio $p_{\bar{1}3}$ of the cross sections $\sigma^{\bar{1}\bar{3}}$ for the capture of two electrons by hydrogen-like ions to states with $n \geqslant 2$ to the cross sections $\sigma^{\bar{1}3}$ for the capture of two electrons by these ions, with an obligatory capture of one of these electrons to the 1s state, we have, according to (7),

$$p'_s = 4 \Big/ \left[\frac{1}{\alpha_1(0)} - 1\right]. \tag{10}$$

The ratios $p_{\bar{1}3}$ in these cases are 0.15–0.6, or smaller by a factor of 2–4 than the ratios

$$p_{\bar{1}2} = \frac{\sigma^{\bar{1}\bar{2}}}{\sigma^{\bar{1}2}} = \frac{\beta_1}{1 - \beta_1 - R_{\bar{1}\bar{2}}}$$

of the cross sections for the capture of an electron by hydrogen-like ions to states with $n \geqslant 2$ and to the 1s state. Here β_1 is the relative number of metastable helium-like ions produced as a result of the capture of an electron by hydrogen-like ions.[3,12] The values of $p_{\bar{1}3}$ are smaller than $p_{\bar{1}2}$ perhaps because the charge-exchange probability decreases with increasing impact parameter.[13] The cross sections for the capture of one and two electrons are related by

$$\sigma^{\bar{1}3} = W_1\sigma^{\bar{1}2}, \quad \sigma^{\bar{1}\bar{3}} = W_2\sigma^{\bar{1}\bar{2}}, \tag{11}$$

where W_1 and W_2 are the average probabilities for the capture of an electron to states with $n \geqslant 2$ at those values of the impact parameters ρ_1 and ρ_2 which dominate the cross section for the capture of one electron to states with $n = 1$ and $n \geqslant 2$, respectively. Since $\rho_1 < \rho_2$ holds, we have $W_1 > W_2$ and thus $p_{\bar{1}3}/p_{\bar{1}2} = W_2/W_1 < 1$.

For the ratios of the cross sections for the capture of an electron to states with $n \geqslant 2$ by metastable and unexcited helium-like ions, $p_{23} = \sigma^{\bar{2}\bar{3}}/\sigma^{23}$, we find from (8)

$$p_{23} = \frac{4(1-\beta)}{\beta} \Big/ \left[\frac{1}{\alpha_2(0, \beta)} - 1 - \frac{4}{p_{\bar{2}3}}\right], \tag{12}$$

where $p_{\bar{2}3} = \sigma^{\bar{2}\bar{3}}/\sigma^{\bar{2}3}$ are the ratios of the cross section for the capture of an electron by excited helium-like ions to states with $n \geqslant 2$ and to the $1s$ state, which were found in Ref. 1 from experimental values of α_s. The values of p_{23} found from $\alpha_2(0,\beta_s)$ and $\alpha_2(0,\beta_3)$ and the experimental values of β from Ref. 7 and of $p_{\bar{2}3}$ from Ref. 1 depend only weakly on $p_{\bar{2}3}$ and have values of 0.8 ± 0.2, i.e., close to 7/8, the ratio of the numbers of vacancies in the L shell of these ions (Table I).

For given values of p_{23} and $p_{\bar{2}3}$, the values of $\alpha_2(0,\beta)$ depend on the relative number of metastable particles, β, in the beam of helium-like ions, according to (8). The minimum values of β are observed in the beams of these ions which are formed through the ionization of lithium-like particles ($\beta = \beta_3$) or which emerge from a thick gas target ($\beta = \beta_g$). The maximum values are observed when these ions are formed through the successive capture of two electrons by hydrogen-like ions ($\beta = \beta_1$).[3,7,12]

Figure 3 shows values of $\alpha_2(0,\beta)$ calculated for $v = 8 \cdot 10^8$ cm/s for $\beta = \beta_3$, β_g and β_1 and also for $\beta = 1$. The values of $\alpha_2(0,\beta_1)$ should be roughly the same as $\alpha_1(0) \sim 0.1$, i.e., roughly the same as in the case in which these ions are formed through the capture of two electrons in a single collision. The values of $\alpha_2(0,1)$ for $\beta = 1$ increase by a factor of 4 as Z is increased from 4 to 8 (in accordance with the increase in the ratio $p_{\bar{2}3}$, while the values of $\alpha_2(0,\beta_s)$ and α_s decrease by approximately the same factor due to the reduction caused in the values of β_s by the decrease in the ratio of the cross sections for the loss of K and L electrons. Consequently, the differences among the values of $\alpha_2(0,\beta_s)$, $\alpha_2(0,\beta_1)$ and $\alpha_2(0,1)$ increase rapidly with increasing Z.

For the average cross sections for the loss of a K electron by ions with $\nu = 3$ and 4, we find from (9)

$$\langle\sigma^{\nu,\,\overline{\nu-1}}\rangle_{3,4}=8\alpha_3(T)/T^2(p_{23}\sigma^{23}+\sigma^{34}). \tag{13}$$

The values of $\langle\sigma^{\nu,\,\overline{\nu-1}}\rangle$ found from the values of $\alpha_3(T)$ for $T<0.5\cdot 10^{16}$ atoms/cm^2, from the experimental electron-capture cross sections σ^{23} and σ^{34} (Refs. 6 and 14), and from $p_{23} = 7/8$ are smaller by a factor of 10–50 than the cross sections $\langle\sigma^{\nu-1}\rangle_{3,4}$, for the loss of an L electron by unexcited ions.[14,15]

3. To see whether the T dependence found for the α_ν values agrees with the balance equations (5) and with the experimental results on the cross sections for the loss and capture of electrons by fast ions,[16–19] we calculated values of $\alpha_\nu(T)$ through a numerical solution of Eqs. (5). In these calculations, transitions accompanied by a unit change in the ion charge were taken into account; the two-electron transitions $\bar{1} \to \bar{3}$ and $\bar{1} \to 3$ were also taken into account in the calculation of $\alpha_1(T)$. The electron-capture cross sections required for these calculations were found from the experimental cross sections $\sigma_{Z-1,Z-3} = \sigma^{\bar{1}3} + \sigma^{\bar{1}\bar{3}}$, $\sigma_{Z-2,Z-1} = \sigma^{\bar{1}2} + \sigma^{\bar{1}\bar{2}}$ and $\sigma_{Z-\nu,Z-\nu-1} = \sigma^{\nu,\nu+1}$ for $\nu \geqslant 2$ (Ref. 6), from the ratios $p_{\bar{1}3}$ and p_{23} found in the present study, from the ratios $p_{\bar{1}2}$ from Refs. 3 and 12, and from $p_{\bar{2}3}$ from Ref. 1. The electron-loss cross sections were determined from the behavior established previously[15–19] on the basis of the experimental values of $\sigma_{Z-2,Z-1} = \sigma^{2\bar{1}}$ and $\sigma_{Z-\nu,Z-\nu+1} = \sigma^{\nu,\nu-1} + \sigma^{\nu,\,\overline{\nu-1}}$ for $\nu \geqslant 3$ (Refs. 14 and 15). The details of the calculations and the expressions for the cross sections $\sigma^{\nu\mu}$ are given in the Appendix.

For all target thicknesses T, the calculated values of $\alpha_\nu(T)$ generally agree with the experimental values within the experimental errors. The agreement of the theoretical and experimental values of $\alpha_3(T)$ means that one can ignore the formation of metastable particles through the collisional transition $(1s^2 2s)\,{}^1S_{1/2} \to (1s2s2p)\,{}^4P_{5/2}$ with electron spin flip at $T \geqslant 0.5 \cdot 10^{16}$ atoms/cm^2.

4. The appearance of metastable particles in a beam of lithium-like ions gives rise to a change in the measured average cross sections for the loss and capture of electrons, $\bar{\sigma}_{ij} = (1-\alpha)\sigma_{ij} + \alpha\sigma^*_{ij}$, by a relative amount

$$\delta\sigma_{ij}=(\bar{\sigma}_{ij}-\sigma_{ij})/\sigma_{ij}=\alpha\delta\sigma_{ij}^*, \tag{14}$$

where $\delta\sigma^*_{ij} = \sigma^*_{ij}/\sigma_{ij} - 1$, σ_{ij} and σ^*_{ij} are the cross sections for the loss or capture of electrons by lithium-like ions in the $1s^2 2s$ and $1s2s2p$ states, respectively (here and below, $i = Z-3$).

Since the L electrons double in number, and their binding energy increases somewhat, as we go from unexcited particles to metastable particles, we have the result $\delta\sigma^*_{i,i+1} = 0.5$–$0.8$ for the cross sections for the loss of one electron with $V_z \sim 0.5$–1 [according to (A2)]. For the cross sections for the loss of two electrons we have $\delta\sigma^*_{i,i+2} \sim 2$ at $V_z \sim 1$ according to estimates based on the results of Ref. 20. At $V_z \lesssim 0.5$, the values of $\delta\sigma^*_{i,i+2}$ increase to ~ 40 as a result of a sharply strengthened dependence of the cross sections on the electron binding energy. The capture of an electron by metastable ions for $V_z \gtrsim 1$ occurs predominantly to the L shell, so we have $\delta\sigma^*_{i,i-1} = 0.4$–$0.7$, while for $V_z \leqslant 0.5$, in which case the electrons are captured primarily to rapidly autoionizing excited states, the values of $\delta\sigma^*_{i,i-1}$ are close to -1 (Ref. 12).

Since the maximum values of α do not exceed 15%, we thus find from (14)

$$\delta\sigma_{i,\,i+1}\leqslant 0.1, \qquad \delta\sigma_{i,\,i+2}\leqslant 6; \qquad |\delta\sigma_{i,\,i-1}|\leqslant 0.15.$$

5. CONCLUSION

This study has shown that metastable ions in the quartet state $(1s2s2p)\,{}^4P_{5/2}$ form in fast ion-atom collisions in significant numbers only in processes involving the capture of an electron and the conservation of the spin directions of the electrons in the ion, so that in one-electron charge exchange these ions form from helium-like metastable particles in the $(1s2s)\,{}^3S$ state. The largest relative number of autoionizing particles is detected in beams of lithium-like ions formed as a result of the simultaneous capture of two electrons by fast hydrogen-like ions: $\alpha_1(0) = 6$–12%. The charge exchange of helium-like ions which have passed through the celluloid film leads to values of $\alpha_2(0,\beta_s)$ which are equal to or smaller than $\alpha_1(0)$. The relations between the values of α found for the various methods for forming the lithium-like particles depend to a large extent on the reduced ion velocity $V_z = v/Zv_0$. As V_Z increases from 0.4 to 0.9 (primarily because of the decrease in the difference between the cross sections for the loss of K and L electrons), the difference between these quantities decreases rapidly.

The experimental dependence of the values of α on the thickness of the gas target in which the metastable ions are formed is reproduced by the solutions of a system of differential equations incorporating autoionizing transitions and the main collisional transitions involving a change in the ion charge.

The appearance of a metastable component in a beam of lithium-like ions results in an increase in the measured average cross sections for the loss of one and two electrons, by $\sim 10\%$ and a factor of 6, respectively. The average cross sections for the capture of one electron increase or decrease (depending on the velocity V_z) by up to 15%. The presence of particles in the $^4P_{45/2}$ state in the ion beam can be detected easily on the basis of the spontaneous increase in their charge over a distance of about a meter from the point at which they form.

APPENDIX

The cross sections for the capture of electrons to the $1s$ shell and to states with $n \geqslant 2$ have been determined from the experimental total cross sections for the charge exchange of unexcited ions, $\sigma_{z-1,z-3}$ and $\sigma_{z-\nu,z-\nu-1}$, for $\nu \geqslant 1$ (Ref. 6), from the experimental ratios $p_{\bar{1}3}$ and p_{23} found in the present study, and from the ratios $p_{\bar{1}2}$ and $p_{\bar{2}3}$ from Refs. 1, 3, and 12. In the calculations, the average values $p_{\bar{1}2} = 0.4 V_z^{-2}$ and $p_{\bar{2}3} = 0.42 V_Z^{3.6}$ were used. The ratios $p_{\nu,\nu+1} = \sigma^{\bar{\nu},\overline{\nu+1}}/\sigma^{\nu,\nu+1}$ for $\nu \geqslant 3$ were determined in accordance with the number of L vacancies in these ions, from the relation

$$p_{\nu,\nu+1} = p_{23}\frac{8(9-\nu)}{7(10-\nu)}.$$

The ratios $p_{\bar{\nu},\nu+1} = \sigma^{\bar{\nu},\nu+1}/\sigma^{\bar{\nu},\nu+1}$ for $\nu \geqslant 3$ were assumed equal to the ratio $p_{\bar{2}3}$. As a result we found

$$\begin{gathered}
\sigma^{\bar{1},\bar{3}} = p_{\bar{1}3}(1+p_{\bar{1}3})^{-1}\sigma_{Z-1,\,Z-3},\ \sigma^{\bar{1},3} = (1+p_{\bar{1}3})^{-1}\sigma_{Z-1,\,Z-3},\\
\sigma^{\bar{1}\bar{2}} = 0{,}4V_Z^{-2}(1+0{,}4V_Z^{-2})^{-1}\sigma_{Z-1,\,Z-2},\\
\sigma^{\bar{1}2} = (1+0{,}4V_Z^{-2})^{-1}\sigma_{Z-1,\,Z-2},\\
\sigma^{\bar{\nu},\overline{\nu+1}} = p_{23}\frac{8(9-\nu)}{7(10-\nu)}\sigma_{Z-\nu,Z-\nu-1},\\
\sigma^{\bar{\nu},\nu+1} = p_{23}\frac{2{,}7(9-\nu)}{(10-\nu)}V_Z^{3{,}6}\,\sigma_{Z-\nu,Z-\nu-1},\\
\sigma^{\nu,\,\nu+1} = \sigma_{Z-\nu,\,Z-\nu-1},\ \text{where } \nu \geqslant 2.
\end{gathered} \tag{A1}$$

The cross sections for the loss of a $1s$ electron, $\sigma^{\nu,\nu-1}$, and the cross sections for the loss of L electrons, $\sigma^{\nu,\nu-1}$ and $\sigma^{\bar{\nu},\nu-1}$ for $\nu \geqslant 3$ were determined from the experimental cross sections for the loss of an electron by unexcited ions, $\sigma_{z-\nu,z-\nu+1}$, for $\nu \geqslant 2$ (Refs. 14 and 15), and from the dependence of the average loss of individual nl electrons on their binding energy I_{nl} (Ref. 18). In accordance with the experimental results of Refs. 14 and 18, we assumed that the cross sections for the loss of an individual electron by the various ions were essentially the same at identical values of I_{nl} and v.

The ratios $\eta_\nu = \sigma^{\bar{\nu},\nu-1}/\sigma^{\nu,\nu-1}$, of the cross sections for the loss of L electrons by metastable and unexcited ions, are smaller than the ratio of the numbers of L electrons in these ions, $\eta_3 = 1.8 \pm 0.1$ and $\eta_4 = 1.35 \pm 0.1$, by only 10%, since their binding energies are approximately the same. The ratios of the cross sections for the loss of K and L electrons by unexcited ions, $\zeta_\nu = \sigma^{\nu,\nu-1}/\sigma^{\nu,\nu-1}$ at $\nu \geqslant 3$, depend primarily on the number of L electrons, which is $\nu - 2$, and on the reduced ion velocity V_z.

Since beams of helium-like ions are always a mixture of particles in the $(1s^2)\,^1S$ ground state and the $(1s2s)\,^{1,3}S$ metastable states,[3,7] the cross sections $\sigma_Z^{2\bar{1}}$ and $\sigma_Z^{\bar{2}\bar{1}}$ for ions of atomic number Z were determined from the experimental cross sections $\sigma_{Z-1}{}^{10}$, for the loss of an electron by hydrogen-like ions with an atomic number $Z-1$, and the cross sections σ_{Z+1}^{32}, for the loss by lithium-like ions with an atomic number $Z+1$, respectively. As a result we found

$$\begin{aligned}
&\sigma_Z^{2\bar{1}} = 0{,}6\,(ZV_Z)^{0{,}6}\,\sigma_{Z-1}^{\bar{1}0},\ \sigma_Z^{\bar{2}\bar{1}}\\
&= V_Z^{-0{,}2}\sigma_{Z+1}^{32},\ \sigma^{\nu,\,\nu-1} = (1+\zeta_\nu)^{-1}\sigma_{Z-\nu,\,Z-\nu+1},\\
&\sigma^{\bar{\nu},\,\overline{\nu-1}} = \zeta_\nu(1+\zeta_\nu)^{-1}\sigma_{Z-\nu,\,Z-\nu+1}\sigma^{\bar{\nu},\,\bar{\bar{\nu}}-1} = \eta_\nu(1+\zeta_\nu)^{-1}\sigma_{Z-\nu,\,Z-\nu+1},
\end{aligned} \tag{A2}$$

for $\nu \geqslant 3$, $\zeta_3 = 0.4V_Z^3$, $\zeta_4 = 0.2V_Z^{3.4}$, $\eta_3 = 1.8$, and $\eta_4 = 1.35$. The values of $A_{\bar{\mu}\bar{\nu}}$ for $Z = 5$ and 6 were taken to be the same as for $Z = 4$ and 7, respectively, and we used $R_{\bar{1}\bar{2}} = 0.125$.

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