SIMULTANEOUS EXCITATION AND IONIZATION OF RARE GAS ATOMS BY AN ELECTRON IMPACT. ARGON

V.-F.Z. PAPP, L.L. SHIMON, M.M. POVCH

Uzhgorod National University, Faculty of Physics
(54, Voloshyna Str., Uzhgorod 88000, Ukraine; e-mail: vidor@vpapp.com)

UDC 539.186.2; 539.184.52

The processes of single and double ionizations of argon atoms using its excitation by an electron impact have been investigated experimentally. The effective cross-sections of the spectral line excitations from levels $3s^13p^6$, $3p^44s$, $3p^44s'$, $3p^44s''$, $3p^43d$, $3p^43d'$, and $3p^43d''$ of the ArII configuration and level $3s^13p^5$ of the ArIII one have been studied in the electron energy interval from the excitation threshold up to 400 eV. The mechanism of populating the corresponding energy levels through radiative cascade transitions and the Auger-decay of autoionization levels is discussed, as well as an opportunity to determine the partial cross-sections of s- and sp-ionization.

This work, being a continuation of the researches of the electron excitation of vacuum ultraviolet (VUV) lines of inert gas atoms [1], is devoted to a study of the effective cross-sections of spectral line excitations of singly and doubly charged ions of argon at electron-atom collisions. The researches of the excited ion transitions onto the ground energy level were carried out earlier in a few works [2—7]. However, those investigations were done under different experimental conditions, significant divergences between the derived values of excitation probabilities were observed, they are not full enough, and so on. For example, a considerable number of the spectral lines of a singly charged ion were investigated in [3, 4], but the structure of the excitation functions was not established precisely, only the $3p$-ionization with excitation and the $3s$-electron detachment were studied. A simultaneous knocking out of two $3s$- and $3p$-electrons in a single collision event was not observed at all. In [5], only the excitation functions of lines λ91.98 nm ($3s^13p^6\ ^2S_{1/2} \rightarrow 3p^5\ ^2P_{3/2}$ ArII) are presented. Despite a good energy resolution, the researches were carried out in a narrow area of the energy of electrons which ionize and excite the argon. In [4, 6, 7], on the contrary, the wide energy interval, from the excitation threshold up to 1.5 keV, was investigated, but the results were obtained at the low monoenergeticity of electrons and the insufficient structure resolution by the excitation functions. All this gives no opportunity to thoroughly analyze the mechanism of excitation of ArII spectral lines and to reveal the role of additional processes, for example, the Auger-decay of various autoionization states, including those with a participation of internal electrons and the occupation of the top level of a spectral transition.

In this work, the researches of the effective cross-sections and excitation functions of the principal, by intensity, spectral lines of singly and doubly charged ions of argon, which appear due to the detachment of one and excitation of another $3p$-electrons of the atom, and to the simultaneous detachments of one $3s$- and one $3p$-electrons in the same collision event with electrons, were carried out provided the identical conditions of experiments. Moreover, the analysis of the possible contributions of inner shells and various autoionization states to the probability of excitation of a certain energy level was done.

1. Experimental Conditions

For carrying out the researches, the experimental installation, which was described in detail in our previous works [1, 8], was used. We note only that, in contrast to the researches of other authors, in order to obtain a sufficiently large desired signal in measurements, the electron beam was formed with the help of a four-electrode gun as a tape 20 mm in length. The energy nonhomogeneity of 90% of electrons did not exceed 1—1.5 eV.

The collision chamber was pumped out by an oil-free sorption pump down to the vacuum $p \leq 5 \times 10^{-7}$ Pa. The pressure of argon in the collision space was $p < 5 \times 10^{-2}$ Pa. The excitation functions were studied in the spectral region $\lambda\lambda$35—200 nm. The relative errors of the measurements were 2—3% for the spectral line intensities and 25—30% for the absolute values of the effective cross-sections.

2. Experimental Results and their Discussion

Similarly to the neon case [1], the VUV emission at electron energies $E > 100$ eV in the beam consists mainly of the spectral lines of singly and doubly charged ions. Most of the lines appear due to the simultaneous detachment of one and an excitation of the next $3p$-electrons, to the excitation of the resonant level of an argon atom and of the lines that are emitted after the removal of a $3s$-electron. Appreciable by intensity are also the lines which appear owing to the simultaneous detachments of one $3s$- and one $3p$-electrons. In this work, the effective cross-sections of excitations of the majority of the lines, which belong to the mentioned types of transitions, were investigated.

1. After the detachment of one $3p$-electron and the excitation of another $3p$-electron in the same collision event, an ion of Ar is appeared in any $3p^4n'l'$ state of the electron configuration:

$$\begin{aligned} \mathrm{Ar}(3s^2 3p^6) + \mathrm{e} \rightarrow \quad & \mathrm{Ar}^{+*}(3s^2 3p^4 n'l') + 2\mathrm{e} \\ & \downarrow \\ & \mathrm{Ar}^{+}(3s^2 3p^5) + h\nu. \end{aligned} \tag{1}$$

Due to the peculiarities of the energy level structure of a singly charged Ar ion, the VUV spectrum of emission consists of a lot of closely located lines, the overwhelming majority of which we managed to resolve spectroscopically. The excitation functions for the principal spectral lines which are emitted from levels $3p^44s$, $3p^44s'$, $3p^44s''$, $3p^43d$, $3p^43d'$, $3p^43d''$, and other configurations are shown in Fig. 1, with the values of their effective cross-sections being quoted in the table.

The line excitation functions from levels $3p^44s$ of the configuration are shown in Fig. 1,*a*. It is seen that, for λ72.34 nm ($4s\ ^2P_{3/2} \rightarrow 3p^5\ ^2P^{\circ}_{3/2}$) and λ72.56 nm ($4s\ ^2P_{1/2} \rightarrow 3p^5\ ^2P^{\circ}_{1/2}$), the presence of two maxima in the energy ranges of 50—60 and 80—100 eV, respectively, is typical. Those excitation functions were studied earlier [4], and an idea was suggested that this form of curves is characteristic of the ionization and ionization-with-excitation processes. In that case, the process of ionization is described by the maximum in the region of 80—100 eV, with the first peak being connected to autoionization effects. The analysis of our experimental data and of the known results of photoelectron researches concerning the energy arrangement of autoionization levels confirms, in general, such an explanation of the curve structure origin. The relevant autoionization states can be the $3s^13p^5n'l'$ and $3s^13p^5n'l'n''l''$ states. However, it is impossible to determine the absolute value of the contribution of each specific state precisely because of the lack of enough data on the probabilities of decay of autoionization states through different channels. Moreover, as was shown in [3, 4], a radiative cascade population from the $3p^44s$-configuration levels can play a significant role in occupying the top level of the spectral transition from the levels of the $3p^44s$ configuration. In some cases, the contribution of such a process can achieve 70%. Thus, one may unequivocally assert only that for the lines, which belong to the transitions from levels $4s\ ^2P_{3/2,1/2}$, the existence of two equal by amplitude maxima is typical, i.e. the contributions of the autoionization processes and of the direct ionization process are approximately equal. On the contrary, for the lines which correspond to the transitions from quartet levels, e.g., λ74.49 nm ($4s\ ^4P_{5/2} \rightarrow 3p^5\ ^2P^{\circ}_{3/2}$) (see panel *a*, curve *3*), the maximal value of the effective excitation cross-section is observed at $E = 52$ eV.

The excitation function of the line λ67.19 nm ($4s'\ ^2D_{5/2} \rightarrow 3p^5\ ^2P^{\circ}_{3/2}$) (panel *b*, curve *2*) has the maximal value at $E = 53$ eV, while, for the lines which correspond to the transitions from the $4s''\ ^2S_{1/2}$ level, e.g., λ59.78 nm ($4s''\ ^2S_{1/2} \rightarrow 3p^5\ ^2P^{\circ}_{3/2}$) (panel *b*, curve *1*), a cusp on the curve clearly manifests itself at that energy value, and the effective cross-section reaches the maximal value at the much greater value of the electron energy, $E = 104$ eV. The characters of the excitation functions which correspond to transitions from levels $3p^44s'$ and $3p^44s''$ are therefore different. On the basis of the well-known data [3, 4], it is possible to come to a conclusion that the cascade contribution for levels $4s'\ ^2D_j$ is considerably smaller than that for levels $4s\ ^2P_{3/2,1/2}$ and amounts to 15–25%. However, the configuration interaction with the $3d\ ^2D_j$ levels can appreciably affect the excitation of the specified state.

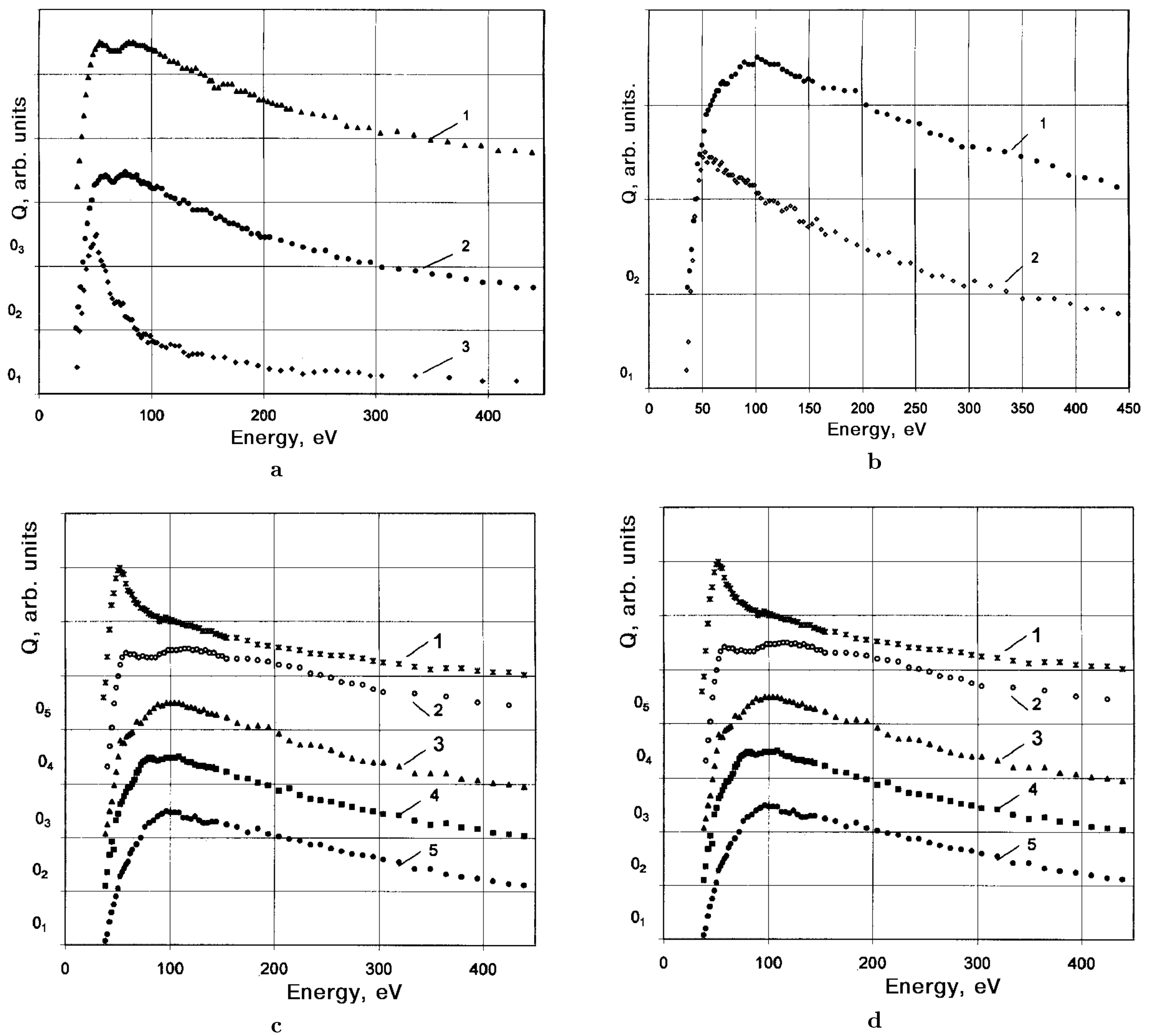

Fig. 1. Excitation functions of the ArII lines which correspond to the transitions from the levels: a — $4s\ ^2P_{3/2}$ (λ72.34 nm) (*1*), $4s\ ^2P_{1/2}$ (λ72.56 nm) (*2*), and $4s\ ^4P_{5/2}$ (λ74.49 nm) (*3*); b — $4s''\ ^2S_{1/2}$ (λ59.78 nm) (*1*) and $4s'\ ^2D_{5/2}$ (λ67.19 nm) (*2*); c — $3d\ ^4F_{5/2}$ (λ69.88 nm (*1*), λ70.45 nm (*2*)), $3d\ ^2F_{5/2}$ (λ66.6 nm) (*3*), and $3d\ ^2D_{5/2}$ (λ66.19 nm) (*4*); d — $3d'\ ^2F_{5/2}$ (λ61.24 nm) (*1*), $3d''\ ^2D_{5/2}$ (λ55.68 nm) (*2*), $3d'\ ^2D_{3/2}$ (λ58.34 nm) (*3*), $3d'\ ^2D_{5/2}$ (λ58.03 nm) (*4*), and $3d'\ ^2P_{3/2}$ (λ57.34 nm) (*5*)

The excitation functions of the lines, which correspond to transitions from the $3p^43d$, $3p^43d'$, and $3p^43d''$ configurations, are of special interest because, due to their high energy position, the radiative cascade contribution of the $3p^4np$ states should be significantly smaller than that of the $3p^44s$ ones, and the values of the effective cross-sections of the spectral lines should be close to those of the corresponding energy levels. The excitation functions of the relevant spectral lines are shown in panel c. One can see that the absence of any structure of the excitation function and a well-defined maximum in a narrow interval of energies of 50—55 eV are typical of all the spectral lines from levels $3d(^4F_{5/2}$, $^4F_{3/2}$, $^2F_{5/2}$, $^2D_{5/2})$.

A different behavior of excitation curves is observed for the spectral lines from levels $3p^4 3d'$ of the configuration (panel d). The maximum at 52 eV stands out for the line excitation functions from the doublet $^2F_{5/2}$ states of the λ61.24 nm ($3d'\ ^2F_{5/2} \rightarrow 3p^5\ ^2P^\circ_{3/2}$) transition (curve *1*), while for the λ58.34 nm ($3d'\ ^2D_{3/2} \rightarrow 3p^5\ ^2P^\circ_{1/2}$) (curve *3*), λ58.03 nm ($3d'\ ^2D_{5/2} \rightarrow 3p^5\ ^2P^\circ_{3/2}$) (curve *4*), and λ57.34 nm ($3d'\ ^2P_{3/2} \rightarrow 3p^5\ ^2P^\circ_{3/2}$) (curve *5*) transitions a broad maximum at 100 eV and a cusp at smaller energies is typical. Line λ55.68 nm ($3d''\ ^2D_{3/2} \rightarrow 3p^5\ ^2P^\circ_{3/2}$) (curve *2*) attracts a special attention. In addition to two maxima at $E = 58$ and 114 eV, a slow decrease of the effective cross-section and a weak manifestation of a broad maximum at the energy $E > 200$ eV are observed as the electron energy increases. Such a behavior of the curve can be connected to the influence of autoionization states located above.

Thus, three types of excitation functions are observed for the $3p$-ionization with excitation: (i) with two equal maxima (panel a, curve *1*), (ii) with a well-defined maximum at 48—60 eV (panel c, curves *1—4*), and (iii) with a cusp at 50—60 eV and a maximum near to 100 eV (panel d, curves *4* and *5*). Such a behavior of the curves is probably connected to different relations between the probability of the basic ionization-with-excitation process and that of additional processes of occupying the top levels of the spectral transition, namely, the decay of autoionization states located above and the configuration interaction of the levels. The exact analysis appears to be impossible in each specific case due to the lack of the data concerning the absolute values of the probabilities of the additional processes indicated above.

The absolute values of the effective cross-sections of the spectral lines from levels $3p^4nl$ of the configurations (see the table) vary in wide limits, from 7×10^{-20} to 2.2×10^{-18} cm^2.

2. In Fig. 2, the excitation function of the spectral line λ91.98 nm $Ar^+(3s^1 3p^6\ ^2S_{1/2} \rightarrow 3p^5\ ^2P_{3/2})$, which is a source of information about the partial effective cross-section of a single ionization of an argon atom, due to a detachment of the $3s$-electron by an electron impact,

$$\begin{aligned} \mathrm{Ar}(3s^2 3p^6) + \mathrm{e} \rightarrow\ & \mathrm{Ar}^{+*}(3s^1 3p^6\ ^2S_{1/2}) + 2\mathrm{e} \\ & \downarrow \\ & \mathrm{Ar}^+(3s^2 3p^5) + h\nu_1 \end{aligned} \quad (2)$$

is presented. In occupying the top $3s^1 3p^6\ ^2S_{1/2}$ level, the accompanying processes, namely the Auger-decay of the autoionization levels located above and the radiative cascade transitions, may play a certain role as well.

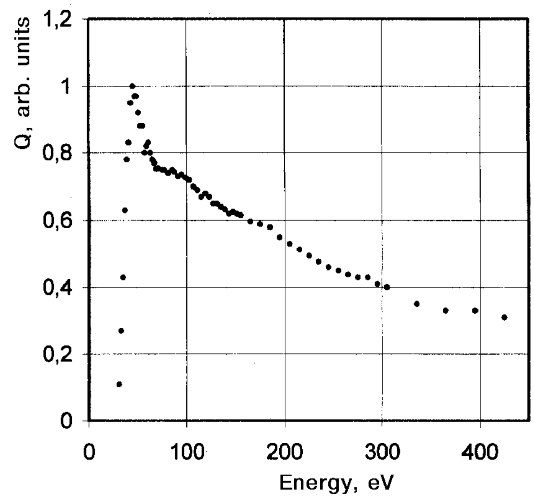

Fig. 2. Excitation function of the λ91.98 nm line which corresponds to the transition from the level $3s3p^6\ ^2S_{1/2}$

The analysis of the energy spectrum of the autoionization levels and the channels of their decay makes it possible to suggest that, at energy of 48—50 eV, excitations $3s^1 3p^5 n'l'$ of the autoionization states may probably be of some importance. As to the $3s^1 3p^6\ ^2S_{1/2}$ state, its radiative population occurs through transitions from levels $3p^4 4p'$ (λ154.74, λ156.02, λ157.5 nm) and $3p^4 4p$ (λ194.1, λ197.3, λ214.3 nm). Their contribution, according to the data on the effective cross-sections of the corresponding spectral lines, is rather small, being no more than 10%. Theoretical calculations showed [7] that the excitation $3s^1 3p^6\ ^2S_{1/2}$ of the ArII configuration is affected by a configuration interaction with levels $3s^2 3p^4 3'd'\ ^2S_{1/2}$ and $3s^2 3p^4 3'd'\ ^2S_{1/2}$ of the ArII configuration and with other levels of the $3s^2 3p^4 n'l'$ type. Therefore, the function of the λ91.98 nm excitation does not describe the direct detachment of a $3s$-electron, i.e. the $3s$-ionization, precisely.

Note that the excitation of ionic autoionization levels with the subsequent cascade radiative transition, for example,

$$\mathrm{Ar}^+(3s^1 3p^5 n'l') \rightarrow \mathrm{Ar}^+(3s^1 3p^6) + h\nu, \quad (3)$$

may also be of some importance, in principle. Theoretical calculations showed [9] that such transitions do exist. However, the Auger-decay of the $Ar^+(3s^1 3p^5 n'l')$ states is more probable than the radiative one and, consequently, the contribution of processes (3) should be considered insignificant.

The absolute value of the effective cross-section of excitation λ91.98 nm ArII at the energy of incident electrons of 100 eV equals 6.8×10^{-18} cm^2. It should be noted that the function of the λ91.98 nm excitation was studied in several works, for example, [3, 5–7]. The form of the curve in Fig. 2 agrees satisfactorily with the results of [2—7], i.e. two maxima are observed. But a discrepancy between the absolute values of the cross-section obtained by different authors in some cases exceeds 100%.

3. At the inelastic collision of an argon atom with an electron, the simultaneous detachment of one $3s$- and one $3p$-electrons may take place, i.e. there is the formation of a two-charge ion in an energy state, whose relaxation is realized only through a transition to the ground state of a two-charge ion:

$$\begin{aligned} \mathrm{Ar}(3s^2 3p^6) + \mathrm{e} \rightarrow \quad & \mathrm{Ar}^{++*}(3s^1 3p^5\ {}^1P_1, {}^3P_{210}) + 3\mathrm{e} \\ & \downarrow \\ & \mathrm{Ar}^{++}(3s^2 3p^4\ {}^1S_0, {}^1D_2, {}^3P_{210}) + h\nu_3. \end{aligned} \tag{4}$$

We have studied the effective cross-sections of the spectral lines which are emitted in reaction (4), and

Effective excitation cross-sections of the spectral lines of Ar ions

Element	Transition	Wavelength λ, nm	E_{thresh} of excitation, eV	$E_{\max}$ of excitation, eV	$Q_{\max} \times 10^{19}$, cm^2
ArII	$4s\ {}^2P_{3/2} \rightarrow 3p^5\ {}^2P^{\circ}_{3/2}$	72.34	32.9	56	22
	$4s\ {}^2P_{3/2} \rightarrow 3p^5\ {}^2P^{\circ}_{1/2}$	73.09	32.9	56	2.8
	$4s\ {}^2P_{1/2} \rightarrow 3p^5\ {}^2P^{\circ}_{3/2}$	71.81	33.0	60	3.6
	$4s\ {}^2P_{1/2} \rightarrow 3p^5\ {}^2P^{\circ}_{1/2}$	72.56	33.0	60	6.5
	$4s\ {}^4P_{5/2} \rightarrow 3p^5\ {}^2P^{\circ}_{3/2}$	74.49*	32.4	52	15
	$4s\ {}^2P_{3/2} \rightarrow 3p^5\ {}^2P^{\circ}_{3/2}$	74.82	32.5	52	1.8
	$4s\ {}^2P_{1/2} \rightarrow 3p^5\ {}^2P^{\circ}_{3/2}$	74.53*	32.6		
	$4s'\ {}^2D_{5/2} \rightarrow 3p^5\ {}^2P^{\circ}_{3/2}$	67.19	34.2	53	20
	$4s'\ {}^2D_{3/2} \rightarrow 3p^5\ {}^2P^{\circ}_{3/2}$	67.29	34.2	54	0.7
	$4s'\ {}^2D_{3/2} \rightarrow 3p^5\ {}^2P^{\circ}_{1/2}$	67.94**	34.2	54	11
	$4s''\ {}^2S_{1/2} \rightarrow 3p^5\ {}^2P^{\circ}_{3/2}$	59.78	36.5	104	7.2
	$4s''\ {}^2S_{1/2} \rightarrow 3p^5\ {}^2P^{\circ}_{1/2}$	60.29	36.5	105	5.3
	$3d\ {}^2D_{5/2} \rightarrow 3p^5\ {}^2P^{\circ}_{3/2}$	66.19	34.4	54	11
	$3d\ {}^2F_{5/2} \rightarrow 3p^5\ {}^2P^{\circ}_{3/2}$	66.60	34.4	50	5
	$3d\ {}^4P_{1/2} \rightarrow 3p^5\ {}^2P^{\circ}_{3/2}$	67.92**	34.0		
	$3d\ {}^4\mathrm{F}_{5/2} \rightarrow 3\mathrm{p}^5\ {}^2\mathrm{P}^{\circ}_{3/2}$	69.88	33.5	49	6.5
	$3d\ {}^4F_{3/2} \rightarrow 3p^5\ {}^2P^{\circ}_{1/2}$	70.45	33.5	52	2.6
	$3d'\ {}^2P_{3/2} \rightarrow 3p^5\ {}^2P^{\circ}_{3/2}$	57.34	37.4	96—102	9.5
	$3d'\ {}^2P_{3/2} \rightarrow 3p^5\ {}^2P^{\circ}_{1/2}$	57.81***	37.4	96—102	6.3
	$3d'\ {}^2D_{5/2} \rightarrow 3p^5\ {}^2P^{\circ}_{3/2}$	58.03	37.1	103	14.1
	$3d'\ {}^2D_{3/2} \rightarrow 3p^5\ {}^2P^{\circ}_{1/2}$	58.34	37.2	103	6.8
	$3d'\ {}^2D_{3/2} \rightarrow 3p^5\ {}^2P^{\circ}_{3/2}$	57.86***			
	$3d'\ {}^2F_{5/2} \rightarrow 3p^5\ {}^2P^{\circ}_{3/2}$	61.24	36.0	52	8
	$3d''\ {}^2D_{3/2} \rightarrow 3p^5\ {}^2P^{\circ}_{3/2}$	55.68	38	58; 114	2.4
ArII	$3s^1 3p^6\ {}^2S_{1/2} \rightarrow 3p^5\ {}^2P^{\circ}_{3/2}$	91.98	29.2	42	68
	$3s^1 3p^6\ {}^2S_{1/2} \rightarrow 3p^5\ {}^2P^{\circ}_{1/2}$	93.21	29.2	42	38
	$3s^1 3p^5\ {}^1P^{\circ}_1 \rightarrow 3p^4\ {}^1D_2$	76.92	61.3	136	1.5
	$3s^1 3p^5\ {}^3P^{\circ}_2 \rightarrow 3p^4\ {}^3D_2$	100.21	57.5	142	0.39
	$3s^1 3p^5\ {}^3P^{\circ}_2 \rightarrow 3p^4\ {}^3P_2$	87.87	57.5	142	2.1
	$3s^1 3p^5\ {}^3P^{\circ}_2 \rightarrow 3p^4\ {}^3P_1$	88.74	57.5	142	1.3
ArIII	$3s^1 3p^5\ {}^3P^{\circ}_1 \rightarrow 3p^4\ {}^1S_0$	120.6	57.7	142	0.1
	$3s^1 3p^5\ {}^3P^{\circ}_1 \rightarrow 3p^4\ {}^3P_2$	87.11	57.7	142	1.1
	$3s^1 3p^5\ {}^3P^{\circ}_1 \rightarrow 3p^4\ {}^3P_1$	87.96	57.7	142	1.0
	$3s^1 3p^5\ {}^3P^{\circ}_1 \rightarrow 3p^4\ {}^3P_0$	88.32	57.7	142	1.0
	$3s^1 3p^5\ {}^3P^{\circ}_0 \rightarrow 3p^4\ {}^3P_0$	87.55	57.8	142	1.3

N o t e. Lines, denoted by identical combinations of asterisks, were not resolved from one another spectroscopically

 ISSN 0503-1265. Ukr. J. Phys. 2004. V. 49, N 12

the mechanism of the double $3s3p$-ionization has been analyzed.

Typical excitation functions are shown in Fig. 3, and the values of excitation probability are listed in the table. Provided the other processes are absent, the effective excitation cross-sections of spectral lines $\lambda 76.92$ and $\lambda 88.74$ nm reproduce the probability of excitation of the energy levels $\mathrm{Ar}^{++*}(3s^1 3p^5\ {}^1P_1,\ {}^3P_2)$, i.e. of a direct removal of the $3s$- and $3p$-electrons in a single event of electron-atom collision. However, the behavior of the excitation functions of spectral lines $\lambda 76.92$ from the singlet level and $\lambda 88.74$ nm from the triplet one is somewhat different (Fig. 3, curves *1* and *2*). A broad maximum is observed for $\lambda 76.92$ nm at energies $E > 250$ eV. As is well known from photoelectron spectrometric experiments [10], there is a numerous group of autoionization states in this energy region. The analysis of the possible channels of their decay shows that, at the energy of an electronic beam appreciably greater than the threshold value of excitation of levels $\mathrm{Ar}^{++*}(3s^1 3p^5\ {}^1P_1,\ {}^3P_2)$, the $3s3p$-ionization does not run completely through the channel of a "direct detachment" of electrons. The top level of transition (4) can be partially populated through excitation and the Auger-decay of the $\mathrm{Ar}^{+*}\ [3s^1 3p^5\ ({}^1P_1)nl]$ ionic autoionization states. For example, according to theoretical calculations [9], the Auger-transition

$$\mathrm{Ar}^{+*}[3s^1 3p^5\ ({}^1P_1)nl] \to \mathrm{Ar}^{++*}(3s^1 3p^5\ {}^3P_j) + \mathrm{e}_{\mathrm{Auger}}$$

is of some importance for the triplet $\mathrm{Ar}^{++}(3s^1 3p^5\ {}^3P_j)$ levels, while the decay of the singlet $\mathrm{Ar}^{++}(3s^1 3p^5\ {}^1P_1)$ energy state is accompanied by an emission from the autoionization state with a double vacancy in the $3s$-shell: $\mathrm{Ar}^{++}(3s^0 3p^6\ {}^1S_0) \to \mathrm{Ar}^{++}(3s^1 3p^5\ {}^1P_1) + h\nu$. The contribution of such a transition can be appreciable, contrary to a similar transition in the atom of neon, because state $3s^0 3p^6\ {}^1S_0$ is undoubtedly excited at the collision of an electron with the atom, and the indicated transition is a single way of its relaxation (similar processes of creating and occupying the double vacancy in the ns-shell take place also for krypton and xenon). But, unfortunately, it is impossible to discuss the role of this process at the quantitative level now, because the experimental data on the effective excitation cross-sections of the specified level are absent.

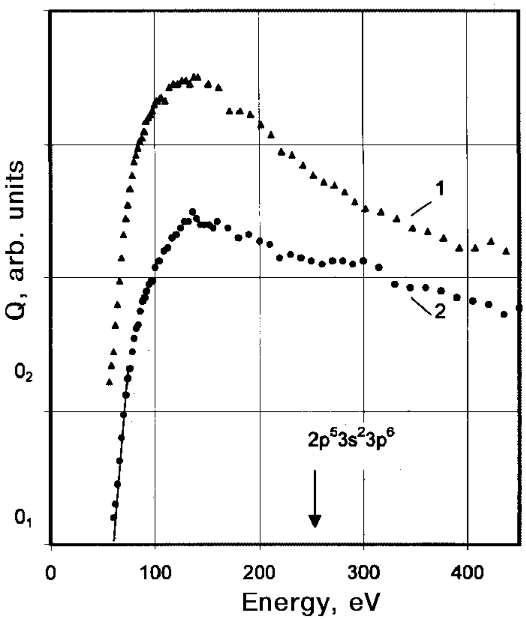

Fig. 3. The same as in Fig. 1 but for the levels $3s^1 3p^5\ {}^1P_1$ ($\lambda 76.92$ nm) (*1*) and $3s^1 3p^5\ {}^3P_2$ ($\lambda 88.74$ nm) (*2*)

On the basis of the spectroscopic data concerning the distribution of energy levels, experimental results, and theoretical calculations of the argon atom photoionization, one may assume that, when considering the occupying of level $3s^1 3p^5\ {}^1P_1$, it is possible, in principle, to take into account the contributions of other radiative cascade transitions and the decay of highly located autoionization states. However, the allowed transitions of the $3s^2 3p^3 n'l'\ {}^1L_j \to 3s^1 3p^5\ {}^1P_1 + h\nu$ type have not been observed experimentally. The relevant spectroscopic lines must be of low intensity, and, consequently, those transitions are not essential in the additional populating of the $3s^1 3p^5\ {}^1P_1$ level.

The population of the $3s^1 3p^5\ {}^1P_1$ level can be influenced by the $3s^0 3p^6 n'l'n''l''$ ArI and $3s^0 3p^6 n'l'$ ArII states, as well as by those connected with the excitation or withdrawal of the $2p$-electron, namely, the $2p^5 3s^2 3p^6 n'l'$ ArI and $2p^5 3s^2 3p^6$ ArII ones. It is confirmed, as has been already indicated above, by an observable maximum of the excitation function of line $\lambda 76.92$ nm Ar^{++*} in the energy region of ~ 250 eV, which may be connected to the process

$$\begin{array}{ll} \mathrm{Ar}(3s^2 3p^{6\,1}S_0) + \mathrm{e} \to & \mathrm{Ar}^{+}(2p^5 3s^2 3p^{6\,2}P_j) + 2\mathrm{e} \\ & \downarrow \\ & \mathrm{Ar}^{++*}(3s^1 3p^{5\,1}P_1) + \mathrm{e} \to \mathrm{Ar}^{++}(3s^2 3p^{4\,1}D_2) + h\nu. \end{array} \qquad (5)$$

One should not also exclude an opportunity of the excitation of the atomic level $2p^53s^23p^6n'l'$ ArI with a subsequent Auger-transition:

$$\mathrm{Ar}(2p^53s^23p^6n'l') \rightarrow \mathrm{Ar}^{++*}(3s^13p^5\ ^1P_1) + 2\mathrm{e}. \qquad (6)$$

The detailed analysis of the mechanism of the double ionization of the argon atom through the withdrawal of one $3s$- and one $3p$- electrons requires the experimental data on the effective cross-sections of autoionization state excitations and the probabilities of the Auger-transitions by different channels. Note also that the ionic autoionization states $\mathrm{Ar}^+(ns^1np^5n'l')$ can occupy a number of levels [9]. The radiative transitions are possible directly onto the levels that are connected to the $3p$-ionization with excitation $[\mathrm{Ar}^+(ns^1np^5n'l') \rightarrow \mathrm{Ar}^+(ns^2np^4n'l') + h\nu]$, the $3s$-ionization $[\mathrm{Ar}^+(ns^1np^5n'l') \rightarrow \mathrm{Ar}^+(ns^1np^6) + h\nu]$, etc.

One can see that the efficiency of ionization is relatively high. At the electron energy E = 100 eV, it reaches the value of 1.5×10^{-19} cm^2 for $\mathrm{Ar}^{++*}(3s^13p^5\ ^1P_1)$ and 3.79×10^{-19} cm^2 for $\mathrm{Ar}^{++*}(3s^13p^5\ ^2P_1)$.

Conclusions

The excitation functions of the main spectral lines, which are irradiated from levels $3p^44s$, $3p^44s'$, $3p^44s''$, $3p^43d$, $3p^43d'$, and $3p^43d''$ of the configurations are characterized by three types of curves: with a single maximum at 50-60 eV, two maxima at 50—60 and 100 eV, and a single maximum at 100 eV. The following processes influence appreciably the values of the effective excitation cross-sections of the corresponding levels: the radiative cascade population, the Auger-decay of higher located autoionization energy states, and the configuration interaction of levels. The maximal absolute value of the effective cross-section is observed for the spectral line λ72.34 nm, which corresponds to transitions from the $4s\ ^2P_{3/2}$ level.

The energy dependence of the effective excitation cross-sections of the λ91.18 and λ93.2 nm spectral lines of the singly charged argon is influenced by the interaction with levels $3s^23p^43'd'\ ^2S_{1/2}$ and $3s^23p^43'd'\ ^2S_{1/2}$ and by a decay of the located above $3s^13p^5nln'l'$, $3s^13p^5n'l'$ and other autoionization states. Therefore, the above-mentioned functions do not reproduce the function of the Ar $3s$-ionization in pure form, and the effective cross-section of the $3s^13p^6\ ^2S_{1/2}$ level is not a partial cross-section of the s-ionization of the argon atom.

The excitation functions of the λ76.92 and λ88.74 nm spectral lines reproduce, as a whole, the energy dependence of the excitations of levels $\mathrm{Ar}^{++*}(3s^13p^5\ ^1P_1,\ ^3P_2)$, i.e. of the direct withdrawal of $3s$- and $3p$-electrons at a single collision event . However, the population of the $3s^13p^5\ ^1P_1$ level can grow due to the radiative transitions from the $3s^03p^6\ ^1S_0$ level and the Auger-decay of the $3s^03p^6n'l'$ ArII and $3s^03p^6n'l'n''l''$ ArI states. At the energy $E > 250$ eV, some effect is induced by the excitation and decay of the $2p^53s^23p^6n'l'$ ArI and $2p^53s^23p^6$ ArI levels, which are connected to the excitation or withdrawal of $2p$-electrons. An additional process that makes contribution to a populating of the $\mathrm{Ar}^{++*}(3s^13p^5\ ^3P_2)$ level, is, probably, the Auger-decay of the autoionization states located above, e.g., the valence-multiplet transition $2s^12p^5(^1P_1)n'l' \rightarrow 2s^12p^5(^3P_j) + \hat{\mathrm{e}}$.

The energy dependences of the effective excitation cross-sections of the top $3p^5\ ^3P_j^\circ$ and $3p^5\ ^1P_1^\circ$ states do not reproduce the partial cross-section of the sp-ionization in the considered energy interval.

The absolute values of the effective cross-sections of the studied processes are relatively large, with the removal of the internal $3s$-electron being more effective by a factor of almost 10 as compared to the simultaneous detachment of $3s$- and $3p$-electrons in a single collision event.

1. *Papp V.-F. Z., Shimon L. L., Povch M. M.* // Ukr. Fiz. Zh.— 2001.— N 4. — P. 462—468.
2. *Ajello J.M., James G.K., Franklin B., Howell S.* // J. Phys. B: Atom. Mol. Opt. Phys.—1990.— **23**.— P. 4355—4376.
3. *Tan K.H., Donaldson F.G., McConkey J.W.* // Can. J. Phys.— 1974.— **52**.—P. 786—794.
4. *Tan K.H., McConkey J.W.* // Phys. Rev. A.— 1974.— **10**, N 4.— P. 1212—1222.
5. *Zapesochnyi I.P., Zhukov I.G., Feltsan P.V.* // Zh. Eksp. Teor. Fiz.— 1973.— **65**, N 4(10).— P. 1357—1366.
6. *Luyken B.F., Baas R.C., de Heer F.J.* // VII ICPEAC: Abstr., Amsterdam, 1971.— P. 726—727.
7. *Luyken B.F., de Heer F.J., Baas R.C.* // Physica.— 1972.— **61**, N 2.— P. 200—219.
8. *Papp V.F.Z.* // Nauk. Visn. Uzhgorod. Univ. Ser. Fiz.— 1999.— N 5.— P. 99—104.
9. *Armen G.B., Larkins F.P.* // J. Phys. B: Atom. Mol. Opt. Phys.— 1991.— **24**.— P. 741—759.
10. *Hayaishi T., Murakami E., Yagishita A. et al.* // Ibid.— 1988.— **21**.— P. 3203—3209.

Received 14.01.04.
Translated from Ukrainian by O.I.Voitenko

ІОНІЗАЦІЯ ЗІ ЗБУДЖЕННЯМ АТОМІВ ІНЕРТНИХ ГАЗІВ ЕЛЕКТРОННИМ УДАРОМ. АРГОН

В.-Ф.З. Папп, Л.Л. Шимон, М.М. Повч

Р е з ю м е

Експериментально досліджено процеси одно- і двократної іонізації зі збудженням атома аргону електронним ударом. Вивчено ефективні перерізи збудження спектральних ліній з рівнів $3s^13p^6$, $3p^44s$, $3p^44s'$, $3p^44s''$, $3p^43d$, $3p^43d'$, $3p^43d''$ конфігурацій ArII і $3s^13p^5$ ArIII в інтервалі енергій електронів від порога до 400 еВ. Обговорено механізм заселення відповідних рівнів шляхом каскадних переходів і розпаду автоіонізаційних рівнів, а також можливість визначення парціальних перерізів *s*- і *sp*-іонізації.