RADIATIVE TRANSITIONS BETWEEN THE $4d^{10}5p^2(^3P_j)nl$ AND $4d^{10}5s5p(^3P_1^o)nl$ AUTOIONIZING STATES OF In ATOM IN COLLISIONS OF SLOW ELECTRONS WITH In$^+$ IONS

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The radiative transitions between the $4d^{10}5p^2(^3P_{0,1,2})nl$ and $4d^{10}5s5p(^3P_1^o)nl$ autoionizing states of an indium atom that represent dielectronic satellites of the $4d^{10}5p^2\ ^3P_0 \rightarrow 4d^{10}5s5p\ ^3P_1$ ($\lambda = 171.7$ nm), $4d^{10}5p^2\ ^3P_1 \rightarrow 4d^{10}5s5p\ ^3P_1$ ($\lambda = 166.7$ nm), and $4d^{10}5p^2\ ^3P_2 \rightarrow 4d^{10}5s5p\ ^3P_1$ ($\lambda = 160.7$ nm) spectral lines of an In$^+$ ion have been observed for the first time. The energy dependences of the effective excitation cross sections of dielectronic satellites, as well as near-threshold regions of these spectral lines, were investigated in the range of electron energies $9 \div 15$ eV with the help of the spectroscopic method using crossed beams of electrons and In$^+$ ions. The absolute excitation cross sections of dielectronic satellites amount to $(0.7 \div 2) \times 10^{-16}$ cm^2 and are of the same order of magnitude as the effective excitation cross sections of the corresponding ionic lines. It is found that a considerable increase of the probability of radiation decay of the $4d^{10}5p^2(^3P_{0,1,2})nl$ autoionizing states of the In atom is related to strong relativistic and correlation effects, in particular to the configuration interaction of the $5p^2nl$ levels both with one another and with the levels of the $5s5dnl$ and $4d^95s^25p^2$ configurations.

1. Introduction

Progress in many fields of science and technology depends on the knowledge about quantitative and qualitative characteristics and mechanisms of the processes accompanying electron-ion collisions. Data on these processes are important for the successful development of such areas of the modern science as plasma physics, astrophysics, physics of nuclear reactions with heavy ions, laser and analytical technology, thermonuclear energetics, quantum chemistry, *etc.* [1–3]. Elementary processes of electron-ion collisions also clearly manifest themselves in the phenomena taking place in the upper atmosphere of the Earth and other planets. It is worth noting that spectral lines of heavy many-electron elements have been recently observed in spectra of stars and in the interstellar space [4].

The results of experimental and theoretical researches performed during recent years in leading scientific groups of the world testify to the complicated mechanism of inelastic processes running in the case of collisions between slow electrons and ions [5,6]. It is mainly explained by resonance effects related to the formation and decay of autoionizing states (AIS) of the "electron+ion" system. In the case of electron-ion collisions, the long-range Coulomb field of an ion not compensated by electrons results in the infinite number of AISs converging to each ion level. They decay both via the electron channel (radiationless decay accompanied by the ejection of an electron), which results in a complicated resonance structure of the scattering cross sections and a considerable addition to the effective cross section of direct excitation, and via the radiation channel in the process of dielectronic recombination (DR) of the ion. As is known [7,8], in addition to the DR process proper (which is in many cases determinative for the ionization equilibrium of plasma), DR of ions also manifests itself in the form of satellites of the resonance and other lines of an ion appearing in the case of radiative transitions from AISs (so-called dielectronic satellites). They are present in spectra of recombining plasma (for example in spectra of solar flares, laser plasma, plasma of tokamaks, *etc.*). The wavelengths of dielectronic satellites are close to those of the corresponding spectral line of an ion and very suitable for the diagnostics of laboratory and astrophysical plasmas, as the ratio between the intensities of satellites and resonance lines essentially depends on the temperature [9].

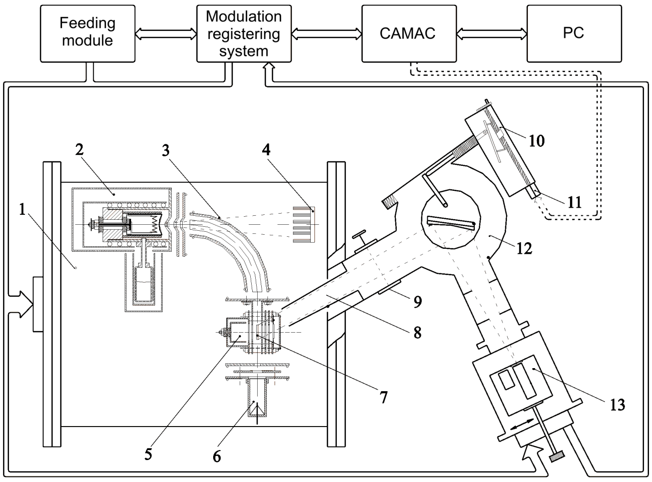

Fig. 1. Diagram of the set-up: *1* – collision chamber, *2* – ion source, *3* – ion selector, *4* – cooled atom trap, *5* – electron gun, *6* – ion collector, *7* – crossing region of beams, *8* – radiation from the collision area, *9* – vacuum shutter, *10* – control mechanism of the grating rotation, *11* – step motor, *12* – vacuum monochromator, *13* – radiation detector unit

A special kind of this type of dielectronic satellites is presented by those radiating in the case of radiative transitions between AISs. This radiation channel of decay is realized for the AISs that converge to ion levels located above resonance (lowest) ones. It is worth noting that, during almost three decades of experimental investigations of DR, the radiation observed in experiments corresponded to transitions, for which only the upper level was autoionizing, whereas the lower level represented one of the bound levels of a neutral atom (or an ion with charge multiplicity lower by unity in the case of multiply charged ions) [2, 5]. Radiative transitions between the $4d^9(^2D_{5/2,3/2})5s^2nl$ and $4d^{10}5p(^2P^o_{1/2,3/2})nl$ AISs in the process of DR in the case of electron-ion collisions were for the first time observed in the course of investigations of the near-threshold regions of the effective excitation cross sections of the $(4d^95s^{2\,2}D_{3/2} \rightarrow 4d^{10}5p^2P^o_{1/2,3/2})$ laser transitions of a Cd^+ ion [10] (there were also obtained the energy dependences of their effective cross sections). The results of this research have demonstrated that the effective excitation cross sections of dielectronic satellites amount to $\sim 10^{-17}$ cm^2 and are comparable to the effective excitation cross sections of the corresponding spectral lines.

Investigations of the electronic excitation of an In^+ ion are first of all interesting from the viewpoint of atomic physics, as it represents an atomic system with completed valence ($5s^2$) and subvalence ($4d^{10}$) shells. Moreover, it is characterized by strong correlations both inside the shells and between them and the effective simultaneous excitation (except for one of the *s*- or *d*-electrons) of two *s*-electrons, which considerably complicates the spectrum of this ion.

In this work, we present the results of the spectroscopic analysis of the excitation of the radiative transitions between the $4d^{10}5p^2(^3P_{0,1,2})nl$ and $4d^{10}5s5p(^3P^o_1)nl$ AISs of an indium atom in the case of collisions between slow electrons and In^+ ions.

2. Experimental Apparatus

The experiment was performed using the spectroscopic method under the crossing of the electron and In^+ ion beams at the right angle. As one can see from the diagram of the set-up presented in Fig. 1, it consists of a high-vacuum collision chamber that contains an ion source, ion selector, electron gun, vacuum monochromator with a mechanism allowing one to control the rotation angle of the diffraction grating, unit of radiation detectors, vacuum pumping system, power supply unit, modulation system for registration of the investigated radiation, CAMAC crate, and personal computer for the processing and storage of data. Experiments with indium metal make strict demands for the construction of the ion source, breakdown protection of the isolators of the ion-optical lens system, and the choice of optimal parameters of the experiment. The basic units of the set-up are described in [11,12] in detail. The present work includes only the aspects most important for performing these precision measurements.

A number of technical improvements of the construction of the ion source, as well as the optimal mode of its operation, allowed us to obtain a stable beam of In^+ ions (mainly in the ground-state) with a cross section of 2×2 mm^2 and a current of $I_i = 2 \times 10^{-6}$ A at an energy of 700 eV. The low-energy three-anode gun formed a strip-like electron beam with a cross section of 1×8 mm^2 in the range 9÷15 eV with a current equal to $I_e = (1 \div 1.2) \times 10^{-4}$ A.

As is known, under real conditions of studying the electron-ion collisions, one registers superweak signals from the investigated processes, which is related, first of all, to low ($< 10^7$ cm^{-3}) concentrations of the interacting particles (which are five orders of magnitude lower than the concentrations of atoms in similar experiments in the case of electron-atom collisions). That is why, in order to obtain a proper level of the useful signal, one should deal with rather high values of I_e. In turn, this results in the worsening of the energy homogeneity of the electron beam. Whence it follows that, adjusting the electron gun, it is necessary to find a reasonable compromise in the matching of the electron current I_e and the maintenance of a sufficient energy homogeneity of the electron beam. Thus, the energy homogeneity of the electron beam in our experiments amounted to $\Delta E_{1/2} \sim 0.8$ eV.

Spectral decomposition of the radiation was realized with the help of a 70-degree Seya–Namioka vacuum monochromator with a concave toroidal grating (1200 lines per mm) and the reciprocal linear dispersion $\partial\lambda/\partial l \sim 1.7$ nm/mm. The radiation was detected by means of a solar blind photomultiplier. The time of data storage at each experimental point amounted to 2000 s, whereas the magnitude of the useful signal was equal to $0.5 \div 0.2$ pulses per second at a signal/background ratio from 1/10 to 1/30.

In order to obtain the absolute cross section of electron excitation of dielectronic satellites, it was necessary to determine the spectral sensitivity of the experimental apparatus η_λ [2]. For this purpose, the intensity of the investigated radiation was to be thoroughly compared to the absolute standard. As the studied spectral lines lie in the wavelength range 100–200 nm (that is, in the ultraviolet spectral region), the most accurate calibrated source in this region is the synchrotron radiation of electron accelerators. As we had no possibility to use a synchrotron, the spectral sensitivity of the set-up was determined with the help of the technique, where the calibrated radiation source was presented by one of the gases excited by the electron impact. This technique was described in [13] in detail, and its essence consists in that, under constant measurement conditions, the spectral sensitivity of a set-up η_λ is a function of only the effective excitation cross section of the spectral line σ. Thus, knowing the electron excitation cross sections of several spectral lines of the given gas, we can determine the relative spectral sensitivity of the experimental set-up. In our case, the discrete values of the function $\eta_\lambda = f(\lambda)$ are determined according to the formula

$$\eta_{\lambda_i} = \frac{C_1\sigma_i}{C_i\sigma_1}\eta_{\lambda_1}, \tag{1}$$

where η_{λ_i} and η_{λ_1} denote the sensitivities for two spectral lines with the wavelengths λ_i and λ_1, respectively, C_i and C_1 are the signals measured at these wavelengths, and σ_i and σ_1 represent the corresponding effective excitation cross sections. Index 1 indicates the spectral line, for which η_λ was accepted to be equal to unity, and the number of values taken on by i is equal to the number of lines with known excitation cross sections.

Based on the above-stated considerations, we determined the relative spectral sensitivity of the experimental set-up with the help of the electron-impact excitation cross sections of nitrogen spectral lines [14]. Our measurements were carried out at an electron energy of 100 eV and a pressure in the collision chamber of 10^{-5} Torr. The absolute spectral sensitivity of the set-up in the wavelength range $110 \div 180$ nm was determined with an error not exceeding 30 % using, as a reference, the absolute electron-impact excitation cross section of the resonance line of an In$^+$ ion at the wavelength $\lambda = 158.6$ nm [11] obtained by normalizing the experimental data at an energy of 300 eV to the results of theoretical calculations by the semiempiric Van Regemorter formula.

3. Results and Their Discussion

An In$^+$ ion is isoelectronic with respect to a cadmium atom that obeys the general regularities of spectra with completed valence $5s^2$ and subvalence $4d^{10}$ shells. The ground state of the In$^+$ ion has the $4d^{10}5s^2\ {}^1S_0$ configuration. A simultaneous excitation of two valence $5s^2$ electrons results in the formation of additional ion states along with the common ones. Those are the so-called "shifted terms" [15], for which the radiative decay to the ground state is forbidden according to the selection rules. That is why they can combine only with each other or with common terms. The positions of the ${}^3P_{0,1,2}$, ${}^1D_2$, and ${}^1S_0$ shifted terms of the $5p^2$ configuration for the In$^+$ ion are known from the literature [16] (see Fig. 2). According to the selection rules for shifted terms [15] (if $\Delta l_i = \pm 1$ for one electron, then $\Delta l_i = 0,\ \pm 2$ for the other one; moreover, $\Delta J = 0,\ \pm 1$, except for the cases $J_1 = 0 \to J_2 = 0$), the most probable decay channel of the levels of the $5p^2$ configuration is their radiative decay into the $5s5p$ (${}^3P^o_j$, ${}^1P^o_1$) resonance levels of the In$^+$ ion.

In the course of studying the electron excitation of radiative transitions from the $4d^{10}5p^2\ {}^3P_{0,1,2}$ shifted terms of the In$^+$ ion [12] according to the reaction

$$e + \mathrm{In}^+(4d^{10}5s^2)^1S_0 \to e_1 + \mathrm{In}^{+*}(4d^{10}5p^2)^3P_{0,1,2} \to$$

$$\to e_1 + \mathrm{In}^{+*}(4d^{10}5s5p)^3P^o_1 + h\nu_{1,2,3} \tag{2}$$

($\lambda_1 = 171.7$ nm, $\lambda_2 = 167.7$ nm, and $\lambda_3 = 160.7$ nm), we revealed a radiation lower than the excitation thresholds in the wavelength interval $\lambda_i \pm 2.0$ nm with respect to each line. In order to interpret the nature of this radiation, we performed the precision investigations of the

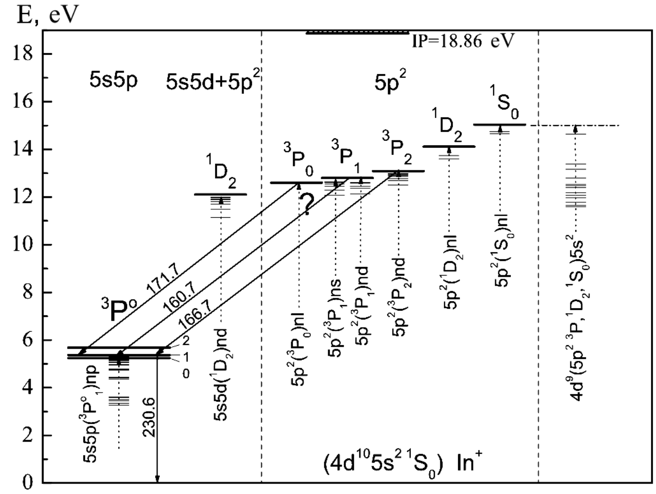

Fig. 2. Diagram of the lower levels of an In$^+$ ion and AISs converging to them

near-threshold regions of the energy dependences of the electron excitation of the indicated spectral lines.

Figure 3 presents the investigation results, the confidence interval indicated at each point with the probability 68 %, and the threshold excitation energies of the shifted terms of the In$^+$ ion [17]. The mean square error of relative measurements did not exceed ±20 % in the whole investigated energy interval. The accuracy of the energy scale determination amounted to ±0.1 eV. The absolute values of the measured excitation functions were obtained to within ±30%.

As one can see from Fig. 3, the energy dependences in the region below the excitation thresholds of the $5p^2\ {}^3P_{0,1,2}$ levels (9÷12 eV) are characterized by resonance peculiarities. Comparing their energy positions to the excitation energies of the $5p^2({}^3P_j)nl$ autoionizing states of the In atom with regard for the fact that these resonance peculiarities result from the radiation of satellite lines lying in the experimentally observed wavelength interval ($\lambda_i \pm 2.0$ nm), we concluded that they are related to the excitation of the radiative transitions between the $5p^2({}^3P_j)nl$ [16] and $5s5p({}^3P_1^o)nl$ [18] AISs. Moreover, the most probable mechanism of their excitation is the DR process:

$$e + \mathrm{In}^+(4d^{10}5s^2)\ {}^1S_0 \rightarrow \mathrm{In}^{**}\left[4d^{10}5p^2({}^3P_{0,1,2})nl\right] \rightarrow$$

$$\rightarrow \mathrm{In}^{**}\left[4d^{10}5s5p({}^3P_1^o)nl\right] + h\nu_n, \qquad (3)$$

where $\lambda_1 = 171.7 \pm 2.0$ nm; $\lambda_2 = 167.7 \pm 2.0$ nm; $\lambda_3 = 160.7 \pm 2.0$ nm, i.e. they represent dielectronic satellites of the studied spectral lines. It is worth noting that, in this case, the radiation stabilization of AISs is realized to the AISs of the $5s5pnl$ configuration (rather than to the bound states of the atom), whose convergence limit is presented by the $5s5p\ {}^3P_1^o$ resonance level of the In$^+$ ion. Moreover, the dielectronic satellites are most probably formed with participation of only those AISs of the $4d^{10}5p^2nl$ configuration, whose energies are lower than that of the $5p^2\ {}^3P_0$ level. Above the excitation threshold of this level, there exists a more energy-efficient electron channel of decay of such AISs into levels of the $5p^2$ configuration of this ion.

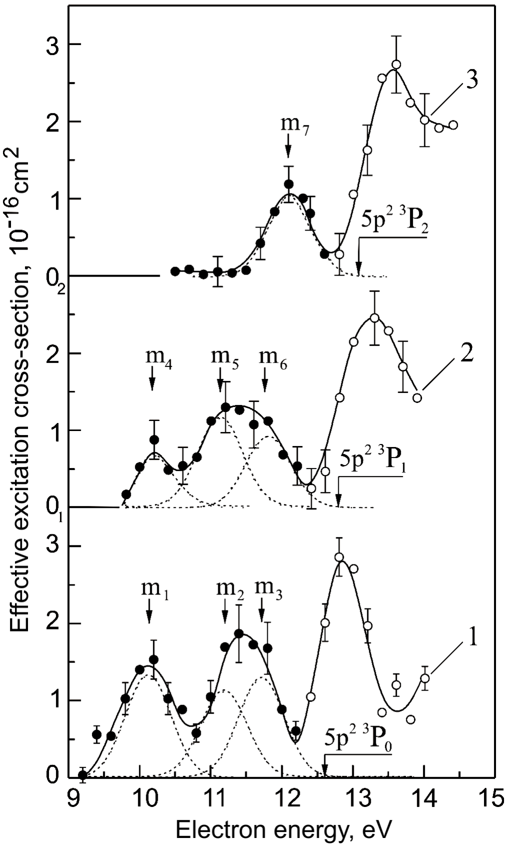

Fig. 3. Energy dependences of the effective excitation cross sections of dielectronic satellites of the spectral lines $\lambda = 171.7$ nm (*1*), $\lambda = 166.7$ nm (*2*), $\lambda = 160.7$ nm (*3*) of an In$^+$ ion

Due to the lack of data on energy positions of the AISs of the indium atom, a clear interpretation of the revealed structure is complicated. For example, among all possible AISs converging to the levels of the $5p^2$ configuration, only the energy positions of the AISs of the $5p^2({}^3P_1)ns$, $5p^2({}^3P_1)nd$, $5p^2({}^3P_2)nd$, $5p^2({}^1D_2)nl$, and $5p^2({}^1S_0)nl$ configurations are present in the literature [16]. It is strange that there are no data on the $5p^2nl$ AISs, whose convergence limit is the ${}^3P_0$ level, though such AISs for Ga^+ and Tl^+ ions are known [16]. However, for this energy region (below the $5p^2\ ^3P_0$ level), there were observed AISs identified in [16] as those of the $5p^2(^1D_2)nd$ configuration. That is, it was considered that the $5p^2\ ^1D_2$ level in In^+ is located below the triplet $5p^2\ ^3P_j$ levels. The investigations performed in [17] gave clear evidences of the fact that there exists a strong configuration interaction between the $5p^2\ ^1D_2$ and $5s5d\ ^1D_2$ levels, both of them divide between the $5p^2$ and $5s5d$ configurations. Moreover, only the latter configuration can be ascribed to the lower level. In addition, there takes place the configuration mixing among all the shifted levels of the $5p^2$ configuration, as well as among the shifted and ordinary levels. It follows from here that the AISs converging to the above-mentioned levels are also configurationally mixed, which considerably complicates, on the one hand, the identification of the revealed structural peculiarities, but, on the other hand, represents a strong argument of the fact that such a configuration mixing of the levels substantially increases the probability of radiation decay of the AISs.

It is worth noting that the obtained electron excitation functions are a superposition of the true electron excitation functions of the investigated transitions, and the energy homogeneity of the electron beam $\Delta E_{1/2} \sim 0.8$ eV. That is why, in order to study the structural peculiarities of the energy dependences below the electron excitation thresholds of the $(4d^{10}5p^2\ ^3P_j \rightarrow 4d^{10}5s5p\ ^3P_1^o)$ radiative transitions, we carried out the procedure of decomposition of the measurement results into separate components taking the magnitude of the instrument function into account by the procedure presented in [19].

With regard for the above-stated considerations, we may suppose that the structure of the studied energy dependences of the effective excitation cross sections below an energy of 10.8 eV (maxima m_1 and m_4) is caused by the radiative transitions between the lowest ($n = 6$–8) $4d^{10}5p^2(^3P_{0,1})np$ and $4d^{10}5s5p(^3P_1^o)np$ AIS configurations. As for the structural peculiarities in the energy range from 10.8 to 12.6 eV (maxima m_2, m_3, m_5, m_6, and m_7), they are resulted probably from the radiative transitions between the lowest $4d^{10}5p^2(^3P_{0,1,2})ns, np, nd$ and $4d^{10}5s5p(^3P_1^o)ns, np, nd$ AIS configurations. It is worth noting that, first, the decay of these AISs is of random nature. Second, the AISs of the $4d^95s^25p^2$ configuration are also efficiently excited in the investigated region of electron energies [16], which can considerably influence the above-mentioned mechanisms of excitation of the investigated dielectronic satellites.

4. Conclusions

The analysis of the energy dependences of the effective excitation cross sections of dielectronic satellites of the spectral lines $(4d^{10}5p^2\ ^3P_j \rightarrow 4d^{10}5s5p\ ^3P_1^o)$ of the In^+ ion has demonstrated that, along with the excitation of dielectronic satellites of the resonance lines corresponding to the radiative transitions between AISs and bound atomic states [20], there also takes place the effective excitation ($\sigma \sim 10^{-16}$ cm^2) of those related to the radiative transitions between the $4d^{10}5p^2(^3P_{0,1,2})nl$ and $4d^{10}5s5p(^3P_1^o)nl$ AISs of the indium atom. Moreover, the radiative transitions $(4d^{10}5p^2\ ^3P_j \rightarrow 4d^{10}5s5p\ ^3P_1^o)$ (or radiative cascades) represent an important factor of the population of excited atomic states and, therefore, one of the basic mechanisms of formation of the intensities of the spectral ion lines, including the dielectronic satellites of resonance lines.

The radiative transitions between the AISs initiated by DR of an ion that were chosen as the investigation object, as well as the obtained results, are interesting from the viewpoint of general physics and are important for the practical solution of a number of applied problems of plasma physics and controlled thermonuclear fusion. Among the latter, we mention the problem of ionization balance, the development of radiation models for plasma diagnostics, *etc.*. As DR represents an important element of the ionization balance and an error in its determination can substantially influence the result, a correct allowance for radiative transitions between AISs, whose main excitation mechanism is DR, is a necessary condition of the establishment of the proper relation between the observed intensities of spectral lines and plasma parameters, which forms a basis of its spectroscopic diagnostics.

Though the effective DR cross sections (or reaction rates) have been theoretically investigated for decades, the used theoretical methods give an error from 50% to a factor of 2 [5]. In this case, the calculated constants are considerably lower than the experimentally observed values. The allowance for such additional factors as relativistic effects and the influence of the external electric field on the DR behavior allowed one to approach theoretical data to experimental ones. But in spite of the substantial mathematical apparatus used in theoretical works, a large discrepancy between theory and experiment makes one think that the theoretical calculations do not take into account some fundamental peculiarity of DR. The analysis of the results of our researches gives grounds to state that one of such peculiarities is the radiative cascade from AISs to lower AISs.

In addition to a substantial improvement of the experimental conditions (in particular, the energy homogeneity of the electron beam), a more solid analysis of the manifestation of AISs in inelastic collisions of slow electrons with such complex many-electron system as In^+ ion requires theoretical calculations with regard for the radiation decay of AISs. This especially concerns the energy region near the excitation thresholds of spectral lines, where the resonance contribution of AISs is dominant, which will allow one to solve a number of problems related to the competition between the processes of autoionization and radiation.

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РАДІАЦІЙНІ ПЕРЕХОДИ МІЖ АВТОІОНІЗАЦІЙНИМИ $4d^{10}5p^2(^3P_j)nl$- ТА $4d^{10}5s5p(^3P_1^o)nl$-СТАНАМИ АТОМА In ПРИ ЗІТКНЕННІ ПОВІЛЬНИХ ЕЛЕКТРОНІВ З ІОНАМИ In^+

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Резюме

Вперше виявлено радіаційні переходи між $4d^{10}5p^2(^3P_{0,1,2})nl$ та $4d^{10}5s5p(^3P_1^o)nl$ автоіонізаційними станами атома індію, що є діелектронними сателітами $4d^{10}5p^2\ ^3P_0 \rightarrow 4d^{10}5s5p\ ^3P_1$ ($\lambda = 171,7$ нм), $4d^{10}5p^2\ ^3P_1 \rightarrow 4d^{10}5s5p\ ^3P_1$ ($\lambda = 166,7$ нм) та $4d^{10}5p^2\ ^3P_2 \rightarrow 4d^{10}5s5p\ ^3P_1$ ($\lambda = 160,7$ нм) спектральних ліній іона In^+. Спектроскопічним методом в умовах пучків електронів та іонів In^+, що перетинаються, досліджено енергетичні залежності ефективних перерізів збудження діелектронних сателітів та біляпорогових ділянок цих спектральних ліній в інтервалі енергій електронів 9÷15 еВ. Абсолютні величини перерізів збудження діелектронних сателітів становлять $(0,7 \div 2) \cdot 10^{-16}$ см^2 і є одного порядку величини з ефективними перерізами збудження відповідних іонних ліній. Показано, що суттєве зростання ймовірності радіаційного розпаду $4d^{10}5p^2(^3P_{0,1,2})nl$-автоіонізаційних станів атома In пов'язано з сильними релятивістськими та кореляційними ефектами, зокрема, з конфігураційною взаємодією $5p^2nl$-рівнів як між собою, так і з рівнями $5s5dnl$ та $4d^95s^25p^2$-конфігурацій.