Investigation of double ionization of inert-gas atoms by simultaneous knockout of *s* and *p* electrons by the bombarding electron beam

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We have investigated simultaneous *s* and *p* ionization of Ne, Ar, Kr, and Xe atoms by electron impact, by detecting the ultrasoft x radiation ($\lambda \sim 40$–120 nm), produced in the decay of the states $ns\ np^5$ ($^1P_1^0$, $^3P_{210}^0$) of doubly charged ions. The energy dependences and the quantitative characteristics of the investigated phenomena are studied.

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In ordinary experiments on ionization of atoms by electron impact it is practically impossible to determine the contribution of the ions produced when electrons are removed from the internal shells. For inert-gas atoms, the

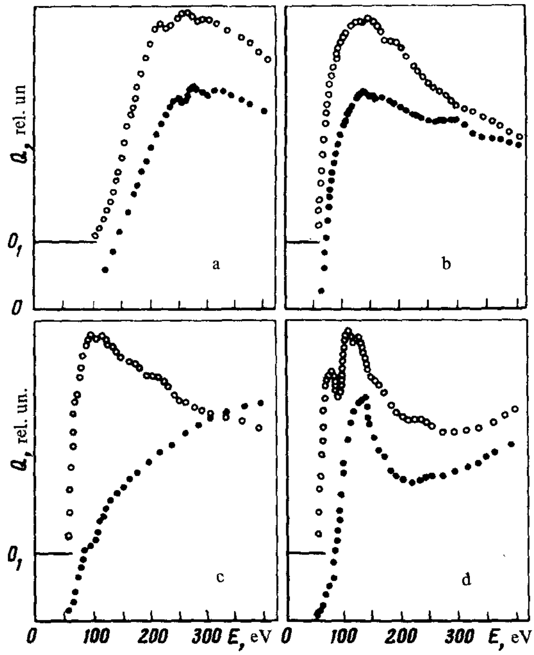

FIG. 1. Energy dependences of simultaneous s and p ionization of inert-gas atoms in triplet $^3P_j^0$ (circles) and single $^1P_j^0$ (dots) states: a—Ne, b—Ar, c—Kr, d—Xe.

process of single s ionization was investigated with the aid of the ultrasoft x rays produced when the s vacancies are filled with p electrons of the outer shell.[1,2] on the other hand, no investigations were made of processes in which s and p electrons were simultaneously knocked out when doubly-charged inert-gas ions were produced, with the exception of some data cited in[3].

We have investigated for the first time and in detail the simultaneous s and p ionization, by electron impact, of neon, argon, krypton, and xenon atoms, accompanied by emission of ultrasoft x rays (USX):

$$A(ns^2np^6) + e \rightarrow A^{++}(ns\,np^5\,{}^3P^o_{210},\ {}^1P^o_1) + 3e$$

$$\rightarrow A^{++}(ns^2np^4\,{}^3P_{210},\ {}^1D_2,\ {}^1S_0) + h\nu + 3e\ .$$

The measurements were made with a special setup using an extended ribbon-shaped electron beam.[4] The USX were detected with a vacuum-ultraviolet monochromator and a secondary-electron multiplier operating in the photoelectron counting regime. The sensitivity of the apparatus was calibrated against the data of[5], and the values of the effective cross sections were determined with an error $\pm 30\%$.

The results of the measurement of the effective cross section for the excitation of some of the most intense USX lines are listed in Table I, while Fig. 1 shows their energy dependences. Judging from the manner in which they are obtained the investigated USX lines and the behavior of their excitation cross sections with changing electron energy describe directly to a sufficient degree the elementary process of simultaneous of s and p ionization of atoms of inert gases by electron collisions.

TABLE I.

Ion	USX transition	λ, nm	E_{thr}, eV	E_{max}, eV	$Q_{max} \times 10^{19}$ cm²
Ne III	$2s\,2p^5\,{}^1P_1^o \to 2s^2 2p^4\,{}^1D_2$	37.93	98.5	278	0.4
	$2s\,2p^5\,{}^3P_2^o \to 2s^2 2p^4\,{}^3P_2$	48.95*	88.0	–	–
	$2s\,2p^5\,{}^3P_2^o \to 2s^2 2p^4\,{}^3P_1$	49.11*	88.0	–	–
	$2s2p^5\,{}^3P_1^o \to 2s^2 2p^4\,{}^3P_2$	48.81*	88.0	–	3.9
	$2s\,2p^5\,{}^3P_1^o \to 2s^2 2p^4\,{}^3P_1$	48.96*	88.0	264	–
	$2s\,2p^5\,{}^3P_1^o \to 2s^2 2p^4\,{}^3P_0$	49.03*	88.0	–	–
	$2s2p^5\,{}^3P_0^o \to 2s^2 2p^4\,{}^3P_1$	48.89*	88.1	–	–
Ar III	$3s\,3p^5\,{}^1P_1^o \to 3s^2 3p^4\,{}^1D_2$	76.92	61.3	136	1.5
	$3s3p^5\,{}^1P_1^o \to 3s^2 3p^4\,{}^3P_1$	88.74	57.5	142	1.3
Kr III	$4s\,4p^5\,{}^1P_1^o \to 4s^2 4p^4\,{}^1D_2$	78.60	56.2	400	4.2
	$4s\,4p^5\,{}^3P_1^o \to 4s^2 4p^4\,{}^3P_2$	83.77	53.4	116	3.4
Xe III	$5s\,5p^5\,{}^1P_1^o \to 5s^2 5p^4\,{}^3P_0$	90.18	48.1	108	2.7
	$5s\,5p^5\,{}^3P_2^o \to 5s^2 5p^4\,{}^3P_2$	101.77	45.5	134	7.6

*The lines were not resolved spectroscopically.

It follows from the results that these processes are characterized by a relatively high efficiency ($\sigma \approx 10^{-18}$–10^{-19} cm^2), the maxima of the cross sections increasing with increasing atomic number of the element. Transitions with a common upper level (even at different j) have for a given atom identical energy dependences. For different atoms, there are noticable differences and the levels exhibit also a definite structure, which manifests itself most pronouncedly in the case of heavy atoms.

In view of the absence of theoretical data on the investigated process, it is impossible to discuss the results in detail. Only some hypotheses can be advanced. The value of the cross section and the energy behavior of the simultaneous s and p ionization, when investigated by UMX spectroscopy, can vary as a result of radiative cascade transitions from higher excited levels to the states of the ion A^{++} ($nsnp^5\,{}^3P^0_{210}$, ${}^1P^0_1$), the decay of the autoionization states, and also configuration interaction.

It follows from the spectroscopic data[6] that radiative cascade transitions are not observed at all in neon and argon, and are quite weak in krypton and xenon. It can therefore be assumed that the cascade population does not play a noticable role. The presently known highest-lying autoionization states of the type $ns\,np^5n'l'n''l''$ and $ns\,{}^2np^4n'l'n''l''$ [7] cannot contribute to the population of the investigated states because of their energy locations. On the other hand, a configuration interaction with the states $ns^2np^3n'l'^{1,3}L$ is possible. We propose that the tendency of the heavy atoms to exhibit more pronounced maxima is due precisely to the decrease of the energy spacing between the interacting levels, i.e., to a manifestation of configuration interaction.

On the basis of the foregoing, it must be assumed that only in the case of neon does simultaneous *s* and *p* ionization appear in purest form. In the case of the other inert gases it is probably masked to one or another degree by configuration interaction.

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