COLLISIONS OF FAST Li, Na, K *ATOMS AND IONS WITH ALKALI-METAL AND INERT-GAS ATOMS (20–155 keV)*

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Measurements have been carried out of the electron-loss cross sections and the equilibrium charge distributions for Li^+, Na^+, and K^+ ion beams passing through sodium and potassium vapor and helium, neon, and argon gas. Data obtained on the equilibrium charge distributions and the results reported in[9] have been used to determine the electron-loss cross sections of Li, Na, and K atoms. Estimates are reported of the electron-capture cross sections of the doubly charged ions Li^{2+}, Na^{2+}, and K^{2+}. The largest ionization cross sections of fast atoms were observed for collisions between identical alkali-metal atoms.

1. INTRODUCTION

THERE are few papers on the stripping of fast alkali-metal atoms and ions during interaction with gas atoms and molecules. Studied in this field have been largely confined to the region of relatively low energies[1-3]. Measurements in a broad energy range[4-8] have been carried out only for Li ions and atoms. Determinations of the electron-loss cross section of Na^+ in air at intermediate energies have also been reported in[4].

The stripping of fast alkali atoms and ions on alkali-metal atoms has not been investigated at all. In this research we have measured the electron-loss cross sections of Li^+, Na^+, and K^+ ions and the equilibrium charge fractions in beams of these particles after passage through helium, neon, and argon gas, and sodium and potassium vapor. The measured charge fractions $F_{0\infty}$ and $F_{1\infty}$ and the charge-transfer cross sections of Li^+, Na^+, and K^+ reported earlier[9] for the above targets have enabled us to determine the electron-loss cross sections of fast Li, Na, and K atoms.

The results reported here are of interest both from the practical and the purely scientific points of view. For example, data on the equilibrium charge distributions may be very useful in various branches of technology in the development of ion engines, electrostatic charged-particle accelerators, shaping of fast neutral-particle beams, and so on. In addition, the results can be used to estimate the effect of the structure of the outer electron shells of target atoms by comparing the data for inert-gas atoms with those for the adjacent alkali atoms.

2. APPARATUS AND EXPERIMENTAL METHOD

The present investigation was carried out with the apparatus used earlier and described with the various modifications and additions in[9-11]. The intensities of the particle-beam components were determined as described in these papers.

To determine the equilibrium charge distributions in ion beams, entrance and exit channels 50 mm long and 1 mm in diameter were introduced into the collision chamber. A check was made on whether the steady-state charge distribution in the beam had been reached at each ion energy. This was done by investigating the charge distribution as a function of vapor or gas density in the collision chamber near the equilibrium state. In most cases, it may be supposed that the particle beam consisted of only the two components $F_{0\infty}$ and $F_{1\infty}$ in the energy region which we have investigated. The third component, $F_{2\infty}$, becomes appreciable as the ion velocity increases. However, even in this case we can neglect processes involving the loss and capture of two or more electrons without introducing any substantial errors, and then determine the electron-loss cross section σ_{01} of fast atoms for the entire velocity range from the formula[12]

$$\sigma_{01} = \sigma_{10}F_{1\infty} / F_{0\infty}. \quad (1)$$

Similarly, the electron-capture cross sections of Li^{2+}, Na^{2+}, and K^{2+} in gases can be determined from the formula

$$\sigma_{21} = \sigma_{12}F_{1\infty} / F_{2\infty}. \quad (2)$$

Measurements of the electron-capture cross section σ_{10} were reported in our previous paper[9] together with an estimate of the possible effect of metastable states on the cross sections. Analysis showed that the contribution to the cross section due to metastable atoms did not exceed 10–15%. The total error in the electron-loss cross section σ_{01} was therefore 20–25%. The electron-loss cross sections of the singly-charged ions Li^+, Na^+, and K^+ were measured by a mass-spectroscopic method. The target-atom density in the collision chamber was determined as described previously in[9]. The total error associated with measurements of the atom density, charge fractions, and ion energies was about 15–20%. We note that the method used to release the alkali metals from the sealed cells by remote control under vacuum was described in a separate paper[13].

3. RESULTS AND DISCUSSION

In our measurements we have used Li^+, Na^+, and K^+ ion beams and chemically pure sodium and potassium in the form of vapor, and gaseous helium, neon,

Target	Sodium			Potassium			Neon			Argon		
$v\cdot10^{-8}$, cm/sec	$F_{0\infty}$	$F_{1\infty}$	$F_{2\infty}\cdot10^2$	$F_{0\infty}$	$F_{1\infty}$	$F_{2\infty}\cdot10^2$	$F_{0\infty}$	$F_{1\infty}$	$F_{2\infty}\cdot10^2$	$F_{0\infty}$	$F_{1\infty}$	$F_{2\infty}\cdot10^2$
Li^+ ion												
0.665	0,95	0,05										
0.78	0,95	0,05		0,94	0,06		0,06	0,94		0.23	0,77	
0,86	0,95	0,05		0.93	0,07		0.08	0.92		0.23	0.77	
1	0,92	0,08					0,16	0.84		0,24	0,76	
1.2	0,85	0,15		0,64	0.36		0,18	0.82		0.225	0,775	
1.37	0.71	0,29					0,19	0.81		0,215	0,785	
1,47	0,64	0,36		0,335	0,665		0,195	0.805		0,205	0,795	
1.63	0,51	0,49		0.25	0.75		0,2	0.7977	0,23	0,195	0,805	
1.71	0,41	0,5893	0,07	0.192	0,8075	0.045	0,205	0.7918	0,32	0.185	0.8134	0.16
1,82	0,285	0.712	0.3	0.12	0.8786	0.135	0.2	0,7948	0,52	0,17	0,8275	0,25
1.89	0.234	0.7614	0.46	0.115	0,882	0.31	0.2	0,792	0.8	0,165	0.8305	0.45
2	0,17	0.8215	0.85	0.11	0,8555	0.45	0.2	0,788	1.2	0.158	0.8335	0,85
Na^+ ion												
0.5	0,95	0.05		0,94	0,06		0.078	0.922				
0,6	0.9	0.1		0,92	0,08		0,085	0.915		0,19	0 81	
0.67	0.83	0,17		0.82	0.18		0.087	0,913		0.2	0.8	
0.758				0.80	0.2		0.086	0.9087	0,53	0.22	0,78	
0.82	0,76	0,24		0,77	0,23		0.086	0,905	0,9	0.23	0.77	
0,896				0.75	0,25		0.093	0,892	1,5	0.241	0,7572	0.175
0,96	0,74	0,2588	0.124	0.73	0,2698	0.02	0,095	0.884	2,1	0,245	0.752	0.3
1,02				0.71	0,2896	0.04	0,095	0.874	3,1	0.23	0.7655	0,45
1,05	0,725	0,2727	0,23	0,68	0,3194	0,06	0.095	0,865	4.0	0,215	0.7785	0.65
1.12	0,70	0,297	0,3	0.6	0,399	0,10	0.095	0.838	6.7	0,2	0,789	1.1
K^+ ion												
0.362	0,83	0,17		0.96	0,04							
0,428	0,83	0.17		0,91	0,09							
0,51	0,83	0.17		0.9	0.1		0.08	0,92		0,185	0.815	
0.59				0,87	0.13		0,09	0,91		0.223	0.777	
0,63	0,81	0,19		0.86	0,14		0,091	0.893	1,6	0,224	0,7605	1,55
0,69	0,80	0.2		0,845	0,155		0,092	0.868	4	0.224	0.751	2,5
0,725	0.8	0.2		0.84	0,16		0,0925	0.856	5,15	0.23	0.735	3.3
0,775	0,78	0,218	0.2	0,81	0,1895	0.145	0,093	0.8334	7.36	0.23	0,725	4.5
0,81	0,775	0,2235	0,25	0,78	0,2175	0.25	0.093	0.831	7.6	0,235	0,7105	5,45
0,866	0.77	0,225	0.5	0,775	0,2208	0.42	0.093	0.802	10,5	0.23	0,6995	7,05

and argon with impurities not exceeding 0.1%. The results of measurements of the equilibrium charge composition of Li, Na, and K beams after passage through the target are shown in the Table. It is clear that the fractions $F_{0\infty}$ for the above ions in alkali-metal vapor are substantially greater than the corresponding fractions for gas targets throughout the energy range which we have investigated. This is a direct consequence of the enormous differences between the electron-capture cross sections σ_{10} for collisions with alkali-metal atoms and inert-gas atoms[9], since the cross sections for the competing electron-loss process involving fast atoms are also greater in vapors of alkali elements than in gases (Fig. 1). The character of the dependence of the fractions $F_{0\infty}$ on the ion velocity is also different in the alkali and gas targets. Broad flat maxima are observed in the case of neon and argon targets.

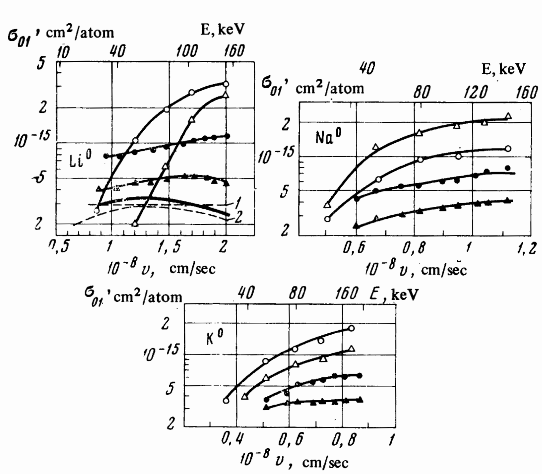

FIG. 1. Electron-loss cross sections of Li, Na, and K atoms as functions of velocity: Δ—in sodium vapor, ○—in potassium vapor, ●—in argon, ▲—in neon, thick curve—in helium; broken curves 1 and 2—data from [6] for nitrogen and helium, respectively.

For sodium and potassium targets, on the other hand, the fractions $F_{0\infty}$ fall monotonically with increasing velocity. This is again connected with the difference between the velocity dependence of the charge-transfer cross sections σ_{10} in the case of collisions with inert-gas and alkali-metal atoms. In the former case, the cross sections increase, whereas in the second case they decrease with increasing ion velocity in the energy range under consideration[9]. The very large relative fractions $F_{0\infty}$ of fast neutral particles in the maxima, which approach unity in the case of interaction of ions with Na and K atoms, are particularly noticeable. As already noted, this is a consequence of the dominating effect of the capture of the weakly bound electron at small energy defect ΔE.

The electron-loss cross sections of fast Li, Na, and K atoms, determined from Eq. (1), are shown in Fig. 1. The data obtained by Allison et al.[6] for Li atoms are given for comparison. Our data are in agreement, to within experimental error, with the data in[6] for the chosen control gas (helium). It is clear from the graphs that the electron-loss cross sections in gases increase with increasing energy, and the maxima of σ_{01} as a function of velocity are reached relatively early. Thus, for example, in the case of fast Li atoms, the velocities corresponding to the maxima of σ_{01} are close to the orbital velocity of the electron lost by the incident atom. In the case of ionization of fast Na and K atoms in gases, the maxima of the $\sigma_{01}(v)$ curves have not been reached at the maximum velocities which we have investigated, but the slope of the curves is then quite small, indicating that the maxima cannot be far off.

A different picture is characteristic for the interaction between fast alkali atoms, on the one hand, and alkali-atom targets on the other. Here, the velocity dependence of the electron-loss cross section σ_{01} is steeper, and the cross sections at some velocities are substantially greater than in gases. Judging by the nature of the $\sigma_{01}(v)$ curves we may conclude that their maxima should appear at velocities appreciably greater than in the case of interaction with gases.

Since the inner electron shells of alkali atoms are similar to those of the adjacent inert-gas atoms, the above substantial difference between the nature and value of the electron-loss cross sections of fast alkali atoms must be ascribed to the interaction between the outer electrons of the colliding alkali atoms. Because of the large size of these shells, and the low binding energies, the main contribution to the electron-loss cross section σ_{01} should be provided by distant collisions, and this corresponds to large σ_{01}. The minor importance of the inner shells of alkali atoms in the process is well illustrated by the very large difference between the electron-loss cross section σ_{01} for collisions of alkali atoms with each other and collisions of alkali atoms with inert-gas atoms.

The shift of the maxima of the $\sigma_{01}(v)$ curves toward higher energies in the case of interactions between alkali atoms can be explained by the high losses of inelastic energy through the removal of electrons with similar electron binding energies from the incident and target atoms. On the other hand, in the case of the interaction of a fast alkali atom with a gas atom, an electron is lost only by the incident atom. As a rule, the electron-loss cross section of fast atoms increases systematically with increasing atomic number of the target particles[8,14], at least up to argon. Some deviations from this rule toward higher values of σ_{01} have been observed for alkali atom-inert atom neighboring pairs at lower energies[3].

A very much greater violation of the above rule has been found in the present investigation above certain velocities in the case of interaction of alkali atoms with each other. As an illustration, Fig. 2 shows the electron-loss cross section σ_{01} as a function of the atomic number of the target particles for fast Li atoms and $v = 2 \times 10^8$ cm/sec. It is clear from the figure that in sodium and potassium vapor the cross sections σ_{01} are substantially greater than in neon and argon gas. The same situation is observed for ionizing collisions of fast Na and K atoms with Na and K atoms and, correspondingly, with Ne and Ar atoms.

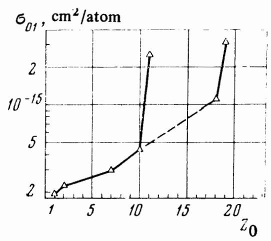

FIG. 2

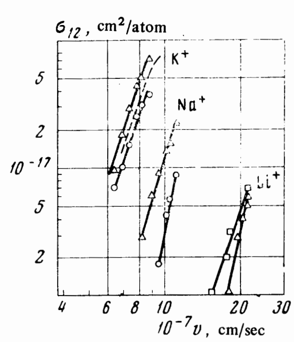

FIG. 3

FIG. 2. Electron-loss cross section of Li atoms as a function of the atomic number Z_0 of target atoms for $v = 2 \times 10^8$ cm/sec.

FIG. 3. Electron-loss cross sections of Li^+, Na^+, and K^+ as functions of velocity: Δ—in neon, O—in argon, □—in helium, broken curve—in argon, taken from [16].

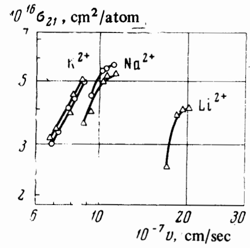

FIG. 4. Electron-capture cross section of Li^{2+}, Na^{2+}, and K^{2+} as functions of velocity: Δ—in neon, O—in argon.

It is clear from Fig. 1 that the cross sections σ_{01} of fast Na and K atoms on Na and K atoms, respectively, are appreciably greater than in the case of collisions between different alkali atoms (Na^0 + K, K^0 + Na).

Similar results at lower energies were reported in[15], which was concerned with the stripping of inert-gas atoms. It follows from the above facts that there are substantial deviations in the character of the dependence of σ_{01} on the charge of the target nucleus in the case of pairs of alkali-metal atoms. This is probably also due to the fact that the main contribution to the stripping process is due to distant collisions which involve practically exclusively the outer shells of the colliding alkali-metal atoms.

Figure 3 shows the measured electron-loss cross sections of the singly charged ions Li^+, Na^+, and K^+ in helium, neon, and argon gas. For comparison, the figure also shows the data taken from[16]. It is clear that the velocity dependence of the electron-loss cross section σ_{12} can be represented by $\sigma = Av^m$ (where $m \approx 5-6$). For the stripping cross sections σ_{12} of Li^+ in helium and K^+ in argon we have a satisfactory agreement with the data reported in[6,16]. Heavier ions have larger cross sections σ_{12} which differ by more than an order of magnitude at equal velocities. It is interesting to note that the cross sections σ_{12} decrease with increasing atomic number of the target in the velocity ranges which we are discussing. However, further increase in the ion velocity will probably lead to a directly opposite relation, which is indicated by the example of Li^+ ions[6].

The reduction in the cross section σ_{12} with increasing atomic number of the target was reported for some inert-gas ions in[17] where it was explained in terms of the possible competing processes of the stripping of the incident ion and the ionization of the target atom. This approach will also, in some measure, explain the stripping cross sections σ_{12} of Li^+, Na^+, and K^+ ions on Na and K atoms, which we have found to be much lower than in the above gases. However, the reduction in the cross sections may be due to the screening effect of the outer shell of the alkali atom which is deformed by the field of the incident ion. We do not report these cross sections in the present paper because the low intensities of the ion beams led to considerable errors in the resulting values. The fact that the cross sections σ_{12} are relatively low in the case of interaction with Na and K atoms is indicated indirectly by the Table.

The data given in the Table and in Fig. 3 can be used to estimate the electron-capture cross sections of the doubly-charged ions Li^{2+}, Na^{2+}, and K^{2+} in Ne and Ar gases with the aid of Eq. (2). The corresponding data are given in Fig. 4, from which it is clear that the cross sections σ_{21} increase rapidly with increasing velocity, and larger cross sections correspond to smaller energy defects ΔE.

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