Triply excited states in dielectronic recombination with excited He-like uranium

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(Received 15 June 2018; published 9 July 2018)

We study process of dielectronic recombination with He-like uranium initially being in one of the metastable states [$(1s2s)_0$ and $(1s2p_{1/2})_0$]. We consider resonant regions of the incident electron energy corresponding to participation of triply excited states of Li-like uranium. The total and differential cross sections for dielectronic recombination as well as the energies and widths of the autoionizing states are calculated accurately within the QED theory. The cross section of the considered process is comparable in order of magnitude with the cross section of dielectronic recombination with H-like or He-like uranium initially being in the ground states. We investigated the contribution of the Breit interaction to the cross section; in particular, we found that the Breit interaction may both significantly increase and decrease the cross section.

DOI: 10.1103/PhysRevA.98.012503

I. INTRODUCTION

Processes of electron capture by ions [radiative electron capture (REC), dielectronic (DR) and trielectronic (TR) recombinations[and processes of electron loss from ions [direct electron loss, excitation-autoionization (EA) and resonant excitation double autoionization (REDA)] actively proceed in highly ionized laboratory and astrophysical plasmas [1–3]. Accordingly, accurate theoretical description of these processes is required for detailed investigation of the plasma [4,5]. Many of these processes are resonant, and because of that they are very important and interesting subjects for investigation. In general, the autoionizing states determine the resonance structure of the collision processes and, therefore, they continue to trigger the interest of researchers working in different fields of physics from both experimental and theoretical points of view. The autoionizing states can be also interesting for investigation of the two-electron one-photon (TEOP) transitions [6].

In the present paper we focus our attention on the properties of triply excited (autoionizing) states; in particular, on their role in electronic recombination with initially He-like highly charged ions (HCIs). Cross sections for the production and Auger decay of the triply excited states formed in collisions of He-like ions of Pr with H_2 were studied experimentally in [7]. The contribution of triply excited states to the electronic recombination was observed in [8–10], where the processes of di-, tri-, and quadrielectronic recombination with medium-Z ions of Kr, Fe, and Ar were investigated experimentally and theoretically. A large contribution of the tri- and quadrielectronic recombination was reported. The resonant electronic recombination with Si^{q+} ($q = 2$–8) was studied in [11]; in particular, the participation of ions initially being in metastable states was considered and the contribution of autoionizing states (including triply excited states) was investigated in detail.

Autoionizing states are also important for resonant electron loss processes such as EA and REDA, which were investigated in a lot of works; see, for example, [12–16]. The process of REDA was first studied by LaGattuta and Hahn in [13]. This process in electron-ion collisions proceeds via triply excited states significantly contributing to electron-loss cross sections [13–16].

The process of electronic recombination with one and more electron HCI usually is considered as a compound process which includes a nonresonant part (represented by the REC) and a resonant one (DR, TR, etc.). The REC is a one-step (direct) process where HCI captures an electron to a bound state with a simultaneous emission of photon, whereas the DR and TR are more complicated and present two-step processes of electron capture. The first step is formation of an autoionizing state: the incident electron is captured to an excited bound state of HCI, and the released energy is spent for the promotion of other bound electron(s) (one electron for DR and two electrons for TR) of HCI to more excited bound state(s). The second step is the radiative decay of the autoionizing state. The DR and TR are always seen together with the nonresonant process of REC. Hence, for observation of the DR and TR in the electron capture, their partial contributions to the cross section should be comparable with the nonresonant background from the REC.

Electronic recombination with He-like ions is the most simple process where the contribution of triply excited states can be important. We note that, if a He-like ion is initially in its $(1s^2)$ ground state, then triply excited states can participate only in the TR. In this case the formation of triply excited states goes via the excitations of the both $1s$ electrons, which is described by two and more photon exchange corrections. The REC does not require a consideration of the photon exchange corrections. Accordingly, in the case of He-like HCI being in its ground state, the contribution of triply excited states is negligible, which was confirmed by our calculation in [17].

However, if we consider the electron capture by He-like HCI initially being in an excited (metastable) state, the triply excited states can participate also in the DR. In this case the formation of triply excited states requires excitation of only one $1s$ electron, which can be described by one-photon-exchange Feynman graphs. Accordingly, the DR in general can compete with the REC [17]. The present accurate calculations confirm

that the participation of the triply excited states in the DR with He-like HCI initially being in a metastable state is significant. Our results show that the contribution of the triply excited states to the cross section of the DR with He-like HCI initially being in the metastable states is comparable with the cross section of DR with H-like HCI [18] as well as with the cross section of the DR with He-like HCI [17] initially being in the ground states.

II. METHOD OF CALCULATIONS

In the present work we consider the following REC and DR processes, respectively:

$$e^- + U^{90+}(i) \to U^{89+}(f) + \gamma, \tag{1}$$

$$e^- + U^{90+}(i) \to U^{89+}(t) \to U^{89+}(f) + \gamma, \tag{2}$$

where γ denotes an emitted (resonant) photon. The initial state of He-like uranium (i) is a single excited state [$(1s2s)_0$ or $(1s2p_{1/2})_0$]. The intermediate state (t) is one of the following triply excited states: $(2s,2s,2p)$, $(2s,2p,2p)$, or $(2p,2p,2p)$. We consider only those final states of Li-like uranium (f) which can be obtained by one-photon decay of the intermediate states (t). Thus, (f) denotes one of $(1s2s2s)$, $(1s2p2s)$, and $(1s2p2p)$ states. We also assume that the incident electron as well as the initial state of the HCI are unpolarized.

The previous studies reported that the Breit interelectron interaction may play a very important role in the process of electronic recombination with HCI [17–24]. Accordingly, the precise calculation of the DR with HCIs should be performed within the framework of QED.

The present calculations of the processes given by Eqs. (1) and (2) are based on the line-profile approach (LPA) [17,25,26]. Within the framework of the LPA the quasidegenerative QED perturbation theory is used for description of HCIs and their interactions with incident electrons. According to the LPA the amplitude of the process presented in Eqs. (1) and (2) reads as

$$U_{if} = (-ie)\int d^3\mathbf{r}_1 d^3\mathbf{r}_2 d^3\mathbf{r}_3\, \Phi_f(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)\gamma^\nu \big(A_\nu^{(k,\lambda)*}(\mathbf{r}_1) + A_\nu^{(k,\lambda)*}(\mathbf{r}_2) + A_\nu^{(k,\lambda)*}(\mathbf{r}_3)\big)\Phi_i(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3), \tag{3}$$

where i and f denote the initial [e^- and $(1s2s)_0$ or e^- and $(1s2p_{1s})_0$] and the final three-electronic states of the system. Relativistic units are used throughout unless otherwise stated. In Eq. (3) γ^ν are the Dirac gamma matrices ($\nu = 0,1,2,3$) and $A^{(k,\lambda)\nu} = (A_0^{(k,\lambda)}, \boldsymbol{A}^{(k,\lambda)})$ describes the photon with a wave 4-vector $k^\nu = (\omega,\mathbf{k})$ and polarization λ. The transverse gauge is used:

$$A_0^{(k,\lambda)}(\mathbf{r}) = 0, \tag{4}$$

$$\boldsymbol{A}^{(k,\lambda)}(\mathbf{r}) = \sqrt{\frac{2\pi}{\omega}}\boldsymbol{\epsilon}^{(\lambda)} e^{i\mathbf{k}\cdot\mathbf{r}} = \sqrt{\frac{2\pi}{\omega}}\sum_{j_0 l_0 m_0} i^{l_0} g_{l_0}(\omega r)\big(\boldsymbol{\epsilon}^{(\lambda)}, \boldsymbol{Y}^*_{j_0 l_0 m_0}(\boldsymbol{k})\big)\boldsymbol{Y}_{j_0 l_0 m_0}(\boldsymbol{r}), \tag{5}$$

where the multipole expansion was employed [27]. Here, $g_{l_0}(x) = 4\pi j_{l_0}(x)$ and $j_{l_0}(x)$ is the spherical Bessel function, the $\boldsymbol{Y}_{j_0 l_0 m_0}$ are the vector spherical harmonics, and $\boldsymbol{\epsilon}^{(\lambda)}$ is the vector of photon polarization. We introduce two pairs of vectors of the linear photon polarizations:

$$\boldsymbol{\epsilon}_{90^\circ} = \frac{[\boldsymbol{p}\times\boldsymbol{k}]}{|[\boldsymbol{p}\times\boldsymbol{k}]|}, \quad \boldsymbol{\epsilon}_{0^\circ} = \frac{[\boldsymbol{\epsilon}_{90^\circ}\times\boldsymbol{k}]}{|[\boldsymbol{\epsilon}_{90^\circ}\times\boldsymbol{k}]|} \tag{6}$$

and

$$\boldsymbol{\epsilon}_{45^\circ} = \frac{1}{\sqrt{2}}(\boldsymbol{\epsilon}_{90^\circ} + \boldsymbol{\epsilon}_{0^\circ}), \quad \boldsymbol{\epsilon}_{135^\circ} = \frac{1}{\sqrt{2}}(\boldsymbol{\epsilon}_{90^\circ} - \boldsymbol{\epsilon}_{0^\circ}). \tag{7}$$

The circular polarizations of the photon is defined as

$$\boldsymbol{\epsilon}_+ = \frac{1}{\sqrt{2}}(\boldsymbol{\epsilon}_{90^\circ} + i\boldsymbol{\epsilon}_{0^\circ}), \qquad \boldsymbol{\epsilon}_- = \frac{1}{\sqrt{2}}(\boldsymbol{\epsilon}_{90^\circ} - i\boldsymbol{\epsilon}_{0^\circ}). \tag{8}$$

The z axis is defined by the incident electron momentum $\boldsymbol{p}$. Accordingly, the vectors $\boldsymbol{p}$ and $\boldsymbol{k}$ and the polarization vectors look like

$$\frac{\boldsymbol{p}}{|\boldsymbol{p}|} = \begin{pmatrix}0\\0\\1\end{pmatrix}, \quad \frac{\boldsymbol{k}}{|\boldsymbol{k}|} = \begin{pmatrix}\sin\theta\cos\phi\\ \sin\theta\sin\phi\\ \cos\theta\end{pmatrix}, \tag{9}$$

$$\boldsymbol{\epsilon}_{90^\circ} = \begin{pmatrix}-\sin\phi\\ \cos\phi\\ 0\end{pmatrix}, \quad \text{and} \quad \boldsymbol{\epsilon}_{0^\circ} = \begin{pmatrix}\cos\theta\cos\phi\\ \cos\theta\sin\phi\\ -\sin\theta\end{pmatrix}, \tag{10}$$

respectively. The electron-ion collision process has an axial symmetry and does not depend on the angle ϕ.

The functions Φ_i and Φ_f in Eq. (3) are represented as a linear combination of the Slater determinants Ψ_k in the j-j coupling scheme [25]:

$$\Phi_{n_g} = \sum_{k_g\in g} B_{k_g n_g}\Psi^{(0)}_{k_g} + \sum_{k\notin g, l_g\in g}[\Delta V]_{k l_g}\frac{B_{l_g n_g}}{E^{(0)}_{n_g} - E^{(0)}_k}\Psi^{(0)}_k + \cdots, \tag{11}$$

where n_g is a reference state (the initial or final state) and indices k, l_g describe the three-electron configurations: the index l_g runs over all configurations of the set g; the index k runs over all the configurations not included in the set g. Within the framework of the LPA the set g includes all three-electron configurations consisting of one-electron states $1s,2s,2p,3s,3p,3d$ and e (the incident electron). In particular, the set g includes all triply excited states considered in this paper, as well as other three-electron configurations that have an energy close to the energy of the reference states. Here, $E^{(0)}_k$ is the energy of the three-electron configuration $\Psi^{(0)}_k$: sum of the one-electron Dirac energies,

$$\Psi_k(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3) = N\sum_{m_1,m_2,m_3,m_{12}} C^{j_{12}j_3}_{JM}(m_{12}m_3)C^{j_1 j_2}_{j_{12}m_{12}}(m_1 m_2) \times \det\big\{\psi_{n_1 j_1 l_1 m_1}(\mathbf{r}_1),\psi_{n_2 j_2 l_2 m_2}(\mathbf{r}_2),\psi_{n_3 j_3 l_3 m_3}(\mathbf{r}_3)\big\}, \tag{12}$$

where $k = \{JMj_{12}n_1 j_1 l_1 n_2 j_2 l_2 n_3 j_3 l_3\}$ denotes a set of all quantum numbers defining a certain three-electron state, N is the normalization factor, and $C^{j_1 j_2}_{j_{12}m_{12}}(m_1 m_2)$ are the Clebsch-Gordan coefficients [28]. In Eq. (12) the one-electron wave functions $\psi_{n_i j_i l_i m_i}$ denote solutions of the Dirac equation with the corresponding quantum numbers: n_i (the principal

quantum number for the solutions from the discrete part of spectrum or the energy for the solutions from the continuum part of spectrum), j_i (the angular momentum), l_i [defining the parity $(-1)^{l_i}$], and m_i (the projection of the j_i) ($i = 1,2,3$). Coefficients $B_{k_g n_g}$ and $[\Delta V]_{kl_g}$ in Eq. (11) are obtained within the LPA, and in this work they contain, in particular, the electron self-energy (SE), vacuum polarization (VP), one- and two-photon exchange corrections. The ellipsis at the end of Eq. (11) denotes the second and higher order corrections of QED perturbation theory. The application of the LPA for investigation of the DR with He-like HCI is presented in detail in [17].

The cross section differential in solid angle of the emitted photon ($\Omega_{\mathbf{k}}$) reads as

$$\frac{d\sigma}{d\Omega_{\mathbf{k}}} = \frac{1}{2(2\pi)^2}\frac{\varepsilon}{p}\sum_{\mu,\lambda,f}\omega^2|U_{if}|^2, \tag{13}$$

where ε, p, and μ denotes energy, momentum, and polarization of the incident electron, respectively. In this expression we perform the summation over all final states of the system considered in the present work, and average over the polarizations of the incident electron.

We would like to note that the summation over index k in the second term of Eq. (11) runs over the complete three-electron basis set (excluding the states of the set g already taken into account in the first term) which also includes the contribution of the continuum part of the Dirac spectrum. The resonance structure of the DR cross section is determined by the contributions of the triply excited states [see Eq. (2)]. This contribution is given by the first term of Eq. (11), while the second term gives a small nonresonant correction to the cross section. In the present work the second term of Eq. (11) was omitted. The contribution of the second term and, in particular, the contribution of the states containing the continuum electrons (describing also the interaction of the autoionizing states through the continuum [29]) was investigated in works of Yerokhin and Surzhykov [30,31], where this contribution to the energy of three-electron configurations was investigated.

III. RESULTS AND DISCUSSION

The total cross sections of the dielectronic recombination with initially He-like uranium in the metastable $(1s2s)_0$ and $(1s2p_{1/2})_0$ states are presented as a function of the incident electron kinetic energy in the upper and lower panels of Fig. 1, respectively. The resonant nature of the DR is clearly seen in this figure. Each resonance in the cross section reveals the contribution of the intermediate triply excited state(s) in the process given by Eq. (2). In Table I we present the resonance kinetic energies of the incident electron for the DR, the energies of the triply excited autoionizing states, and the corresponding widths. The positions of resonances of the autoionizing states which give the main contribution to the DR (for the certain initial state) are presented in Table I in bold. The other states give a very small contribution because they can be formed (from the initial states of He-like ion and the incident electron) only via exchange of two and more photons. The accuracy of our calculation of the energies is 7 eV; it is determined by the SE screening and VP screening corrections which are taken into account approximately.

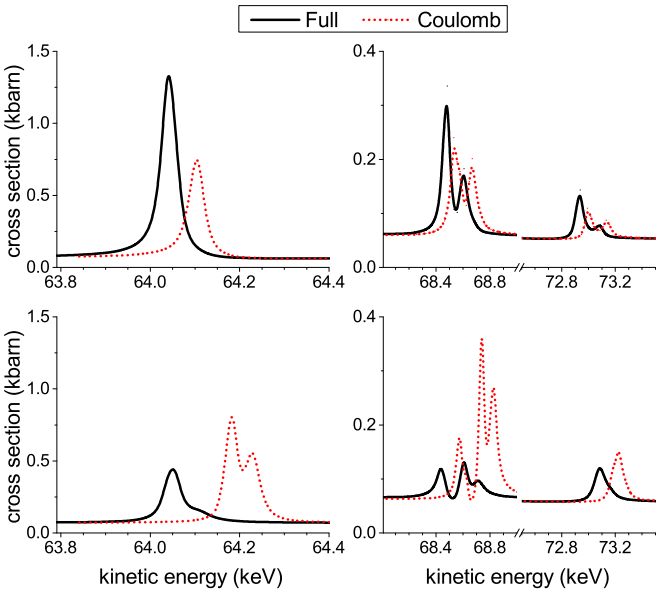

FIG. 1. Total cross sections (in kbarn) for dielectronic recombination with $U^{90+}(1s2s)_0$ (the top panel) and with $U^{90+}(1s2p_{1/2})_0$ (the bottom panel) as a function of incident-electron kinetic energy. The solid curves present calculations with full electron-electron interaction. The dotted curves present calculations where only Coulomb interaction is taken into account.

In this paper, the main attention is paid to the study of the relative role of the Coulomb and Breit parts of the interelectron interaction. However, first we would like to mention that the radiative corrections (SE and VP) have been taken into account. The imaginary part of the radiative corrections gives a dominant contribution to the width of the excited states of HCl. The real part gives a correction to the one-electron energies,

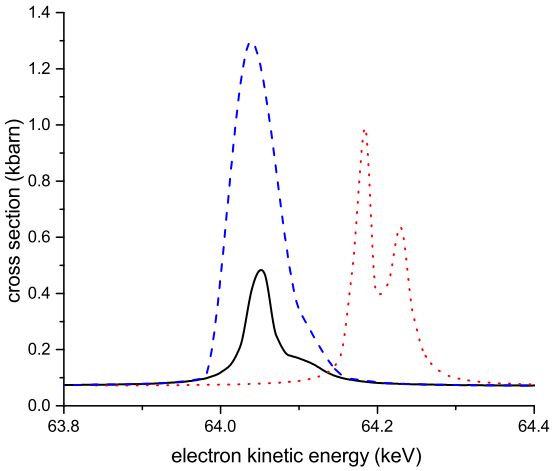

FIG. 2. Total cross section for dielectronic recombination with $U^{90+}(1s2p_{1/2})_0$. The energy region corresponds to the significant participation of $(2s^2 2p_{1/2})_{1/2}$ and $(2s2p_{1/2}^2)_{1/2}$ states. The black solid curve denotes the accurate QED calculation where full interelectron interaction is taken into account. The red dotted curve corresponds to the calculation where only Coulomb interaction is taken into account and the blue dashed curve corresponds to the calculation without retardation in the Breit part of the interelectron interaction.

TABLE I. The positions of resonances ($E_{\rm res1} = E_a - E_{(1s2s)_0} - m_e c^2$,; $E_{\rm res2} = E_a - E_{(1s2p_{1/2})_0} - m_e c^2$), the energies of the triply excited autoionizing states ($E_a^{'} = E_a - 3mc^2$), and the corresponding widths (Γ).

Autoionizing state	$E_{\rm res1}$ (keV)	$E_{\rm res2}$ (keV)	$E_a^{'}$ (eV)	Γ (eV)
$(2s^2 2p_{1/2})_{1/2}$	**64.049**	**64.052**	−101.053	31.4
$(2s2p_{1/2}^2)_{1/2}$	64.104	**64.107**	−100.998	62.2
$((2s2p_{1/2})_0 2p_{3/2})_{3/2}$	68.448	**68.451**	−96.654	57.2
$(2s^2 2p_{3/2})_{3/2}$	**68.481**	68.485	−96.621	38.3
$((2s2p_{1/2})_1 2p_{3/2})_{5/2}$	68.491	68.494	−96.611	57.3
$((2s2p_{1/2})_1 2p_{3/2})_{3/2}$	**68.599**	**68.602**	−96.504	57.3
$((2s2p_{1/2})_1 2p_{3/2})_{1/2}$	**68.599**	**68.602**	−96.504	57.3
$(2p_{1/2}^2 2p_{3/2})_{3/2}$	68.696	**68.699**	−96.407	76.1
$(2s(2p_{3/2}^2)_2)_{5/2}$	**72.932**	72.936	−92.170	52.1
$(2p_{1/2}(2p_{3/2}^2)_2)_{3/2}$	73.055	73.059	−92.047	83.2
$(2p_{1/2}(2p_{3/2}^2)_2)_{5/2}$	73.075	**73.078**	−92.027	83.2
$(2s(2p_{3/2}^2)_2)_{3/2}$	**73.085**	73.089	−92.017	52.2
$(2s(2p_{3/2}^2)_0)_{1/2}$	**73.086**	73.089	−92.016	52.1
$(2p_{1/2}(2p_{3/2}^2)_0)_{1/2}$	73.160	**73.164**	−91.942	83.2

which leads to the corresponding shifts in the resonance positions.

For investigation of the contribution of the Breit part of the interelectron interaction, we present results of calculations performed within the framework of QED and disregarding the Breit interaction. In addition to the shifts of the resonances, the Breit interaction also leads to significant changes in the pattern of the DR cross section. In the upper panels of Fig. 1 we present the cross section corresponding to the $(1s2s)_0$ initial state of uranium. One can see that taking into account the Breit interaction may significantly increase the cross section. The increase of the cross section due to the Breit interaction for various DR processes with HCI was also observed in [17,18,23]. In the lower panels of Fig. 1 we present the cross section corresponding to the $(1s2p_{1/2})_0$ initial state of uranium. The qualitative feature of this case is that the contribution of the Breit interaction may considerably decrease the DR cross section.

In order to explain the origin of such a behavior, we have performed investigation of the role of the retardation in the Breit interaction. In Fig. 2 we present results of calculation for the energy region corresponding to the $(2s^2 2p_{1/2})_{1/2}$ and $(2s2p_{1/2}^2)_{1/2}$ resonances performed within the following approximations: the accurate QED calculation (the black solid curve), only the Coulomb interaction (the red dotted curve). and the Coulomb and Breit interaction, diregarding the retardation (the blue dashed curve). This figure reveals that the effect of retardation is responsible for the large diminishment of the cross section.

We note that the value of the cross section for the considered DR process (i.e., contribution of the triply excited states) is comparable in order of magnitude with one for DR with $U^{90+}(1s^2)$ [17] as well as for DR with $U^{91+}(1s)$ [18,23].

The results of the calculation of differential cross section presented as a function of energy of incident electron and polar angle of the emitted photon (with respect to the momentum of the incident electron) are given in Figs. 3 and 4. One can see that the Breit interaction is also prominent in the differential cross section. As it was seen for the total cross section, the role of the Breit interaction is influenced by the initial state of the system. In particular, the inclusion of the Breit interaction increases the differential cross section for the $(1s2s)_0$ initial state and decreases it for the $(1s2p_{1/2})_0$ initial state.

The angular distribution of the differential cross section in the resonant region depends on the corresponding autoionizing states which determine the resonance. The position of the maximum in the angular distribution of the REC is near 45°,

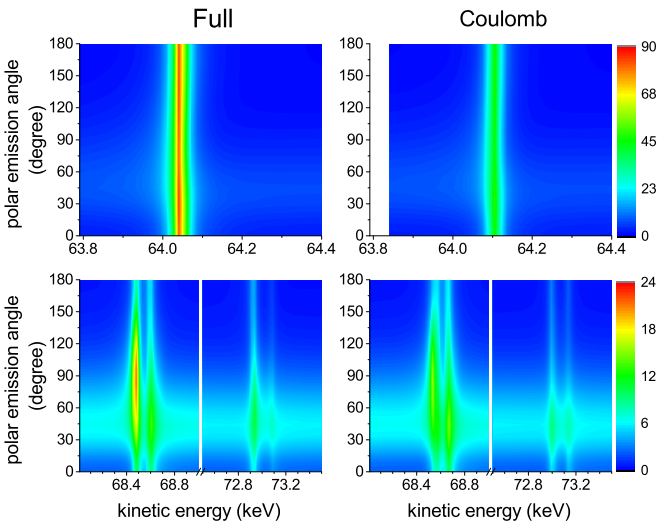

FIG. 3. Differential cross sections (in barn/sr) for dielectronic recombination with $U^{90+}(1s2s)_0$ as a function of incident-electron kinetic energy and polar angle of emitted photon. The left column presents calculations with full electron-electron interaction and the right column presents calculations where only Coulomb interaction is taken into account.

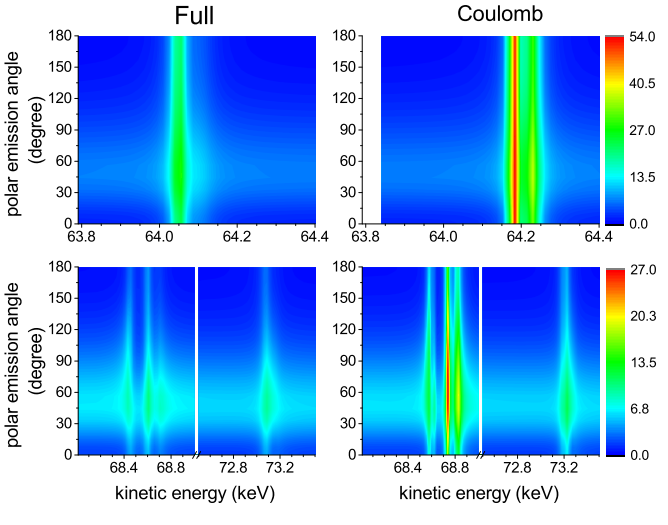

FIG. 4. Differential cross sections (in barn/sr) for dielectronic recombination with $U^{90+}(1s2p_{1/2})_0$ as a function of incident-electron kinetic energy and polar angle of emitted photon. The left column presents calculations with full electron-electron interaction and the right column presents calculations where only Coulomb interaction is taken into account.

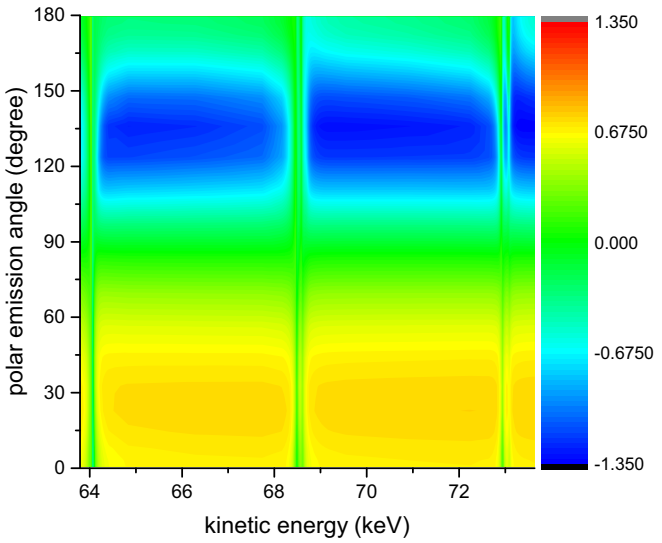

FIG. 5. The relative contribution of the higher multipoles of the emitted photon to the differential cross section of dielectronic recombination with $U^{90+}(1s2s)_0$ [see Eq. (14)].

while the position of the maximum for the DR depends on the particular resonance varying between 40° and 80°. We note that in the case of the DR with He-like HCI initially being in its ground state the angular distribution is different; in particular, characteristic maxima in the cross section are placed near 90° [17].

In the present work the multipole expansion for the photon wave function was utilized [see Eq. (5)]. The terms of the multipole expansion with $j_0 \leqslant 9$ were taken into account, which ensures a good convergence of the series. In Fig. 5 we present the relative contribution to the differential cross section ($\delta\sigma$) of the photons with angular momentum $j_0 > 1$ for the DR with $U^{90+}(1s2s)_{J=0}$:

$$\delta\sigma = \frac{\frac{d\sigma}{d\Omega_{\mathbf{k}}} - \frac{d\sigma^{(j_0=1)}}{d\Omega_{\mathbf{k}}}}{\frac{d\sigma}{d\Omega_{\mathbf{k}}}}, \tag{14}$$

where for the calculation of the $\frac{d\sigma^{(j_0=1)}}{d\Omega_{\mathbf{k}}}$ differential cross section only photons with $j_0 = 1$ ($E1$ and $M1$ photons) were taken into account. From this figure we conclude that for the resonant regions only photons with $j_0 = 1$ give significant contribution. For the energy regions where only the direct channel is important, the higher multipoles of the emitted photon give the major contribution. Indeed, if the resonant DR channel

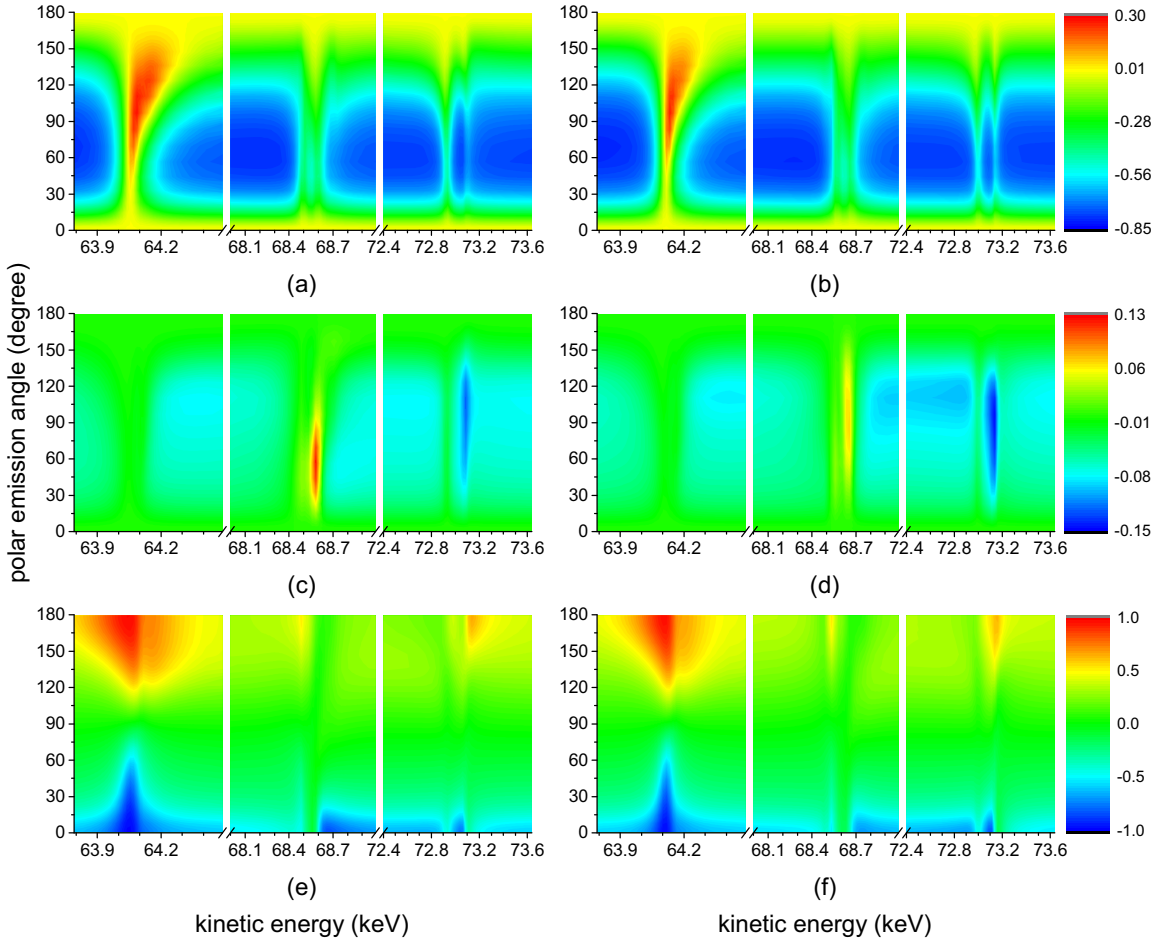

FIG. 6. The Stokes parameters for the dielectronic recombination with $U^{90+}(1s2s)_0$. The first and second rows correspond to the parameters P_1 and P_2, respectively [see Eqs. (15) and (16)]. The third row presents the Stokes parameter for circular polarization P_3 [see Eq. (17)]. The left and right columns correspond to the calculations with and without Briet interelectron interaction, respectively.

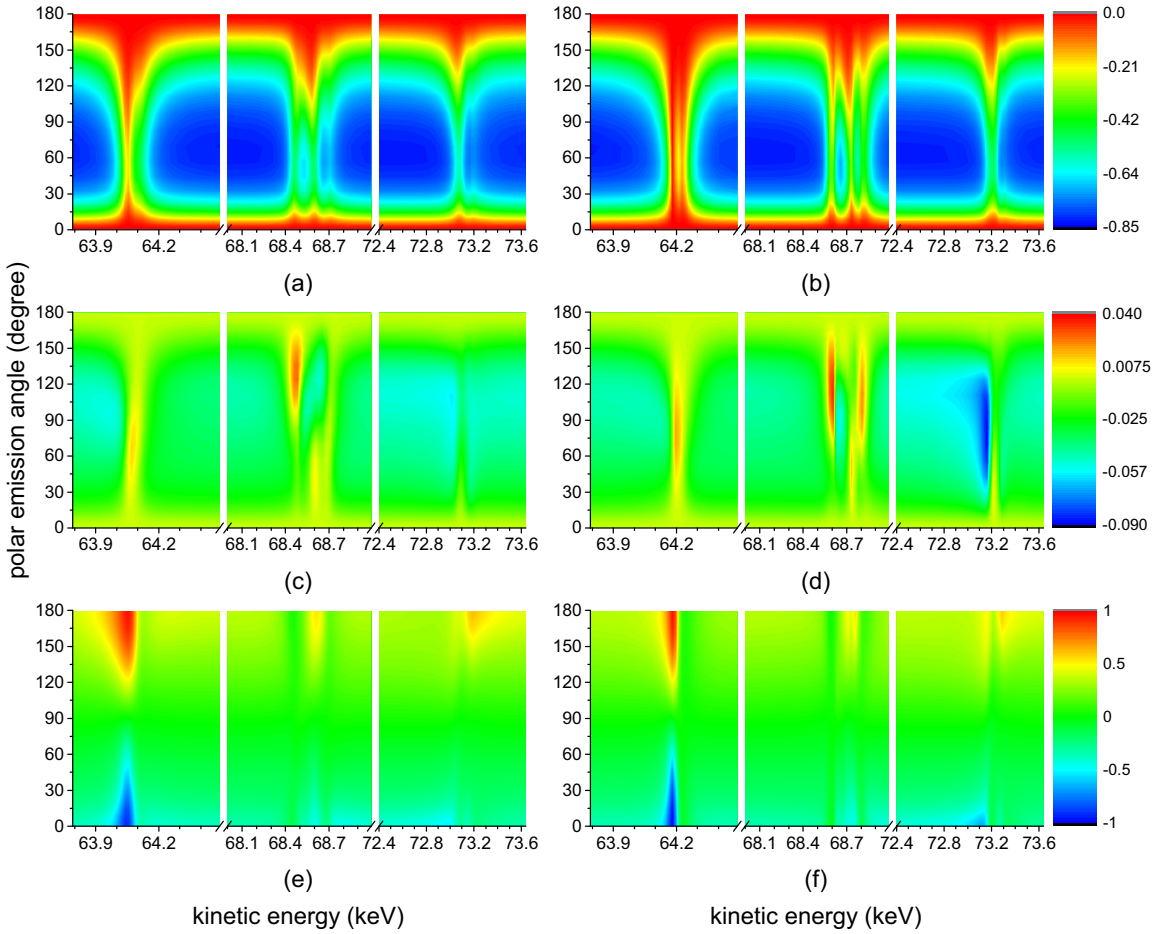

FIG. 7. Same as in Fig. 6, but for the dielectronic recombination with $U^{90+}(1s2p_{1/2})_0$.

dominates over the nonresonant channel, then the angular momentum of the emitted photon (j_0) is determined by the possible one-photon transitions from the corresponding triply excited states [see Eq. (2)]; it is usually $E1$ or $M1$ transitions.

For investigation of the polarizations of the emitted photon we calculated the Stokes parameters

$$P_1 = \frac{\frac{d\sigma^{0^\circ}}{d\Omega_{\mathbf{k}}} - \frac{d\sigma^{90^\circ}}{d\Omega_{\mathbf{k}}}}{\frac{d\sigma^{0^\circ}}{d\Omega_{\mathbf{k}}} + \frac{d\sigma^{90^\circ}}{d\Omega_{\mathbf{k}}}}, \tag{15}$$

$$P_2 = \frac{\frac{d\sigma^{45^\circ}}{d\Omega_{\mathbf{k}}} - \frac{d\sigma^{135^\circ}}{d\Omega_{\mathbf{k}}}}{\frac{d\sigma^{45^\circ}}{d\Omega_{\mathbf{k}}} + \frac{d\sigma^{135^\circ}}{d\Omega_{\mathbf{k}}}}, \tag{16}$$

$$P_3 = \frac{\frac{d\sigma^{+}}{d\Omega_{\mathbf{k}}} - \frac{d\sigma^{-}}{d\Omega_{\mathbf{k}}}}{\frac{d\sigma^{+}}{d\Omega_{\mathbf{k}}} + \frac{d\sigma^{-}}{d\Omega_{\mathbf{k}}}}, \tag{17}$$

where superscripts 0°, 90°, 45°, and 135° denote orientations of the photon polarization vectors with respect to the collision plane ($\boldsymbol{p}$,$\boldsymbol{k}$) which is defined by the electron momentum $\boldsymbol{p}$ and the photon momentum $\boldsymbol{k}$ [see Eqs. (6) and (7)]. The differential cross section $\frac{d\sigma^{\pm}}{d\Omega_{\mathbf{k}}}$ corresponds to the circular $\pm$ polarizations of the photon [see Eq. (8)].

Results of the calculation of the Stokes parameters for DR with $U^{90+}(1s2s)_{J=0}$ and $U^{90+}(1s2p_{1/2})_{J=0}$ are presented in Figs. 6 and 7, respectively. We also investigated the importance of the Breit interaction for the Stokes parameters: in the left column the results of the full QED calculation are presented, and in the right column the results with neglect of the Breit part of the interelectron interaction are given. We conclude that qualitatively the sensitivity of the Stokes parameters to the Breit interaction is the same as for the differential cross section.

In summary, we have presented calculation of the DR cross section for He-like uranium initially being in its metastable states. We investigated the triply excited states and, in particular, calculated the energies, the widths, and their contribution to the resonance structure of the DR. The cross section of the considered process is comparable in order of magnitude with the cross section of DR with He-like uranium being in the ground states. We found that the Breit interaction may both significantly increase and decrease the DR cross section. The angular distribution of the emitted photon differs from the one with He-like uranium in the ground state.

ACKNOWLEDGMENTS

The work of K.N.L. and O.Y.A. on the calculation of the energies and widths was supported solely by the Russian Science Foundation under Grant No. 17-12-01035. The rest of the work of K.N.L. was partly supported by RFBR Grant No. 16-32-00620. The work of O.Y.A. was partly supported by the Ministry of Education and Science of the Russian Federation under Grant No. 3.1463.2017/4.6.

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