EXCITATION OF LASER TRANSITIONS FROM THE $4d^9 5s^2\ ^2D_{5/2,3/2}$ - LEVELS OF Cd^+ ION IN ELECTRON-ION COLLISIONS

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A precise investigation of the electron-impact excitation emission cross sections for the laser transitions of the Cd^+ ion have been carried out by the spectroscopic method using the crossed electron and ion beam technique. A significant role of the resonance processes was found near the excitation threshold up to the Cd II ionization potential. A dominant contribution of the resonance processes via the Coster-Kronig decay of the $4d^9(^2D_{3/2})5s^2nl$ autoionizing states was observed between the $^2D_{5/2}$ and $^2D_{3/2}$ levels splitting for the λ441.6 nm laser line. For the λ325.0 nm and λ353.6 nm lines the dielectronic satellites were found below their excitation thresholds at first time. The energy dependence of excitation cross-sections for the laser lines were compared with the K.Hane *et al.* results, whilst the total excitation cross-section for the laser transitions was compared with the O. Zatsarinny *et al.* 15CC calculation data .

Excitation of positive ions by electron impact enters intimately into the modeling and diagnostics of high-temperature plasmas such as those encountered in astrophysics and controlled fusion. It is unimaginable that the millions of cross sections needed for such modeling could be measured, but accurate experiments on excitation cross sections of relevant ions are needed as benchmarks for testing the theoretical methods used to compute such cross sections.

The development of experimental techniques in recent years has rendered the detailed study of scattering cross sections of electrons by positive ions and, particularly, their resonance structure increasingly practicable. This structure is caused by the capture of an incident electron by the excited ion target into short-lived autoionizing states (AIS), the further multichannel decay of which leads to a sharp variation in the scattering cross section. Resonance phenomena strongly affect all electron-ion collision processes and can considerably influence their cross sections, especially in the near-threshold region. The resonance contributions strongly depend on the type of transition and the size of the direct cross section. They also show a non-regular behaviour when the ion charge is changed, their relative importance varying within a wide range, i.e. from few percent in the case of strong dipole transitions to 2–10 times for weak forbidden transitions.

The data on the interactions of electrons with cadmium ions have many applications, which include modeling of cadmium-vapour lasers and spectroscopic diagnostics of ion-thruster plasmas. One of the most stable and useful metal ion lasers is the positive column He-Cd^+ laser (441.6 nm and 325.0 nm).

The ionic Cd^{+*} $(4d^9 5s^2)$ $^2D_{5/2,3/2}$- and $Cd^{+*}(4d^{10}5p)$ $^2P^o_{1/2,3/2}$-states are the upper and lower states of this laser.The $Cd^{+*}(4d^9 5s^2)$ $^2D_{5/2,3/2}$-states are called the Beutler states in which one of the inner-shell electrons is excited. The cross-section measurement for the excitation of a bound state of an ion by promotion of an inner-shell electron is a subject of some general current interest.The energy dependence of the absolute cross section from the ionic ground state to the ionic Beutler states have been investigated only for the Cd^+ ion experimentally [1,2].

In present work the following processes have been studied from the thresholds up to 120 eV:

$e + Cd^{+}\ (4d^{10}5s)\ ^2S_{1/2} \rightarrow$
$\rightarrow e + Cd^{+*}\ (4d^{9}5s^{2})\ ^2D_{5/2,3/2} \rightarrow$
$\rightarrow e + Cd^{+*}\ (4d^{10}5p)^2P^{o}_{1/2,3/2} + h\nu_{1,2,3}$ (1)

λ_1=441.6 nm (5/2→3/2);
λ_2=325.0 nm (3/2→1/2);
λ_3=353.6 nm (3/2→3/2).

In detail the experimental apparatus (see Fig.1) has been described in [3]. The electron and ion beams are crossed at a right angle under 10^{-8} Torr vacuum condition. The Cd^{+} ions produced in the low-voltage discharge (U_d < 12 V, i.e. certainly less, than the excitation energy of the long-lived Cd^{+*} $(4d^{9}5s^{2})$ $^2D_{5/2,3/2}$ states) ion source were formed into a beam by an ion-optical system and separated from the Cd atoms by a 90^0 electrostatic capacitor. The energy of ions was 600 eV and the ion current was $6{\cdot}10^{-7}$ A. A three-anode electron gun produced a ribbon electron beam in the energy range of 7÷120 eV, with a current of $(7\div10){\cdot}10^{-5}$ A and the full energy width at half maximum (FWHM) of the electron energy distribution curve equal to $\Delta E_{1/2}$=0.35 eV. Spectral separation of the radiation was performed with an optical diffraction monochromator. The inverse linear dispersion of the monochromator was $d\lambda/dl \approx 2$ nm/mm. A cooled FEU-140 ("FOTON") photomultiplier was used as the radiation detector.

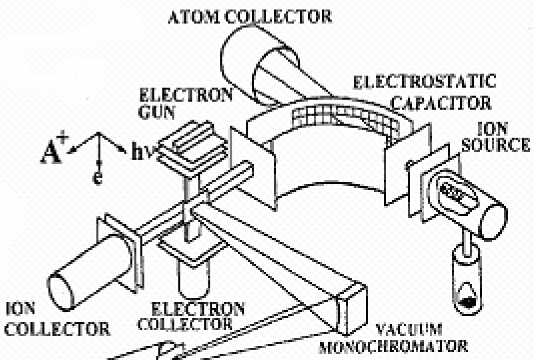

Fig.1. Scheme of the experimental apparatus.

The method of modulation of two beams by square voltage pulses phase-shifted by ¼ of the modulation period was used to extract the signal due to the process under study from the total background (the noise of detector and the background due to the collisions of electrons and ions with residual atoms). A signal of (3÷0.5) s^{-1} magnitude was extracted from the background with signal to background ratio from 1/30 to 1/15. The processes of performing the measurements and analyzing the results was automated using CAMAC modules and IBM PC.

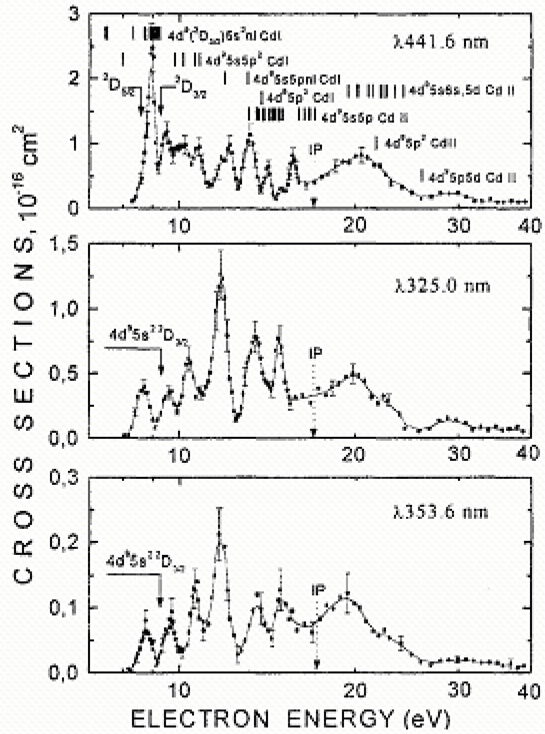

Fig.2. The energy dependence of the electron-impact excitation of laser lines of the Cd^{+} ion.

The results of a detailed investigation of the energy dependence of excitation emission cross section of laser transitions from the Cd^{+} $(4d^{9}5s^{2})$ $^2D_{5/2,3/2}$ – levels are presented in Fig.2. In Fig.2 the energy positions and configurations of the Cd atomic AIS are also shown [4,5,6]. The vertical bars show the errors in the relative measurements. The uncertainty of the relative emission cross section was evaluated to be about ±15÷20%. The absolute value of the emission excitation cross sections were obtained by normalizing the experimental excitation functions on the 15 states close-coupling (15 CC) calculation [7] at the 40 eV electron energy. The uncertainty for the absolute cross section determination was about ±15%. The electron energy scale was calibrated with an accuracy of ±0.1 eV from the threshold part of the excitation function of the Cd atom resonance line (λ=326.1 nm), for which the spectroscopic excitation threshold is known. The excitation functions have revealed the distinct resonance features not observed earlier [1, 2]. In these works the laser lines λ=441.6 nm and λ=325.0 nm were studied, while the laser line λ=353.6 nm was studied by us for the first time. The resonances are due to the electron capture by the Cd^+ ion resulting mainly in the formation of the $4d^9(^2D_{5/2,3/2})5s^2nl$ [4], $4d^95s5p^2$ [5], $4d^95s5pnl$, $4d^95pnln^1l^1$ [6] atomic AIS, the subsequent decay of which leads to the significant population of the upper laser states. The observed broad maximum above the ionization potential of the Cd^+ ion is due to the d-excitation of the $4d^95s6s$, 5d, $4d^95p^2$, $4d^95p5d$ and other Cd II states.

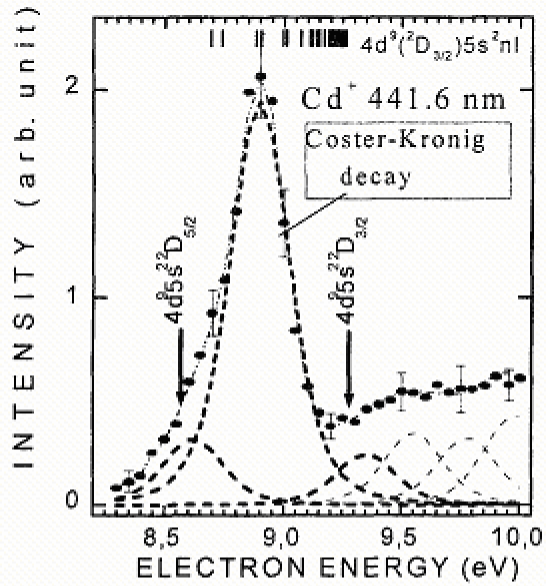

Fig.3. The decomposition of a total resonant contribution into the separate Gaussian-sharped components.

A predominant contribution of the resonance processes via the Coster-Kronig decay of the $4d^9(^2D_{3/2})5s^2nl$ AIS was observed between the $^2D_{5/2}$ and $^2D_{3/2}$ levels splitting (ΔE= 0.69 eV) for the λ441.6 nm line. In this case the Coster-Kronig decay was revealed in a form of three separate components of different intensity (see Fig.3). The most intense component corresponds to the energy positions of the $4d^9(^2D_{3/2})5s^29p,6f$ AIS of the Cd I atom [4]. The decomposition of a total resonant contribution into the separate Gaussian-shaped components had enabled the observed structure in the energy dependence of excitation cross-section to be identified more clearly (see Fig.3).

The dielectronic satellites for the λ=325.0 nm and λ=353.6 nm lines (see Fig.2) were observed by us for the first time below their excitation thresholds in energy range between the $^2D_{5/2}$ and $^2D_{3/2}$ levels splitting. They are due to the radiation transitions between the $4d^9(^2D_{3/2})5s^2nl$ and the $4d^{10}4p(^2P_{1/2,3/2})nl$ atomic AIS. The dielectronic satellites distort the excitation behaviour near threshold.

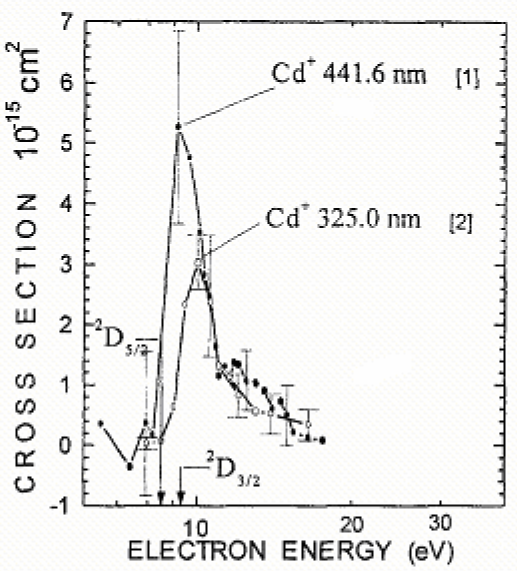

Fig.4. The energy dependence of the electron-impact excitation of laser lines of the Cd^+ ion [1,2].

There is an essential difference between our data and those of K. Hane et al. both in the magnitude (about 20 times) of the absolute excitation cross sections, and in the behaviour of their energy dependences (see Fig.4). These differences are caused by worse experimental conditions in [1,2] as compared to our experiments.

Our experimental energy dependence of the total excitation cross section for the $4d^95s^2\ ^2D_{5/2,3/2} \rightarrow 4d^{10}5p\ ^2P_{1/2,3/2}$ transitions is compared to the 15CC calculation data [7] (see Fig.5).

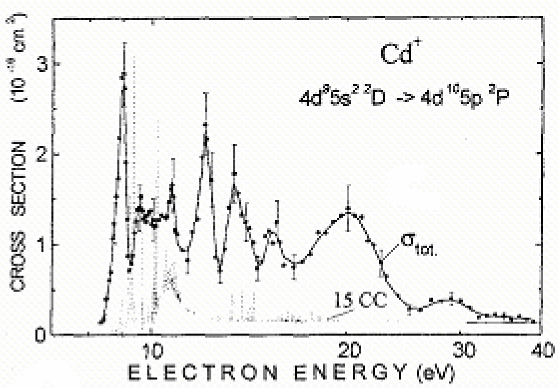

Fig.5. Comparison of the experimental energy dependence of the total emission excitation cross section with the theoretical 15 CC calculation [7].

One should note that our results completely agree with the theoretic data in the (40÷120) eV energy range, but the experiment near the excitation threshold significantly exceeds the value of the FWHM 0.35eV convoluted theoretical data.

Thus, the present studies testify that at electron-ion collisions the population of the laser $4d^9 5s^2\ ^2D_{5/2,3/2}$ - levels of the Cd^+ ion results predominantly from the resonance processes, not from the direct electron-impact excitation of the quadrupole ($4d^{10}5s^2S_{1/2} \rightarrow 4d^9 5s^2\ ^2D_{5/2,3/2}$) transitions.

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ЗБУДЖЕННЯ ЛАЗЕРНИХ ПЕРЕХОДІВ З $4d^9 5s^2\ ^2D_{5/2,3/2}$-РІВНІВ ІОНА Cd^+ ПРИ ЕЛЕКТРОН-ІОННИХ ЗІТКНЕННЯХ

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Спектроскопічним методом в умовах пучків, що перетинаються під прямим кутом, прецизійно досліджено енергетичні залежності ефективних перерізів збудження лазерних переходів іона Cd^+ при електрон-іонних зіткненнях. Встановлено суттєву роль резонансних процесів від порогів збудження до потенціалу іонізації Cd II. Виявлено, що для лазерної лінії 441.6 нм в енергетичному проміжку між $^2D_{5/2}$ і $^2D_{3/2}$ рівнями домінуючим є резонансний внесок $4d^9(^2D_{3/2})5s^2nl$ автоіонізаційних станів через процес Костера-Кроніга. Нижче порогів збудження ліній 325.0 нм і 353.6 нм вперше виявлено їх діелектронні сателіти. Енергетичні залежності ефективних перерізів збудження лазерних ліній порівняно з експериментальними результатами К.Гейна та ін., а повний ефективний переріз збудження для лазерних переходів – з даними О.Зацаринного та ін., розрахованими методом 15СС.