POST-COLLISION INTERACTION AT LOW-ENERGY ELECTRON IMPACT EXCITATION OF Cd ATOM

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Optical excitation functions (OEFs) for 6 spectral lines emerging from n^1S_0 levels (n=6 ÷ 11) of a Cd atom are studied. The investigation was carried out on an experimental setup with a vapor-filled collision cell and a hypocycloidal electron monochromator. The energy spread of electrons was about 50 meV. In the optical excitation functions measured from the excitation threshold up to 15 eV more than 50 features were detected. In the energy range 10.9–12.4 eV near the thresholds of 4 autoionizing states of a Cd atom, the post-collision interaction (PCI) of ejected and scattered electrons was found.

1. Introduction

The study of the elementary processes of slow-electron collisions with atoms of group II is very attractive for physicists within last 5 decades. It is related to the interesting features of the processes of interaction of these atoms with electrons as well as a relative simplicity and convenience of the experimental research. First of all, we mean the relative simplicity of the optical spectrum, its location (the visible and UV ranges), and low temperatures of a working substance in order to obtain the required vapor pressure. One should also note the increased interest in the studies of resonances in collisions of slow monoenergetic electrons with atoms. It is related to a rapid development of a new trend in physics, negative-ion spectroscopy [1, 2].

The first investigations of the excitation of Cd atoms date back to the early 1930s. The total cross-sections of scattering (TCSS) of electrons were determined in [3]. Hickam [4] studied the electron-impact ionization of Cd atoms, and Larshe [5] investigated the emission spectra and OEFs of spectral lines in the visible and UV ranges. Later on, the numerous attempts to study the Cd atom excitation by monoenergetic electrons have been undertaken. The excitation of two spectral lines by electrons with the energy spread of about 0.6 eV was studied in [6], practically no features in OEFs being detected. The OEFs of a Cd atom in the visible and UV spectral ranges were studied in [7], where the observed near-threshold OEF features were explained as the formation and decay of short-lived states of a negative ion. Approximately at the same time, the OEFs of many spectral lines with the energy spread of electrons of about 0.8—1.2 eV were measured in [8], where the absolute cross-sections for a large number of spectral lines were given. The excitation processes for Cd atoms have also been studied in [9] using the electron spectroscopy technique allowing the energy dependences of differential (90°) cross sections for the lower levels to be determined. The electron spectra arising as a result of the decay of the autoionizing states of atoms (AIS) were studied in [10], where the effect of PCI of the ejected and scattered electrons was detected at an impact electron energy of ∼12 eV. Szótér et al. [11] have also observed the displacement of maxima of the fine structure in the OEFs of spectral lines emerging from the n^1S_0 (n = 7, 8, 9) levels of a Cd atom at an energy of ∼12.4 eV. Recently, we have measured the TCSS and total cross-sections of the Cd atom ionization by slow electrons [12, 13]. The features found in the corresponding curves give evidence for a considerable role of resonant phenomena in the processes of collision of slow monoenergetic electrons with a Cd atom. Therefore, here we also undertake an attempt to obtain new data on the excitation of Cd atoms by ultramonoenergetic electrons.

2. Experimental Technique

The studies were carried out on an experimental setup automated with an IBM PC and the corresponding interfaces (see the block chart in Fig. 1.) The setup and the measurement technique were described in [14]. The experiments were carried out by optical technique using a collision cell filled with vapor with the required concentration of atoms in the area of their interaction with electrons. A monoenergetic electron beam within the energy range 1–20 eV was formed in a longitudinal magnetic field by an optimized hypocycloidal electron monochromator (HEM) (see the scheme in Fig. 2 and the detailed description in [15]). The well-collimated

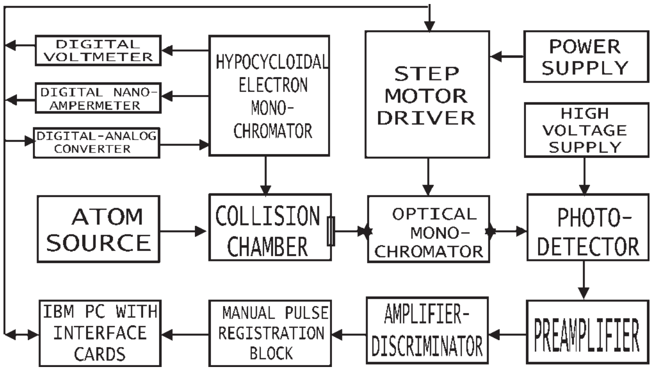

Fig. 1. The experimental apparatus layout

electron beam about 0.5 mm in diameter, having passed through the cell with vapor, is detected by a deep Faraday cup. At the careful choice of the potentials on the HEM electrodes and adjustment of the magnetic field, the electron current was varied by not more than 3% for a broad range of energies. The full width at a half maximum (FWHM) of the differentiated electron current in vacuum vs acceleration voltage (I-V) represents the electron energy homogeneity (energy spread). Its value varies from 10 to 80 meV for currents from 4 to 200 nA. In order to prevent the condensation of atoms on the cell walls and a quartz window, their temperature was kept by 20—30 degrees above the temperature of the container with the substance under investigation. The vapor pressure did not exceed 2×10^{-3} Torr, which corresponds to the concentration of atoms $\sim10^{13}$ cm^3. The residual gas pressure in the cell did not exceed 1×10^{-6} Torr.

The electron energy in the specified interval was scanned cyclically. The required statistic uncertainty of the measured results not exceeding 2—4% was achieved in each specific case by the number of energy scanning cycles and the exposure at a given point. The number of cycles was determined depending on the spectral line intensity and the detector sensitivity to the corresponding radiation. The duration of one measurement cycle usually did not exceed 30 min. For this time, the experiment conditions did not change noticeably. The total exposure time at each point was from 2 to 20 s. The incident electron current during the measurement of the OEFs of spectral lines for all six members of the n^1S_0 ($n = 6\div11$) series was about 40 nA at the $\sim$50-meV energy spread. The energy of electrons was varied with a step of 20 meV.

As indicated above, the electron current in vacuum for the energy range up to 20 eV was constant within 3%. However, when the working pressure of cadmium

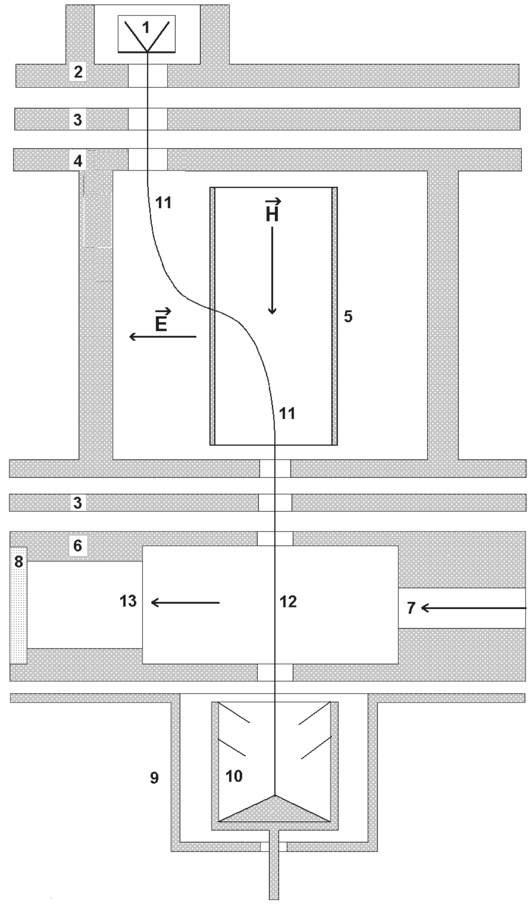

Fig. 2. The scheme of hypocycloidal electron monochromator: *3* — oxide cathode, *2* — first anode of monochromator, *3* — entrance and exit anodes of monochromator of electrons, *4, 5* — external and internal cylinders of electrostatic condenser, *6* — body of vapor-filled cell, *7* — intake of the vapor of investigated atoms, *8* — quartz window for a derivation of radiation, *9, 10* — external and internal cylinders of electron collector, *11* — trajectory of electrons in monochromator, *12* — area of of the collision of atoms with electrons, *13* — direction of a radiation derivation to the spectral device

vapor in the collision cell was achieved, well-defined minima in the I-V characteristics at the energies of (0.34±0.05) eV and (3.97±0.05) eV were observed (transmission experiment). The same minima were observed not only in the transmission experiments [16] but also in TCSS of electrons by a Cd atom which were measured earlier by the crossed-beam technique [13]. The absence of secondary processes was checked by the careful investigation of the OEF of an intercombinative line $\lambda = 326.1$ nm ($5\ ^1S_0 - 5\ ^3P_1$). In the case of a relatively high vapor pressure ($> 10^{-2}$ Torr) in the cell

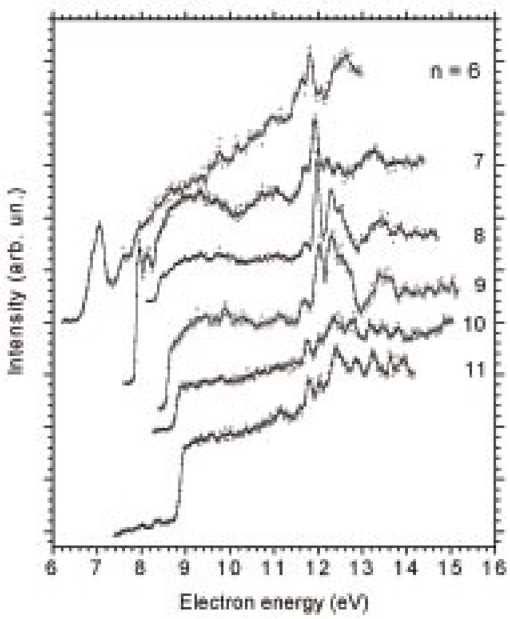

Fig. 3. Optical excitation functions of n $^1S_0$ levels ($n = 6\div11$) of Cd atoms

and at the energies above the double energy of the excitation threshold for the 5 $^3P_1$ level (~8 eV), an additional maximum in the OEF of this line is observed, indicating the presence of the secondary processes.

For a correct treatment of the obtained results, the energy scale calibration of the exciting electrons is important what has already been discussed earlier [13, 14]. In this work, the calibration was carried out both traditionally, from a shift of the collector current-voltage characteristic and from the threshold of the appearance of the most intense resonance line in the Cd spectrum ($\lambda = 326.1$ nm, $E_{\rm thresh} = 3.80$ eV). The calibration was additionally checked from the excitation thresholds of the spectral lines with sharply increasing OEFs at the threshold.

3. Results and Discussion

We have carefully measured OEFs of spectral lines emerging from $n\ ^1S_0$ levels ($n = 6\div11$) of a Cd atom. The measurements were carried out under the same experimental conditions and with the same parameters, the statistical spread being at most 4 %. The obtained OEFs are presented in Fig. 3 (points). The solid lines present the results smoothed by a digital Fourier filter (3 points being used for the smoothing procedure). The OEFs of the measured spectral lines are seen to possess the well-defined excitation thresholds and a rather sharp increase of the excitation cross-sections at the near-threshold energies. In the energy range 7.8—11.2 eV, an insignificant increase of the cross-section with poorly expressed features is observed. At 11.2—15 eV, the sharp features are revealed, and the near-threshold resonant features in the OEFs of the spectral lines emerging from levels 6 $^1S_0$ and 7 $^1S_0$ are worth a special notice. The same features are also seen in the OEFs of the spectral line emerging from the 8 $^1S_0$ level, however they are less pronounced. In order to detect the same near-threshold features in the OEFs of the series of the subsequent terms, one requires the better electron beam homogeneity and a smaller step of the energy scanning. The nature of these resonant features can be unambiguously related to the formation and decay of short-lived states of a Cd negative ion. Note that they were also to some extent observed in [7]. Another part of the OEF features in the energy range from the line excitation threshold up to the ionization potential (8.991 eV) can be basically attributed to the manifestation of higher located "resonances". This is confirmed by a richer and more distinct structure of the features in the OEFs of the spectral lines emerging from the lower excited levels with $n = 6 - 8$, as well as a less rich and sharp structure of the features in the OEFs of the spectral lines emerging from the upper levels with $n = 9 - 11$.

In the energy range above the Cd atom ionization threshold, there is a plenty of AIS which can be effectively excited as a result of collisions of atoms with monoenergetic electrons. This is also confirmed by earlier studies of the spectra of electrons ejected by Cd atoms [10]. The structure in the apparent ionization cross-sections of Cd atoms that was detected near the threshold in [13] also results from the AIS decay. The complicated structure which we have detected in the energy dependences of the excitation cross-sections of the spectral lines above the ionization threshold also confirms the AIS influence on the atomic level excitation character. A sufficiently narrow energy width of the observed features indicates that, in this case, the short-lived $4d^95s^25pnl$ states of a Cd negative ion are also formed. Their spontaneous decay can populate both the excited levels $n\ ^1S_0$ and the AIS of the atom. This is also confirmed by the presence of features in the measured OEFs of spectral lines emerging from 6 $^3S_1$, 7 $^3S_1$, 5 $^3D_1$, 6 $^3D_1$ levels at an energy of 9.42 eV and in the OEFs of spectral lines emerging from 7 $^3S_1$, 5 $^3D_1$, 6 $^3D_1$ levels at an energy of 10.22 eV.

In our opinion, especially important is the structure in the OEFs of spectral lines emerging from $n\ ^1S_0$ levels of a Cd atom in the energy range 10.90—12.45 eV and consisting of four well-resolved maxima (Fig. 4). The data on the energy positions of these maxima for all six spectral lines are presented in the table. The energies of the well-defined and less pronounced maxima in the OEFs are determined, respectively, with the accuracy of ±15 and ±50 meV. For all the four features (*a–d* in Fig. 4 and the table), the trend of a shift of the position of maxima towards higher energies with the main quantum number of the initial level of a spectral line was traced, which is the evidence for the PCI of the ejected and scattered electrons. We note that Szótér et al. [11] have observed a displacement of the maxima of the fine structure in the OEFs of the lines emerging from 7 $^1S_0$, 8 $^1S_0$, 9 $^1S_0$ levels at an energy of 12.4 eV. At two impact energies 11.80 and 12.06 eV, Kazakov et al. [9] observed the broadening of maxima and the shift of the lines of ejected electrons ($E_{\rm eject}$ =3.07 and 2.81 eV) as a result of the Cd atom AIS decay. These data are in good agreement with our results. Based on the data in [17] and on our data, one can assume that the PCI effect at the energies specified in the table is caused by the following AIS of a Cd atom: $4d\,^95s^26d\,^1D_2$ ($E_{\rm eject}$ =1.92 eV), $4d\,^95s^25p\,^3P_2$ ($E_{\rm eject}$ =2.64 eV), $4d\,^95s^25p\,^3F_3$ or $5p\,6s\,^3P_2$ ($E_{\rm eject}$ =2.83 eV) and $4d\,^95s^25p\,^3P_1$ ($E_{\rm eject}$ =3.07 eV). Note that this is the first observation of the PCI effect near to the threshold simultaneously for 4 AIS of a Cd atom.

4. Conclusion

Finally, it should be noted that the high parameters of our HEM and the full automation of measurements have enabled the precise systematic investigations of the OEFs for 6 spectral lines of a Cd atom emerging from $n\,^1S_0$ levels with $n = 6 \div 11$. About 50 features, more than a half of them being previously unknown, were detected in the OEFs of the spectral lines measured from the excitation threshold up to an energy of 15 eV. The analysis of the obtained results has enabled us to explain more deeply the processes of population of the investigated levels and to choose the following basic processes among them: direct electron transitions from the ground state of the atom to the initial levels of the spectral lines, the population of the initial levels of spectral lines due to the decay of the negative-ion short-lived states and the PCI effect of the ejected and scattered electrons.

The energy position of the OEF features for the spectral lines of a Cd atom

λ, nm	Transition	$E_{\rm thresh}$, eV	Energy position of the features, eV *a*	*b*	*c*	*d*
441.3	$5\,^3P_1$–$6\,^1S_0$	6.608	10.94	11.64	11.81	12.04
515.5	$5\,^1P_1$–$7\,^1S_0$	7.819	11.07	11.69	11.93	12.20
430.7	$5\,^1P_1$–$8\,^1S_0$	8.293	11.08	11.71	11.97	12.29
398.2	$5\,^1P_1$–$9\,^1S_0$	8.527	11.11	11.72	12.02	12.31
381.8	$5\,^1P_1$–$10\,^1S_0$	8.661	11.12	11.76	12.03	12.34
372.4	$5\,^1P_1$–$11\,^1S_0$	8.744	11.16	11.79	12.04	12.40

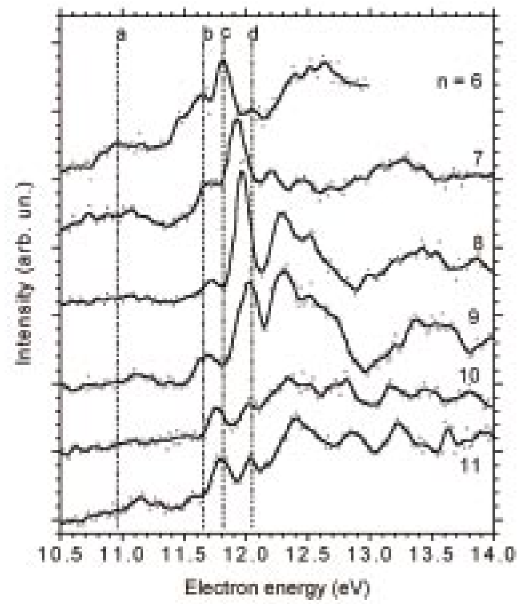

Fig. 4. Features in OEFs at the thresholds of AIS (*a—d*) of a Cd atom

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ВЗАЄМОДІЯ ПІСЛЯ ЗІТКНЕННЯ ПРИ ЗБУДЖЕННІ АТОМА Cd ЕЛЕКТРОНАМИ НИЗЬКИХ ЕНЕРГІЙ

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Р е з ю м е

Досліджено оптичні функції збудження шести спектральних ліній, які виходять з n^1S_0-рівнів атома кадмію ($n = 6 \div 11$), що збуджувалися пучком ультрамоноенергетичних електронів з розкидом за енергією ∼50 меВ. Вимірювання виконано на експериментальній установці з використанням паронаповненої комірки і гіпоциклоїдального монохроматора електронів. На виміряних від порогів збудження до 15 еВ енергетичних залежностях перерізів збудження спостережено понад 50 особливостей. В області енергій 10,9—12,4 еВ поблизу порогів чотирьох автоіонізаційних станів атома кадмію виявлено взаємодію після зіткнення випущеного і розсіяного електронів.