NEAR-THRESHOLD EXCITATION OF THE RESONANCE λ 158.6 nm LINE IN ELECTRON-INDIUM ION COLLISIONS

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Near-threshold electron-impact excitation of the resonance In^+ ion $5s5p\,^1P_1^o \to 5s^2\,^1S_0$ ($\lambda =$ 158.6 nm) line is studied using a spectroscopic method and a crossed (at right angle) monoenergetic electron and ion beams technique. Strong resonance features observed in the energy dependence of the effective excitation cross-section for this line are due to the emission of the dielectronic satellites $4d^{10}5s5p(^1P_1^o)np \to 4d^{10}5s^2np$ of the resonance line below threshold and resonance excitation due to the electron decay of the autoionizing states above threshold. At the threshold of the resonance line excitation the radiative decay of the autoionizing states affects significantly both the shape and the value of the effective excitation cross-section.

Key words: electron, indium ion, excitation, dielectronic recombination, autoionizing state.

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I. INTRODUCTION

Under electron scattering by the positively charged ions the long-range Coulomb field results in the specific features in the effective excitation cross sections. This is due to the formation and decay of the autoionizing states (AIS) of the system "electron + ion", i.e. due to the so-called resonance scattering. The formation of AIS results from the resonance attachment of incident electron with simultaneous excitation of the ionic electron. The above states decay via two channels: electron and radiative ones. The electron channel of the AIS decay within the energy range below the thresholds of new channels is revealed in a form of the resonances in the elastic electron-ion scattering cross-sections, while above these thresholds it is revealed as the resonances in the ion excitation cross-sections. As Gailitis has shown [1], the averaged contribution of the resonances into the electron excitation cross-section for the spectral transition is, by the order of magnitude, equal to the cross-section of the direct excitation via this channel. The radiative decay of AIS results in the dielectronic recombination (DR) of ion.

The DR mechanism was described by Massey and Bates [2] as far back as in 1942. But only beginning with Burgess' paper [3] a considerable (and, sometimes, crucial) role of the above process in the establishment of ionization equilibrium and plasma (in particular, the solar corona one) evolution has been found. Three most essential DR demonstrations are known: (a) DR, i.e. the process, which in the most cases is determinative in the ionization equilibrium in plasma; (b) the resonance and other ionic lines satellites arising in the radiative transitions from AIS (the so-called dielectronic satellites, taking place in the recombinating plasma e.g., in the solar flash spectra, laser and TOCAMAC plasma etc.); (c) additional excitation of ionic levels at the electron decay of AIS (additional satellites), which does not play an essential role in the total DR balance.

In the first two cases, photon emission occurs at the transition of the "inner" AIS electron, and the state of the outer electron is not changed. The radiative transition of the outer electron results in the additional satellites.

Dielectronic satellites (as a rule, belonging to the resonance lines) have their wavelengths close to those of the corresponding ionic spectral line and are very convenient in laboratory and astrophysical plasma diagnostics, since the ratio of the satellite and resonance lines intensities depends strongly on temperature.

In relation with the aforementioned, the direct experimental revelation of the AIS contribution and elucidation of their role in the near-threshold electron-impact excitation of ions is of specific interest.

Earlier [4] we reported on the studies of the energy dependence of the effective excitation cross-section for the resonance In^+ ion $5s5p\,^1P_1^o \to 5s^2\,^1S_0$ ($\lambda = 158.6$ nm) line within the energy range of 7÷300 eV. The results obtained indicated a complicated mechanism of electron excitation, since, besides the direct excitation, the contribution of the resonance processes due to AIS was quite substantial. To study deeper the mechanism of electron excitation of In^+ ion, especially in the near-threshold electron energy range, where the resonance contribution is the largest, it appeared necessary to carry out more precise studies with enhanced electron energy resolution.

In this paper, we present the results of spectroscopic studies of the resonance structure revealed in the near-threshold electron-impact excitation of the resonance In^+ ion λ158.6 nm line and suggest the physical justification of the origin of their formation.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

The experiment was carried out by a photon spectroscopy method using a crossed electron and ion beam technique with an apparatus described elsewhere [5], which allows detailed studies to be performed with the energy resolution $\Delta E_{1/2} \sim 0.4$ eV. The specific features of the experimental technique for studying the processes occurring at the inelastic slow electron collisions with indium ions are described in detail in [4]. The schematic layout of the experimental apparatus is shown in Fig. 1.

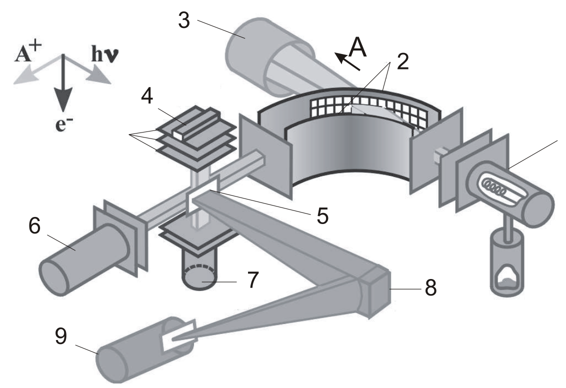

Fig. 1. Schematic layout of experimental setup: 1 — ion source; 2 — electrostatic ion selector; 3 — cooled atom trap; 4 — electron gun, 5 — observed volume; 6,7 — deep Faraday cups; 8 — diffraction grate of the vacuum monochromator; 9 — cooled solar-blind photomultiplier.

The experiments with metal indium are a complicated and laborious task for a number of reasons: (i) desired indium atom vapor pressure in the ion source ($10^{-3} - 10^{-2}$ Torr) is reached at high temperatures (900–1000) °C, while indium melting point is 156 °C; (ii) at such temperatures this metal is chemically aggressive that results in the destruction of ion source parts and intense production of liquid metal phase at the ceramic insulators; (iii) when the ion source operates in the discharge mode, the low-lying metastable $^3P^o_{0,2}$ states of In^+ ion could be produced effectively. The above peculiarities put strict requirements on the ion source design. We have developed new design of the ion source [4], which allowed one to take into account these requirements and obtain a stabilized In^+ ion beam ($E_i = 700$ eV, $I_i = 2 \cdot 10^{-6}$ A). Electron beam current in the energy region of $E_e = (5 \div 17)$ eV was $I_e = (5 \div 10) \cdot 10^{-5}$ A at the energy spread (FWHM) of $\Delta E_{1/2} = 0.4$ eV. Spectral separation of radiation was carried out by means of a vacuum monochromator based on the Seya–Namioka scheme. The inverse linear dispersion of monochromator was $\partial\lambda/\partial l \approx 1.7$ nm/mm. A cooled solar-blind photomultiplier was used to detect radiation.

Modulation of both beams by square voltage pulses phase-shifted by 1/4 of the modulation period was used to extract the signal due to the process under study against the total background. The signal of the $(1 \div 0.2)$ s^{-1} magnitude was extracted against the background at the signal to background ratio of 1/10 to 1/30. The process of the measurements and the analysis of results were automated using an IBM PC.

The valid signal at each point was accumulated for 1500–2000 s. In this case the mean square error at the 68% confidence level (CL) did not exceed 10% at the maximum of excitation function for the resonance In^+ ion line and 15% for the dielectronic satellites. Electron energy scale was calibrated with the ±0.1 eV accuracy.

Measuring the electron excitation of the resonance In^+ ion line was carried out in two stages. First the optical excitation function $f(E)$ of the $\lambda = 158.6$ nm resonance line, i. e. the relative intensity of the above line at different incident electron energies at $I_i = \mathrm{const}$ was measured:

$$f(E) = C/I_e, \tag{1}$$

where C is the valid signal, I_e is a total electron current.

One has to take here into account that the measured excitation function $f_{\mathrm{exp}}(E)$ is, in fact, the convolution of two functions — $f_{\mathrm{true}}(E)$ and $g(E)$, where $f_{\mathrm{true}}(E)$ is the true experimental excitation function, and $g(E)$ is the electron energy distribution function. The use of electron beams with high energy resolution reduces the discrepancies between $f_{\mathrm{exp}}(E)$ and $f_{\mathrm{true}}(E)$ and allows such fine effects in the excitation functions as the resonances to be studied.

On the second stage the absolute values of the effective excitation cross-sections for dielectronic satellites of the resonance In^+ ion line were determined at the threshold taking into account the absolute resonance line excitation cross-section obtained by us earlier (see [4]). The absolute values of the effective excitation cross-sections for dielectronic satellites were obtained with the 25% uncertainty at the 68% CL.

III. RESULTS AND DISCUSSION

We have carried out precise measurements of the near-threshold area of the energy dependence of the effective excitation cross-section for the resonance In^+ ion line within the $5 \div 17$ eV energy range:

$$\begin{array}{l} e + \mathrm{In}^+(4d^{10}5s^2)^1S_0 \to \mathrm{In}^{+*}(4d^{10}5s5p)^1P^o_1 + \tilde{e} \\ \qquad\qquad\qquad\qquad\quad \downarrow \\ \qquad\qquad\qquad\qquad\quad \mathrm{In}^+(4d^{10}5s^2)^1S_0 + h\nu\,(\lambda = 158.6\,\mathrm{nm}) \end{array} \tag{2}$$

The results of the studies are shown in Fig. 2. Vertical bars in this figure indicate the mean-square errors of relative measurement.

As seen from Fig. 2, the energy dependence under study reveals distinct structural features both below and above the threshold of resonance level excitation. The FWHM of the below-threshold maxima is comparable to that of electron beam energy spread, i.e. these maxima are of a resonance character. This allows one to assume that these maxima are due to the resonance capture of incident electrons by $In^+(4d^{10}5s^2)^1S_0$ ions with the excitation of the "electron + ion" system into the indium atom AIS with subsequent radiative decay of the above AIS in the DR process (3), i. e. the radiative stabilization of AIS into the bound atomic states. The electron decay of AIS is a competing channel and this results in the appearance of resonances in the elastic scattering (5):

$$\mathrm{In}^*(4d^{10}5s^2nl) + h\nu_n \qquad (3)$$

$$\nearrow \mathrm{In}^{**}\left[4d^{10}5s5p(^1P_1^o)n_1l_1\right] + h\nu_m \qquad (4)$$

$$\mathrm{In}^{**}\left[4d^{10}5sn\,\mathrm{l}n_1\,l_1\right]$$

$$\searrow \mathrm{In}^+(4d^{10}5s^2)^1S_0 + e_1' \qquad (5)$$

$$\mathrm{In}^{+*}(4d^{10}5s5p)^1P_1^o + e_2' \qquad (6)$$

Beginning from the excitation energy of the $5s5p\ ^1P_1^o$ level, the electron decay of AIS (6) leads to the resonance contribution into the effective excitation cross-section of the resonance line, while the radiative decay (4) results in dielectronic satellites that emit at the radiative transitions between AIS.

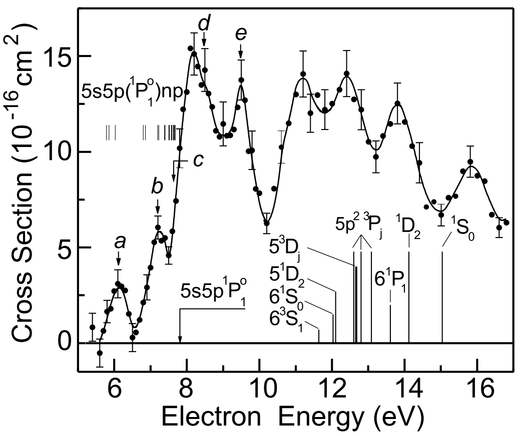

Fig. 2. Energy dependence of the near-threshold electron-impact excitation cross-section for In^+ resonance λ158.6 nm line.

Most probably, below the excitation threshold of the In^+ ion resonance level the In atom AIS of the $4d^{10}5s5p(^1P_1^o)nl$ configuration are involved in the DR process. When such AIS decay radiatively, the photons are emitted with wavelengths close to that of the resonance $4d^{10}5s5p\,^1P_1^o \to 4d^{10}5s^2\,^1S_0$ line of In^+ ion. This radiation distorts the resonance line profile due to the appearance of close additional spectral lines, which are the dielectronic satellites of the resonance line. Indeed, radiative $4d^{10}5s5pnl \to 4d^{10}5s^2nl$ transitions are similar to the resonance $4d^{10}5s5p \to 4d^{10}5s^2$ transition, but are realized with the involvement of an additional electron with the nl quantum numbers. They are revealed in the electron excitation function for the spectral line under investigation as the additional resonances in the near-threshold energy region.

The analysis of the results using the data on the energy positions and configurations of In atom AIS [6–9] has shown that an isolated maximum (a) at 6.1 eV in the energy dependence under study is, most likely, related to the decay of the $In^{**}4d^{10}5s5p(^1P_1^o)6p$ AIS, while the maximum (b) at 7.2 eV — with that of the In^{**} states of the $4d^{10}5s5p(^1P_1^o)8p$ configurations into the $4d^{10}5s^2np$ ($n = 6$ and 8, respectively) In atom states. Beginning from $n \geq 9$, the AISs of the $4d^{10}5s5p(^1P_1^o)nl$ configurations are located very densely within a narrow energy interval, and, therefore, dielectronic satellites are not separated spectroscopically, giving a total contribution into the DR process. However, in this case the most probable contribution to their emission is due to the $4d^{10}5s5p(^1P_1^o)np$ AIS as well.

We failed to separate the energy dependences of the effective cross-sections for dielectronic satellites and those for the excitation of the resonance line at the energies close to the excitation threshold for the $5s5p\ ^1P_1^o$ level (7.81 eV). This is due to the electron energy spread. However, one can see, that the ascending area of excitation function reveals a feature (***c***) in the form of a fold, which coincides energetically with the $4d^{10}5s5p(^1P_1^o)np$ ($n \geq 9$) In atom AIS. This indicates that radiative decay of AIS lying close to the resonance level excitation threshold affects considerably the resonance excitation, reducing, thus, its effective cross-section.

Above the $5s5p\,^1P_1^o$ level excitation threshold, where the resonance AIS contribution is possible only, the (d) and (e) features are observed at 8.5 eV and 9.5 eV, respectively. Note that in the photoabsorption spectra for In atom no AIS were found in this energy region [6, 9]. However, the ejected-electron spectra of In atom [8] just at these energies reveal strong lines identified as the In atom AIS of the $4d^{10}5s5p5d$ configuration.

As seen from Fig. 2, in the vicinity of ~10 eV a deep minimum is observed (by the way, the ejected-electron spectra of In atom also showed no strong lines in this region). Only beginning from the excitation energy for the $5s6s\,^3S_1$ level (11.64 eV), i.e. the first level, which the cascade transitions to the resonance level are possible from, the excitation function again reveals a structure. To analyze this structure in the above energy region we applied the model of electron capture with AIS formation and decay, taking into account the cascade transitions from the higher ionic $4d^{10}n\,\mathrm{l}n_1\,l_1\,^{1,3}L_j$ levels and AIS, which converge to them. It should be noted that AIS of the $4d^95s^25pnl$ configuration produced under excitation of the $4d^{10}$ subvalence shell [9] and, in particular, the AIS of the $4d^95s^25p^2$ configuration, which give considerable additional resonance contribution to the electron-impact excitation of the resonance line, are also observed in this region.

IV. CONCLUSIONS

The energy dependences of the effective excitation cross-sections for dielectronic satellites of the resonance In^+ ion line have shown that the DR process is a major mechanism of their excitation. In this case the direct excitation of the ion affects DR only indirectly due to the influence on the autoionization probability. However, the resonance excitation influences considerably the DR, since these two channels compete, and conversely, threshold excitation of the resonance DR $5s5p\,^1P_1^o$ level results in the decrease of the efficiency of the resonant excitation. Thus, we have confirmed experimentally the theoretical assumption [10] that, though the resonances play an essential role in electron excitation, the radiative transitions resulted in the DR process may damp them considerably.

The absolute values of the excitation cross-sections for dielectronic satellites reach $(3 \div 6) \cdot 10^{-16}$ cm^2 and are only 3–5 times smaller than the maximum value of the resonance line excitation cross-section [4].

The DR efficiency depends strongly of the ratio of radiative and electron AIS decay probabilities. In the case of In^+ ion an essential correlation effects take place together with strong configuration mixing of levels resulted in the pronounced increase of probability of radiative AIS decay.

Measuring the effective electron excitation cross-sections for satellite lines, as well as the effective cross-section of resonance line excitation, allows one to check experimentally the conclusions of the theory concerning the competition between the autoionization and radiative processes and, in particular, to estimate the accuracy of calculated probabilities of both autoionization and radiative AIS decay. As known [11], no interference takes place between autoionization and radiation, and their separation factor has a clear physical sense, even provided the relevant probabilities are of the same order of magnitude. It seems much more difficult to estimate the reduction of the cross-section due to the radiative decay. The above process of radiative decay of AIS, usually ignored in the scattering problems, results in deformation of excitation cross-section at the threshold and its considerable decrease close to the threshold.

Unfortunately, up to date there are no quantum-mechanical theoretical calculations capable of adequate description of electron-impact excitation mechanism for the In^+ ion. Therefore, to provide further progress in studying the AIS revelation in the effective excitation cross-sections for such complex many-electron ions as In^+, one requires quantum-mechanical calculations with the allowance made for radiative, not only electron, decay of AIS. Especially this is related to the near-threshold energy region, where the resonance contribution of AIS dominates.

[1] M. Gailitis, Zh. Eksp. Teor. Fiz. **44**, 1974 (1963) [Sov. Phys. JETP **17**, 1328 (1963)].
[2] H. S. W. Massey, D. R. Bates, Rep. Prog. Phys. **9**, 62 (1942).
[3] A. Burgess, Astrophys. J. **139**, 776 (1964).
[4] A. Gomonai, E. Ovcharenko, A. Imre, Yu. Hutych, Nucl. Instrum. Methods Phys. Res. B **233**, 250 (2005).
[5] A. N. Gomonai, Opt. Spectrosc. **94**, 488 (2003).
[6] M. A. Baig, I. Ahmed, J. P. Connerade, J. Phys. B **21**, 35 (1988).
[7] D. Kilbane *et al.*, J. Phys. B **39**, 773 (2006).
[8] G. K. James, D. Rassi, K. J. Ross, M. Wilson, J. Phys. B **15**, 275 (1982).
[9] J. P. Connerade, Proc. Roy. Soc. London **A352**, 561 (1977).
[10] A. K. Pradhan, Phys. Rev. Lett. **47**, 79 (1981).
[11] B. Shore, Rev. Mod. Phys. **39**, 439 (1967).

ПРИПОРОГОВЕ ЗБУДЖЕННЯ РЕЗОНАНСНОЇ ЛІНІЇ λ 158.6 нм ЙОНА ІНДІЮ ЕЛЕКТРОННИМ УДАРОМ

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Спектроскопічним методом в умовах пучків моноенерґетичних електронів і йонів, що перетинаються під кутом 90°, досліджено припорогове збудження резонансної лінії $5s5p\ ^1P_1^o \rightarrow 5s^2\ ^1S_0$ (λ158.6 нм) йона In^+ електронним ударом. Допорогові особливості на енерґетичній залежності ефективного перерізу збудження цієї лінії пов'язані з діелектронним захопленням налітаючого електрона йоном, збудженням системи "електрон+йон In^+" в $4d^{10}5s5p\ (^1P_1^o)\,np$ автойонізаційні стани та їх радіаційним розпадом на $4d^{10}5s^2np$ стани атома In, тобто є діелектронними сателітами резонансної лінії. У порозі збудження резонансної лінії процес радіаційного розпаду автойонізаційних станів, який зазвичай нехтують у задачах про розсіювання, призводить до деформації перерізу збудження в порозі та його суттєвого зменшення поблизу порога. Вимірювання ефективних перерізів електронного збудження сателітних ліній разом з ефективним перерізом збудження резонансної лінії дає змогу експериментально перевірити висновки теорії про конкуренцію між автойонізацією та радіаційними процесами і, зокрема, оцінити точність розрахованих імовірностей електронного та радіаційного розпаду автойонізаційних станів.