Spectroscopic investigation of the production of doubly charged rubidium and cesium ions by electron-ion collisions

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The process of *s* ionization of rubidium and cesium ions by electron collision was studied for the first time in colliding beams by detecting ultrasoft x rays (USX). A narrow resonance, which can be explained by the capture of a bombarding electron with a simultaneous excitation of *s* and *p* electrons of the outer shell of these ions, was observed near the threshold of the excitation of the USX radiation. The effective cross sections of *s* ionization in the maximum are 3×10^{-17} cm^2 for Rb$^+$ and 5×10^{-17} cm^2 for Cs$^+$.

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At the present time, the ionization of positive ions by electron collision is known for a whole series of elements.[1] A method of colliding beams of electrons and ions with a magnetic separation of the produced ions of different charges was used. As a rule, the total cross section of ionization of ions due to ejection of electrons from both the outer and inner shells is determined in these experiments. However, the mass-spectrometric method does not allow direct determination of the ionization cross section for each shell separately (partial ionization cross sections).

The importance of ejection of an electron from the inner subshells of the ion is that the ions of different charge are produced in excited states. In a number of cases these states are stable relative to autoionization and undergo radiative decay by emitting ultrasoft x radiation.[2] Therefore, the study of the excitation of this emission makes it possible to determine the effective cross sections for the ejection of electrons from the corresponding shells.

In this paper we present the results of a spectroscopic study of *s* ionization of Rb$^+$ and Cs$^+$ ions by electron collision. As a result of the ejection of an *s* electron from the outer shell of an ion of an alkaline element, a doubly charged ion is produced in a stable excited state that undergoes radiative decay with the formation of an ion in the ground state according to the reaction:

$$A^+(ms^2mp^6) + e \to A^{2+*}(msmp^6) + 2e \to A^{2+}(ms^2mp^5) + h\nu + 2e, \tag{1}$$

where $m=4$ for Rb$^+$, and $m=5$ for Cs$^+$, and $h\nu$ is the USX emission.

The excitation functions of USX doublets of these ions ($\lambda=76.9$ nm, $\lambda=81.5$ nm for Rb III and $\lambda=78.2$ nm, $\lambda=87.8$ nm for Cs III) were investigated using electron and ion beams intersecting at a right angle in a device basically similar to that in Ref. 3. For the spectral separation of the emission we used a 70-degree vacuum monochromator based on the Cei-Namiok design. In order to separate the useful

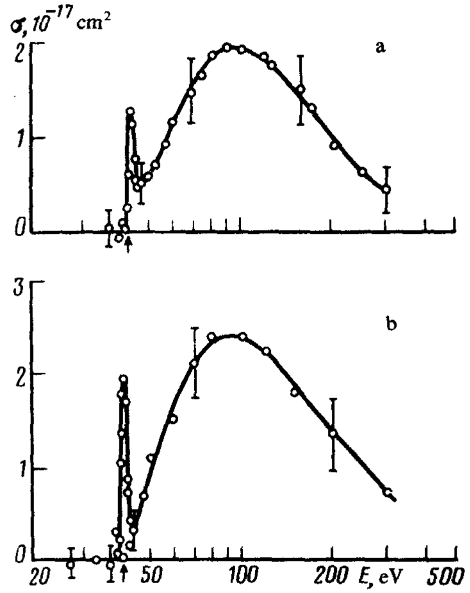

FIG. 1. Energy dependences of the excitation cross sections of the USX lines of doubly charged rubidium and cesium ions: (a) $\lambda = 81.5$ nm for Rb III and (b) $\lambda = 87.8$ nm for Cs III.

signal from the background, we used a procedure based on the modulation of the ion beam and the recording of the signal in two channels. The optimal experimental conditions were as follows: the ion current was 1 μA at energy of 1 keV, the electron current was 400 μA at energy of 50 eV, and the energy nonuniformity was $\Delta E_{1/2} = 2.5$ eV. The useful signal amounted to ~ 0.1 pulses/sec for a signal-to-noise ratio of 1:10.

Figure 1 shows the excitation functions of the USX lines corresponding to the transition $msmp^6\ {}^2S_{1/2} \rightarrow ms^2mp^5\ {}^2P_{1/2}$ of the rubidium and cesium ions. The energy of the electrons is plotted on a logarithmic scale along the x axis and the effective cross section is plotted along the y axis. The vertical bars indicate the root-mean-square error of the relative measurements. The arrows indicate excitation thresholds of the USX lines. As seen in Fig. 1, the energy dependence of the cross sections is similar for both ions and is characterized by the presence of a narrow-maximum directly at the threshold of the process and a broad maximum in the region of 100 eV.[1)] According to the laws governing collision-ionization of ions by electrons[1] the broad maximum and the subsequent smooth decrease evidently represent the process of detachment of the s electron.

The absolute cross sections for excitation of the USX lines were determined by comparing their intensities with the intensity of the 74.1-nm resonance line ($4s^24p^25s[\frac{3}{2}]^0_1 \rightarrow 4s^24p^6\ {}^1S_0$) for Rb II. In turn, the excitation cross section of the resonance line at 74.1 nm was determined by normalizing the experimental curve to the theoretical calculation of the cross section at 400 eV. The calculation was made in the Coulomb-Born approximation using the procedure described in Ref. 4. The error in determining the effective cross sections does not exceed a factor of 2. The effective cross sections of s ionization were obtained by adding the emission intensities of both components. Their maximum values for rubidium and cesium ions were 3×10^{-17} cm^2

and 5×10^{-17} cm^2, respectively.

We shall now examine the nature of the near-threshold maximum. The width of this maximum at half height coincides with the energy inhomogeneity of the beam electrons ($\sim$2.5 eV) and, consequently, has a resonance nature. We note that such sharp resonance at the ionization threshold is unexpected. Apparently, it does not characterize direct ejection of an s electron, and its origin is attributable to other reasons. Earlier in our study of the excitation of potassium ions by electron collision[5] it was established that a capture of incident electrons by singly charged ions occurs in the region of threshold energies. We can assume that in this case the narrow maximum is due to the electron capture process. However, the capture mechanism is more complex and is accompanied by the excitation of two electrons, rather than one, from different subshells:

$$A^{+}(ms^{2}mp^{6}) + e \rightarrow A^{**}\,[msmp^{5}(m+1)s^{2}nl]. \tag{2}$$

In the literature there are no data on the binding energies of such autoionization states. However, an estimate of the binding energy of this type of states indicates that at the threshold of the s ionization the energy of the incident electron is sufficient for the simultaneous excitation of the s and p electrons. The states such as $msmp^5nln_1l_1$ have been observed in the photoabsorption spectra of inert gases.[6]

As for the decay of the autoionization states, this process occurs in two stages:

$$A^{**}[msmp^{5}(^{1}P_{1})(m+1)s^{2}nl] \rightarrow A^{+**}\,[msmp^{5}(^{3}P_{j})(m+1)s^{2}] + \tilde{e}_{1}$$
$$\hookrightarrow A^{2+*}(msmp^{6}) + e_{2} \tag{3}$$

In the first stage the autoionization state decays by means of the most probable Koster-Kronig effect, which leads to the formation of an autoionization state for a singly charged ion and to the ejection of a slow electron $\tilde{e}_1$. The p vacancy is then filled by means of the Auger transition with the ejection of a fast electron e_2. As a result, a stationary excited state of a doubly charged ion is produced, which subsequently undergoes radiative decay in accordance with Eq. (1).

Thus, the spectroscopic method makes it possible to investigate the partial ionization cross sections of ions from different subshells and to determine the fine properties of the mechanism for the production of doubly charged ion as a result of electron-ion collisions.

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[1]As shown in the measurements, the excitation functions of both components of the USX doublet are similar for each ion and the ratio of their intensities is 3:2 for Rb III and 1:1 for Cs III.

[1]K.T. Dolder and B. Peart, Rep. Prog. Phys. **39**, 693 (1976).
[2]C.E. Moore, Atomic Energy Levels Circular of the National Bureau of Standards, Washington, D.C. (1958).

[3]I.P. Zapesochnyĭ, V.A. Kel'man, A.I. Imre, A.I. Dashchenko, and F.F. Danch, Zh. Eksp. Teor. Fiz. **69**, 1948 (1975) [Sov. Phys. JETP **42**, 989 (1975)].
[4]L.A. Vaĭnshteĭn, I.I. Sobel'man, and E.A. Yukov, Secheniya vozbuzhdeniya atomov i ionov electronami (Excitation Cross Sections of Atoms and Ions by Electrons), Nauka, Moscow (1973).
[5]A.I. Zapesochnyĭ, I.S. Aleksakhin, I.P. Zapesochnyĭ, and A.I. Imre, Pis'ma Zh. Eksp. Teor. Fiz. **29**, 231 (1979) [JETP Lett. **29**, 207 (1979)].
[6]R.P. Madden, D.L. Ederer, and K. Codling, Phys. Rev. **177**, 136 (1969).