STUDY OF DIRECT AND RESONANCE PROCESSES IN COLLISIONS OF ELECTRONS WITH ATOMS AND IONS

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High-resolution experimental investigation of direct and resonance processes have been carried out in collisions of electrons with the alkali, alkaline-earth, zinc, cadmium and thallium atoms and with their ions by using the electron and photon spectroscopy methods combined with a crossed beam technique. The energy dependences of the electron-impact excitation cross-sections for the atomic autoionizing states, for the dipole-allowed, intercombinational, non-dipole-allowed transitions and dielectronic recombination in ions have been studied, as well as the energies and widths of the observed resonances. The role of relativistic, electron-correlation effects and configurational mixing in the probability redistribution for electron and radiative atomic autoionizing states decay channels have been established.

The detailed experimental high-resolution investigations of direct and resonance processes have been carried out during last decade in collisions of electrons with the alkali, alkaline-earth, zinc, cadmium and thallium atoms and with their singly-charged ions at the Department of Electron Processes. The electron and photon spectroscopy methods combined with the electron-atom and electron-ion crossed beam techniques were used.

The experimental setups comprise the following innovated elements: a high-temperature metal-vapour beam source; a high resolution electrostatic cylindrical electron monochromator and analyzer; a low-voltage discharge ion source, the spectral monochromators for the 40-830 nm region, a modulation system for the detection of extremely weak photon fluxes; a PC-based unit for controlling the experimental procedures and data processing.

During the investigation the main attention has been paid to: the role of resonances in the excitation of atoms (including that of the autoionizing states (AIS)) and ions; the elucidation of new regularities and phenomena in the dynamics of electron-atom and electron-ion scattering related to the excitation and decay of the negative-ion states and atomic AIS; the search for and study of the emissions related to the radiative decay of AIS.

The atom beam formed by a high-temperature metal-vapour beam source was intersected at a right angle by an electron beam. The high-resolution electrostatic cylindrical electron monochromator and analyzer were used to obtain the monoenergetic electron beam and analyse the ejected electrons.

The ions of metal atoms produced in the low-voltage discharge ($U_d \leq 12$V, i.e. certainly less than the excitation energy of the long-lived ionic states) ion source were formed into a beam by an ion-optical system and separated from the atoms by a 90^0 electrostatic capacitor. The ion beam (E_i=600eV, $I_i=8\cdot10^{-7}$A) was intersected at a right angle by a ribbon electron beam ($E_e=4\div400$eV, $I_e=(5\div35)\cdot10^{-5}$A, $\Delta E_{1/2}=(0.35\div1)$ eV energy spread (FWHM)) at a pressure of 10^{-8} Torr. The radiation from the interaction volume was spectrally separated by means of an optical high-luminosity MDR-2 diffraction monochromator or a 70^o vacuum monochromator using the Seya-Namioka optical scheme and was detected by a cooled FEU-

140 ("Foton") or FEU-142 photomultipliers operating in the counting regime. The signal was distinguished against the background by a rectangular phase-shifted pulse modulation of electron and ion beams. The experimental data were measured and processed by a PC-CAMAC system.

The studies were done using an apparatus with intersecting electron and ion beams, the basic units of which are described in [1]. Since the radiation of the studied metal ions lies in the wavelength range of 40-830 nm, the high-luminosity visible region monochromator and the vacuum monochromator were used.

The following results have been obtained:

- the electron-impact excitation cross-sections for the atomic AIS and their energy dependences;
- the energies and widths of the negative-ion resonances, their probable decay channels;
- the wavelengths of the spectral lines corresponding to the radiative decay of quasimetastable atomic AIS with their tentative assignments;
- the excitation functions and the analysis of excitation mechanisms for these spectral lines;
- the absolute cross-sections of the near-threshold electron-impact excitation and dielectronic recombination of singly-charged ions and their energy dependences;
- the resonance contribution to the electron-impact excitation cross-sections for the dipole-allowed, intercombination and non-dipole-allowed transitions in ions, as well as the energies and widths of the observed resonances;
- the role of relativistic, electron-correlation effects and configurational mixing in the probability redistribution for electron and radiative atomic AIS decay channels in electron-ion collisions.

The most significant results in electron collisions with atoms during last decade include the observation for the first time of core-excited negative-ion resonances in Li, Na and K atoms, their spectroscopic identification, the determination of the decay channels and post-collision interaction (PCI); the search for and study of emissions related to the radiative decay of quasimetastable autoionizing states (QMAIS) and investigation of the energy dependences of their excitation cross-sections.

In present work, only some of our results obtained during last decade in the field of electron-ion collisions will be presented.

For the alkali metal ions the recombination, excitation and s-ionization processes have been studied [1] . The energy dependence of the excitation emission cross sections for the 10 resonance lines and 6 spectral lines for the s-ionization of K^+, Rb^+ and Cs^+ ions were investigated within the energy range from the threshold up to 400 eV. The dielectronic recombination process for the 5 spectral lines lying below the excitation thresholds of the resonance levels of these ions were also studied. The excitation function of the Cs^+ ion for each process mentioned above are presented in Fig.1. One can see that the resonance lines of these ions are most effectively excited, while the lines of the recombination process have their cross-sections of a factor of 3-4 while the lines of the s-ionization are more than one order of magnitude smaller at the excitation efficiency maximum. By order of magnitude, the excitation cross-sections of resonance lines of K^+, Rb^+ and Cs^+ ions are equal to 10^{-17} cm^2 and only in the near-threshold region they are $\sim 10^{-16}$ cm^2. The excitation cross sections increase from K^+ to Cs^+ ions. The results indicate that an important role is played by the capture of the projectile electrons by alkali-metal ions, with the formation of short-lived AIS states of the neutral atoms and ions. For ions with an appreciable spin-orbit splitting of the levels, the decay of the AISs occurs efficiently through the Coster-Kronig effect. In the near-threshold energy region, the population of the excited levels of the alkali-metal ions occurs predominantly due to the resonance processes.

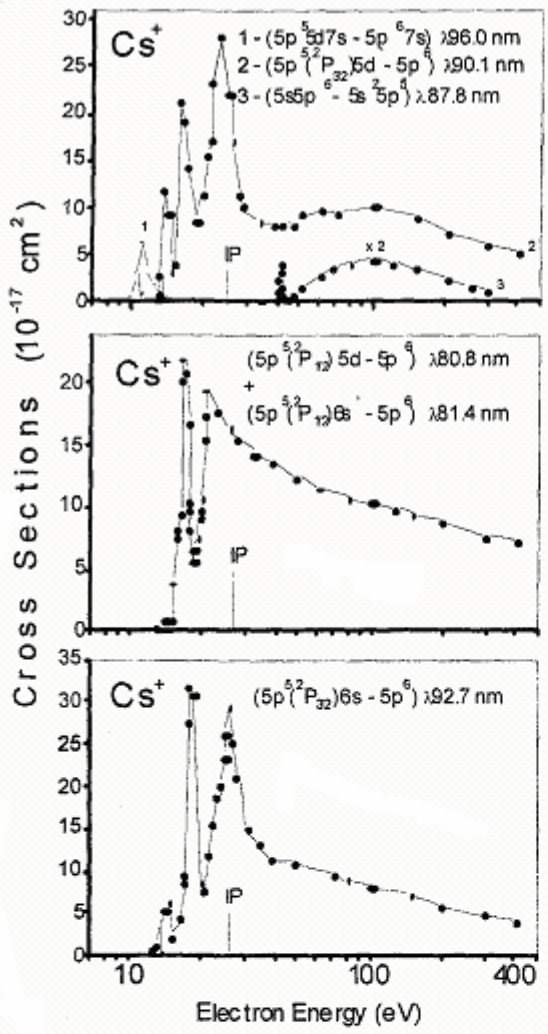

Fig.1. Energy dependence of the excitation cross sections of the Cs^+ ion spectral lines.

A detailed high-resolution study of the excitation of the resonance lines and the first terms of the sharp and diffuse series of alkaline-earth metal ions has been carried out in the energy interval from the threshold up to 15 eV. The excitation functions of the resonance lines for the Ba^+ ion are presented in Fig. 2. The $\Delta E_{1/2}$=(0.1-0.2) eV energy spread (FWHM) achieved in our experiments ensured clear resolution of the structure in the excitation functions of the spectral transitions practically undetectable in electron-ion collisions. A qualitatively new and important result is the existence of a considerable contribution of the resonance processes to the excitation of the lower levels of alkaline-earth ions at the electron energies close to the excitation threshold. The contribution of the resonance processes to the excitation cross section of the lower levels gives a rise to a structure with deep maxima and minima (which should be compared with the structure of the excitation function of the alkali metal ion levels). The reason for this observation is the high efficacy ($\sigma \sim 10^{-15}$ cm^2) of the direct electron-impact excitation of the lower levels of these ions and also the overlap of groups of narrow resonances (with a true width less than 0.1 eV), which caused relatively wide maxima to appear in the excitation curves. Our investigation shows that the role of resonance effects becomes greater along the series of these ions from Mg^+ to Ba^+. This could be a manifestation of the relativistic effects in the outer shells of heavy ions, in which the process of the direct excitation of these ions is influenced significantly by core polarization by the bombarding electrons, while the role of the relativistic effects is much less.

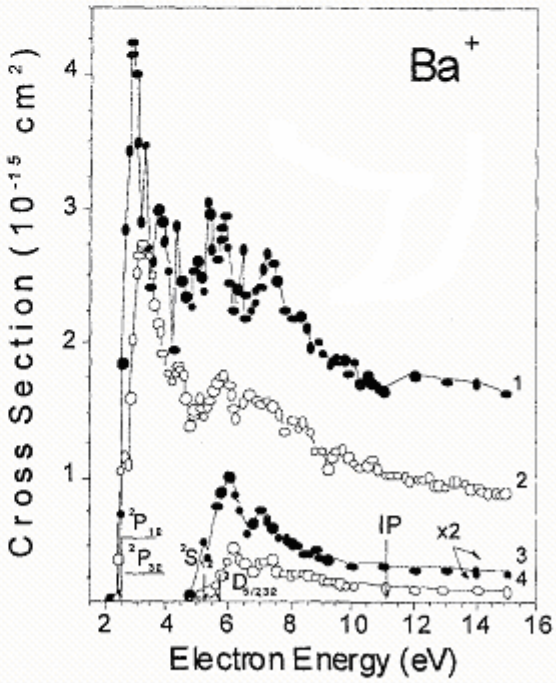

Fig.2. Energy dependence of the excitation cross sections of the Ba^+ ion spectral lines:
1 - ($6p^2P_{3/2}$ - $6s^2S_{1/2}$) λ455.4 nm;
2 - ($6p^2P_{1/2}$ - $6s^2S_{1/2}$) λ493.4 nm;
3 - ($7s^2S_{1/2}$ - $6p^2P_{3/2}$) λ490.0 nm;
4 - ($6d^2D_{5/2, 3/2}$ - $6p^2P_{3/2}$) λ(413.1+416.6) nm.

VUV emission within the 70-200 nm spectral range arising at the electron-impact excitation of valence [3], subvalence [4], two valence [5] electrons and dielectronic recombination [6] of the Tl^+ ion was studied. The energy dependences of excitation emission cross sections for the different spectral transitions in Tl^+ ion (see Fig.3) were measured from the threshold up to 300 eV. Strong resonance features were observed in the near-threshold excitation of all spectral transitions. They result from the decay of the atomic AIS produced by the simultaneous capture of incident electron by ion with the excitation of one of the valence $6s^2$- or subvalence $5d^{10}$-electrons. A broad maximum near 50-60 eV observed in all energy dependence curves is related to the inner-shell electron excitation. The effective excitation of the intercombination transitions, as well as that related to the excitation of two $6s^2$-electrons, are explained by the manifestation of the relativistic and correlation effects in the heavy Tl^+ ion.

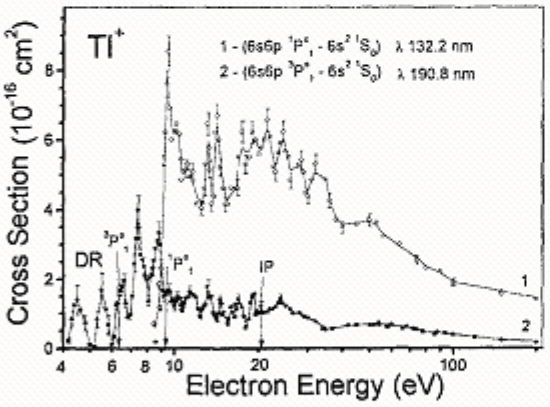

Fig.3 Energy dependence of the excitation cross sections of the Tl^+ ion resonance and intercombination lines.

A detailed high-resolution study of the excitation of the Zn^+ [7] and Cd^+ [8] resonance lines have been carried out in the energy interval from the threshold up to 150 eV. Our results (see Fig.4) attest to a complicated mechanism of near-threshold electron-impact excitation of these lines. The mechanism involves the efficient occurrence of resonance processes – dielectronic recombination and resonance excitation. Dielectronic recombination is the main mechanism of the satellite line excitation lying within a narrow wavelength range close to the resonance lines. The intensity of the dielectronic satellites is determined by the probabilities of both electron capture and radiative decay of the corresponding AISs. The main competing mechanism here is the electronic decay of AISs to the ground or excited states of the ion. The latter is manifested in the resonance excitation of ions. Relativistic and correlation effects strongly influence the ratio of the radiative and electronic decay probabilities of AISs, and these effects become increasingly important for heavy atomic systems.

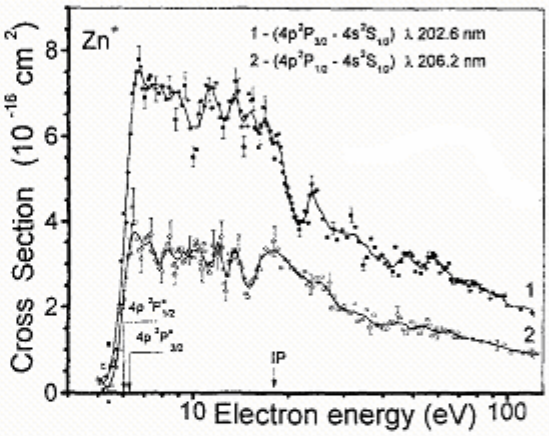

Fig.4 Energy dependence of the excitation cross sections of the Zn^+ ion resonance lines.

High-resolution measurements of the atomic constants and the fundamental knowledge on new mechanisms of different collisional processes (including the resonance phenomena) have a substantial effect on other fields of science: plasma physics, fusion, astrophysics, upper atmosphere physics, quantum electronics, and, in particular, the laboratory and astrophysical plasma diagnostics, radiative plasma cooling in fusion applications, spectroscopic data interpretation and the development of new theoretical models for the processes occurring in the astrophysical objects, active experiments with artificial plasma clouds in the outer space, in the detailed analysis of kinetics of the processes in laser systems and

in the search for the active laser media operating in the short-wave spectral region.

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ВИВЧЕННЯ ПРЯМИХ І РЕЗОНАНСНИХ ПРОЦЕСІВ ЗІТКНЕНЬ ЕЛЕКТРОНІВ З АТОМАМИ ТА ІОНАМИ

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Методами електронної і фотонної спектроскопії в умовах пучків, що перетинаються, проведено прецизійні експериментальні дослідження прямих і резонансних процесів зіткнень електронів з атомами та іонами лужних, лужноземельних металів, цинку, кадмію та талію. Вивчено енергетичні залежності ефективних перерізів збудження для атомарних автоіонізаційних станів, оптично дозволених, інтеркомбінаційних, оптично заборонених переходів та діелектронної рекомбінації іонів, а також енергії і ширини спостережуваних резонансів. Встановлено суттєву роль релятивістських, кореляційних ефектів та конфігураційного змішування рівнів у перерозподілі ймовірностей електронного і радіаційного каналів розпаду автоіонізаційних станів.