Energy distribution of electrons emitted by argon atoms under electron impact

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The absolute values of the differential cross sections for electron emission in collisions between fast electrons and argon atoms are measured by means of a cylindrical electrostatic mirror. The measurements are performed for incident electron energies of 50–2000 eV and an electron emission angle of 54.5°. Data on the total cross sections for excitation of the argon L shell by electron impact are presented which are obtained by integrating the structure corresponding to Auger transitions over the emitted electron energy and solid angle.

INTRODUCTION

Information on the energy distribution of electrons produced when gas atoms are ionized by electron impact plays an important role in the development of ideas concerning the mechanism of inelastic electron-atom collisions and, is at the same time very useful for a large number of practical applications. Many experimental data on the energy distribution of the electrons were obtained recently[1-9]. In a number of studies[1-6], principal attention was paid to the study of the energy-spectrum structure connected with the auto-ionization and Auger transitions. The authors confined themselves in this case to data expressed in relative units. In other investigations[7-9] they measured the absolute values of the differential cross sections for the production of electrons in collisions of fast electrons with atoms of different gases. However, the absolute values of the cross sections were determined by normalizing the experimental data to the known values of the total ionization cross sections. This method entails inevitable errors due to the ambiguity of the extrapolation of the energy-distribution curves into the region of zero values of the electrons and the values of the emission angle near 0 and 180°, a region inaccessible to measurements.

It was the purpose of the present study to determine independently the absolute values of the differential cross sections for the production of electrons without using a normalization procedure. In addition, a study of the structure part of the spectrum has yielded information on the total cross sections for the excitation of the internal shell of the target atom. In the case of isotropic angular distribution of the Auger electrons, it was possible to make do with measurements at only one value of emission angle.

The investigated object was the argon atom. The energy E_0 of the bombarding electrons ranged from 50 to 2000 eV, and the electrons were emitted at an angle $\theta = 54.5°$ relative to the axis of the primary beam. The measurements were performed in an emitted-electron energy range from $E_e = 3$ eV to a certain value determined by the sensitivity of the instrument and by the conditions under which it was possible to neglect the contribution of the scattering of the bombarding electrons. The experimental procedure was analogous to that described by us earlier[10]. The electron energy analyzer was a cylindrical electrostatic mirror with a resolution $\alpha = \Delta E_e/E_e = 0.7\%$. The secondary-electron detector operated in a regime where individual particles were counted.

The absolute values of the differential cross sections were determined from the formula

$$\frac{d^2\sigma}{dE_e\,d\Omega} = \frac{3\cdot 10^{-17}}{p\eta\alpha E_e}\left[\left(\frac{i_e}{I_0}\right)_e - \left(\frac{i_e}{I_0}\right)_b\right] \Big/ \int l\,d\Omega \ [\mathrm{cm^2/eV\text{-}sr}],$$

where p is the pressure of the investigated gas in the collision chamber, l is the length of the region where the electrons were gathered, Ω is the solid angle, η is the detector efficiency, and i_e and I_0 are the currents of the secondary and primary electrons. The subscripts e and b pertain to measurements at the working pressure and at the pressure of the residual gas. The working pressure used by us was 1.5×10^{-4} mm Hg, corresponding to the single-collision regime; the residual-gas pressure was $\sim 5\times 10^{-6}$ mm Hg. The geometric factor was $\int l d\Omega = 3.7\times 10^{-3}$ sr-cm and the detector efficiency was $\eta = 0.45$. The relative measurement error did not exceed 3%, and the error in the determination of the absolute values of the cross sections was ±30%.

MEASUREMENT RESULTS

A. Energy Distribution of Emitted Electrons

In the measurement of the energy distribution of the emitted electrons, it was not our purpose to investigate in detail the structure of the energy spectrum. The energy interval between two successive experimental points was therefore chosen to be appreciably larger than the interval determined by the resolution of the analyzer. The results are shown in Fig. 1, where the abscissas represent the energies of the emitted electrons E_e, and the ordinates show the absolute differential cross sections for electron production $d^2\sigma/dE_e d\Omega$. The numbers near the curves correspond to the energy of the bombarding electrons. The measured energy distributions are characterized by a smooth decrease with an increase of the energy of the emitted electrons. In the region $E_e > 20$ V, this decrease slows down somewhat, apparently as a result of the influence of the ionization of the internal shells. At energies $E_0 \geq 100$ eV, smeared-out maxima are observed on the distribution curves and are due to the kinematics of the pair collisions between the bombarding and atomic electrons. The positions of these maxima correspond approximately to the values of the energy E_m as determined from the momentum conservation law:

$$E_m = E_0 \cos^2\theta.$$

In the region $E_e > E_m$, the cross sections decrease very sharply with increasing energy of the emitted electrons.

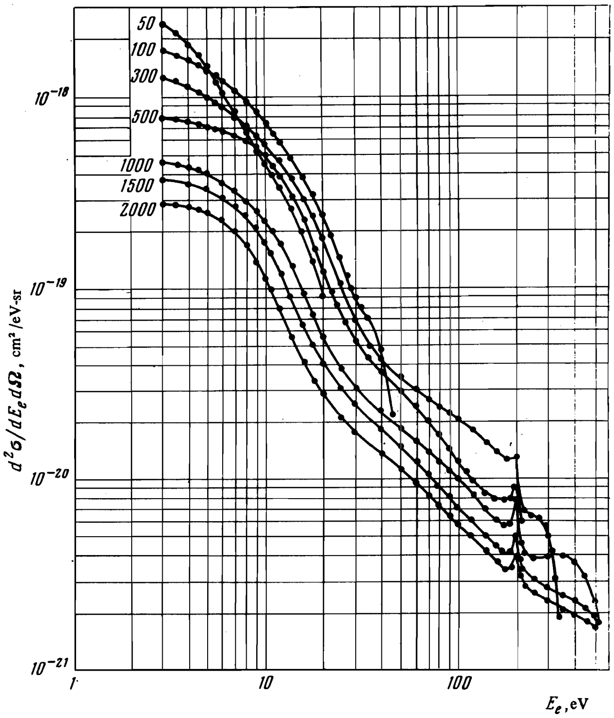

FIG. 1. Energy distribution of electrons emitted from an argon atom following electrom impact. The abscissas represent the values of the energy of the emitted electrons, and the ordinates the absolute values of the differential cross sections for electron production. The numbers at the curves correspond to the energies of the bombarding electrons.

The dependence of the differential cross sections on the energy of the colliding electrons duplicates to a considerable degree the dependence of the polarization on the total cross section[11]. In the investigated interval of the emitted-electron energies, a deviation from such distribution curves is observed only at $E_0 < 90$ eV, which is the energy corresponding to the maximum of a total ionization cross section. The energy distribution is characterized in this case by a steeper rise towards lower energies of the emitted electrons. The differential cross section measured in the present study at $E_0 = 500$ eV are in good agreement with the data of Opal et al.[8], obtained at the same energy and at an electron emission angle $\theta = 60°$. To facilitate reading the plot, the corresponding curve of Opal et al.[8] is not shown in Fig. 1.

B. Excitation Cross Section of L-Shell of Argon

To obtain data on the total cross section for the excitation of the L shell of argon it is necessary to investigate in detail the energy-spectrum structure connected with the Auger transitions to vacancies in the given shell (the contribution of the radiative transition can be neglected in this case[12]). However, since the problem reduces in final analysis to a determination of that area of the distribution-curve section which is occupied by the structure, the requirements with respect to the resolution of the analyzer are not too stringent.

By way of example, Fig. 2 shows a typical structure observed at bombarding electron energies $E_0 = 1500$ eV in the emitted-electron energy interval $E_e = 170–230$ eV. The most intensive lines of the spectrum are due to the "diagram" Auger transitions $L_{2,3}$–MM. There is also an appreciable probability of exciting the states

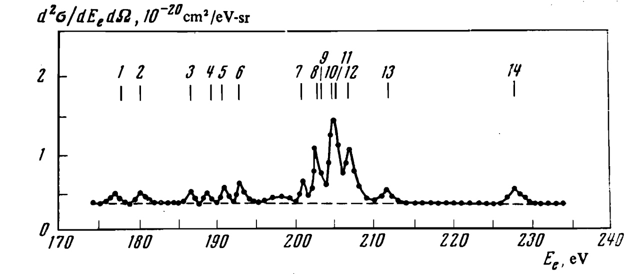

FIG. 2. Spectrum structure corresponding to Auger transitions to a vacancy in the $L_{2,3}$ subshell of Ar. Bombarding-electron energy 1500 eV. The positions of the spectral lines corresponding to the Auger transitions L_{33} – MM (lines 1 – 12) and to transitions from the state $2p^5 3s^2 3p^6 4s$ (lines 13 and 14) are marked.

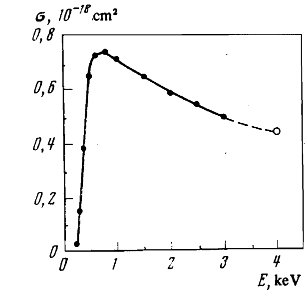

FIG. 3. Dependence of the total cross sections for the excitation of the L shell of argon on the energy of the bombarding electrons: ● – present data, ○ – value determined from the data of[13].

$2p^5 3s^2 3p^6 4s$, the decay of which proceeds via "satellite" Auger transitions $2p^5 3s^2 3p^6 4s - 2p^6 3s^2 3p^4 4s$ and $2p^5 3s^2 3p^6 4s - 2p^6 2s^2 3p^5$ (lines 13 and 14 in Fig. 2). The integration of the structure part of the spectrum with respect to the energy E_S and the solid angle makes it possible to obtain data on the total cross section for the excitation of the $L_{2,3}$ subshell of argon. However, since the decay of the autoionization states with vacancy in the L_1 subshell is effected with overwhelming probability via Koster-Kronig L_1-$L_{2,3}$M transitions [3], the integral cross sections actually correspond to the total cross sections for the excitation of the L shell of argon. In the case considered by us, the angular distribution of the Auger electrons is very close to isotropic [13,14], so that the integration of the cross sections over the solid angle can be replaced, with sufficient degree of accuracy, by a simple multiplication by 4π.

The data on the absolute value of the cross sections for the excitation of the L shell of argon by electron impact are shown in Fig. 3. The cross sections were determined in the colliding-electron energy interval $E_0 = 260–3000$ eV. This figure shows also the value of the cross section at $E_0 = 4000$ eV, obtained from results of independent measurements[15] of inelastic energy losses in collisions of electrons with argon atoms. The excitation cross sections of the L shell are characterized by a sharp increase near the threshold and reaches a maximum at $E_0 = 800$ eV. The cross section at the maximum amounts to 7.5×10^{-19} cm². The cross section decreases smoothly with further increase of the electron energy.

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