KLL dielectronic recombination process of He-like to O-like xenon ions*

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In this work, the *KLL* dielectronic recombination (DR) processes of highly charged He-like to O-like xenon ions are studied systematically by using a DR program, which is based on the multi-configuration Dirac–Fock (MCDF) method. The *KLL* DR resonant energies and the corresponding resonant strengths are calculated, emphasizing especially the effect of the Breit interaction on the DR strengths. The theoretical *KLL* DR spectra are obtained and compared with the latest experimental results obtained in the Shanghai Electron Beam Ion Trap.

Keywords: *KLL* dielectronic recombination, resonant strength, Breit interaction

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1. Introduction

Dielectronic recombination (DR) can be regarded as a resonant radiative recombination process, in which an electron undergoes radiationless capture into an autoionizing doubly excited state and subsequently the doubly excited state is stabilized though radiative decay. It is normally labeled using an inverse Auger process notation, such as *KLL*, *KLM*, and *KLN*. For a *KLL* DR process, the continuum electron is captured into the L shell, whereas the bound electron is promoted from the K shell to the L shell as a consequence of the energy conservation. For different charged ions (initially He-, Li-, or Be-like, etc.), the scheme differs only in the number of electrons in the L shell.

The DR process can play an important role in high temperature plasmas. It strongly affects the ionization balance of a plasma and its emitted X-ray spectrum.[1,2] Knowledge of DR cross sections is, therefore, essential for theoretical modeling of plasmas in both the laboratory and in astrophysical sources, such as the solar corona. DR also leads to satellite line emissions, which have been observed in many high temperature and high density plasmas, such as tokamak and inertial-confinement fusion (ICF) plasmas, and are very useful for plasma diagnostics. Today, the study of DR has already gone beyond the understanding of the DR process itself. In fact, as a versatile tool, DR has been utilized to study a wide range of physics topics, such as relativistic effects,[3] quantum electrodynamics (QED),[4] interference between resonant and non-resonant photorecombinations,[5] polarization of the characteristic X-ray emission,[6] lifetime studies and hyperfine quenching,[7,8] isotope shift and hyperfine splitting.[9]

The *KLL* DR processes of highly charged ions have been of special interest in both theory and experiment for many years due to their strong relativistic and QED effects, and extensive electron correlation effects.[10−17] Recently, Yao *et al.*[17] measured the *KLL* DR resonance strengths for all the possible charge states of Xe ions with an open L shell (from He-like to O-like) by using a fast electron energy scanning technique at the Shanghai Electron Beam Ion Trap (EBIT). A comparison has been made with the calculation by using the flexible atomic code (FAC). Although a good agreement can be found between the

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theoretical and the experimental results for the total resonant strengths except for the Li-like ion, which has a calculated strength 14% smaller than the experiment result, rather remarkable discrepancies still remain for some intermediate-state resolved *KLL* DR strengths. One possible reason is the neglect of the Breit interaction in the calculations of the autoionization rates in the FAC code. In fact, many studies have shown that the Breit interaction can considerably enhance the autoionization rates in such few-electron ions and thus the cross sections.[4,13,18−20] Experimental studies have also proven this effect in the *KLL* DRs of the H-like uranium ion[21] and the Li-like iodine, holmium, and bismuth ions.[4] Therefore, a further calculation including the Breit interaction is still needed.

In this work, by using a newly developed program[13] for the calculation of the DR process, which is based on the relativistic multi-configuration Dirac–Fock (MCDF) method,[22] we systematically study the *KLL* DR processes of the He-like to the O-like xenon ions and compare the obtained results with available experimental and theoretical results. The effects of the Breit interaction on the DR strengths are especially investigated.

2. Theoretical methods

In the treatment of the DR process, the isolated resonant approximation is used. The DR resonant strength is obtained by integrating the DR cross section over the energy. If we designate the initial state as i, the intermediate doubly excited state as j, and the final state as k, the DR resonant strength can be given by[13]

$$S_{ijk} = \frac{\pi^2\hbar^3}{m_{\rm e}E_{ji}}\frac{g_j}{2g_i}A^{\rm a}_{ji}\frac{A^{\rm r}_{jk}}{\sum_{k'}A^{\rm r}_{jk'}+\sum_{i'}A^{\rm a}_{ji'}}, \quad (1)$$

where $\hbar$ is the reduced Planck constant; $m_{\rm e}$ is the electron mass; E_{ji} is the resonant energy; g_i and g_j are statistical weights of states i and j, respectively; $A^{\rm a}$ is the autoionization rate; and $A^{\rm r}$ is the radiative decay rate. The summation runs over all possible autoionization and radiative decay channels from the intermediate doubly excited state.

The radiative decay rate is calculated by[23]

$$A^{\rm r}_{jk} = \frac{4e^2\varepsilon}{3\hbar c^3 g_j}|\langle\Psi_j|T^{(\rm t)}|\Psi_k\rangle|^2, \quad (2)$$

where e is the electron charge, Ψ_j and Ψ_k are the atomic state functions (ASFs) for states j and k, respectively, ε is the photon energy, and $T^{(\rm t)}$ is the multipole tensor operator.[24]

The autoionization rate is calculated by[25]

$$A^{\rm a}_{ji} = \frac{2\pi}{\hbar}|\langle\Psi_j|\sum_{\alpha<\beta}V_{\alpha\beta}\,|\Psi_i\epsilon_i\rangle|^2, \quad (3)$$

where $\Psi_{i\epsilon_i}$ is the ASF of the system formed by an ion in state i and a free electron with energy ϵ_i, $V_{\alpha\beta}$ is the two-electron operator and is the sum of the Coulomb and the Breit operators,[22,26] which in the atomic units can be expressed as

$$V_{\alpha\beta} = \frac{1}{r_{\alpha\beta}} - \alpha_\alpha\cdot\alpha_\beta\frac{\cos(\omega r_{\alpha\beta})}{r_{\alpha\beta}} + (\alpha_\alpha\cdot\bigtriangledown_\alpha)(\alpha_\beta\cdot\bigtriangledown_\beta)\frac{\cos(\omega r_{\alpha\beta})-1}{\omega^2 r_{\alpha\beta}}, \quad (4)$$

where α_α is the Dirac matrix, ω is the wave number of the exchanged virtual photons, and $r_{\alpha\beta}$ is the distance between electrons α and β.

In this work, all the atomic structural parameters are determined within the theoretical frame of the relativistic MCDF method. The MCDF approximation of the atomic states and the transitions between them has been described in detail in the literature (see, e.g. Ref. [22] and references therein). The MCDF model for the electronic structures of free atoms and free ions has been implemented in GRASP92.[27] In the MCDF model, an ASF is represented as a linear combination of configuration state functions (CSFs) each with a well-defined parity P and a well-defined angular momentum (J, M),

$$\Psi_\alpha(PJM) = \sum_{r=1}^{n_{\rm c}} c_r(\alpha)\,|\gamma_r PJM\rangle, \quad (5)$$

where $n_{\rm c}$ is the number of CSFs, $c_r(\alpha)$ is the configuration mixing coefficient of the atomic state in this basis, and γ_r contains all the quantum numbers necessary to distinguish the states. The CSFs are antisymmetrized products of a common set of orthonormal orbitals, which is optimized on the basis of the relativistic Dirac–Coulomb Hamiltonian. In our calculations, the active space of the CSFs includes all single and double excitations from the reference configurations up to all orbitals of the $n = 3$ shell. Further relativistic contributions to the representation $c_r(\alpha)$ of the atomic states due to the (transverse) Breit interactions are added by diagonalizing the Dirac–Coulomb–Breit Hamiltonian matrix. The dominant quantum electrodynamic contributions, i.e. the self-energy and the vacuum polarization effect, have also been included in

the computations of the total energy as a perturbation. In this paper, the radiative decay and the autoionization rates are calculated with the help of the recently developed REOS99 and Auger components of the RATIP package,[28] which is based on the MCDF method.

In order to compare with the experimental results, the calculated resonant strengths should be convoluted with a Gaussian distribution with an energy resolution Γ. The convoluted cross section is given by[14]

$$\sigma_{\rm t}{}^{\rm DR}(\varepsilon) = \sum_{j,k} \frac{S_{ijk}(\varepsilon_j)}{\sqrt{2\pi}\Gamma} \exp\left[-\frac{(\varepsilon-\varepsilon_j)^2}{2\Gamma^2} \right]. \quad (6)$$

An experimental resolution of 42.8 eV (full width at half maximum)[17] is adopted in the present calculations.

3. Results and discussion

In Table 1, we list the *KLL* DR resonant energies and strengths for He-like to O-like xenon ions. The labels used by Yao *et al.*[17] are adopted for the resonant processes of some intermediate doubly excited states, while the data without any label are the new results presented in this work. Available experimental and calculated results are also presented in this table.

Table 1. The *KLL* DR resonant energies and strengths of some intermediate doubly excited states for He-like to O-like xenon ions. Experimental uncertainties are listed in the parentheses. The data in columns C+B and C are the present results with and without inclusion of the Breit interaction into the autoionization rate calculation, respectively.

		Resonant energy/eV			Resonant strength/10^{-20} cm^2·eV				
Label	State	present	Yao[17]	Expt. [10]	C+B	C	Yao[17]	Nilsen[29]	Chen
He1	$[1s2s^2]_{1/2}$	20244	20246	20244(9)	2.52	2.25	2.57	2.62	
	$[(1s2s)_1 2p_{1/2}]_{1/2}$	20275			0.17	0.00		0.00	0.19[a)]
He2	$[(1s2s)_1 2p_{1/2}]_{3/2}$	20290	20293		0.07	0.57	0.56	0.54	0.09[a)]
He3	$[(1s2s)_0 2p_{1/2}]_{1/2}$	20377	20379	20385(9)	4.18	3.27	3.24	3.27	4.52[a)]
	$[1s(2p_{1/2})^2]_{1/2}$	20441			0.08	0.12		0.09	
	$[(1s2s)_1 2p_{3/2}]_{5/2}$	20647			0.01	0.00			0.01[a)]
He4	$[(1s2s)_1 2p_{3/2}]_{3/2}$	20709	20712		0.18	0.41	0.37	0.26	0.23[a)]
He5	$[(1s2s)_1 2p_{3/2}]_{1/2}$	20746	20749		0.49	1.14	1.12	1.07	0.59[a)]
He6	$[(1s2s)_0 2p_{3/2}]_{3/2}$	20773	20776		4.73	4.68	4.57	4.71	5.21[a)]
	$[(1s2p_{1/2})_1 2p_{3/2}]_{3/2}$	20788			0.01	0.03		0.02	
He7	$[(1s2p_{1/2})_1 2p_{3/2}]_{5/2}$	20800	20796		7.09	7.33	7.29	7.24	
	$[(1s2p_{1/2})_1 2p_{3/2}]_{1/2}$	20819			0.11	0.02		0.02	
He8	$[(1s2p_{1/2})_0 2p_{3/2}]_{3/2}$	20837	20833		5.63	6.21	6.20	5.52	
He9	$[(1s(2p_{3/2})^2_2]_{5/2}$	21180	21179		4.85	4.40	4.35	4.48	
He10	$[(1s(2p_{3/2})^2_2]_{3/2}$	21224	21221		1.61	2.34	2.35	2.20	
He11	$[(1s(2p_{3/2})^2_0]_{1/2}$	21248	21246		0.78	0.72	0.77	0.78	
Li1	$[(1s2s^2 2p_{1/2}]_1$	20451	20456	20454(5)	2.08	1.53	1.43		
	$[(1s2s^2 2p_{1/2}]_0$	20457			0.01	0.02			
Li2	$[(1s2s)_1(2p_{1/2})^2]_1$	20544	20540	20535(6)	0.36	0.38	0.41		
	$[(1s2s)_0(2p_{1/2})^2]_0$	20631			0.15	0.15			
Li3	$[(1s2s^2 2p_{3/2}]_2$	20825	20827		0.53	0.55	0.86		
Li4	$[1s2s^2 2p_{3/2}]_1$	20859	20862		0.38	0.45	0.43		
Li5	$[((1s2s)_1 2p_{1/2})_{1/2} 2p_{3/2}]_2$	20868	20865		0.14	0.21	0.21		
Li6	$[((1s2s)_1 2p_{1/2})_{3/2} 2p_{3/2}]_3$	20896	20893		3.50	3.61	3.74		
Li7	$[((1s2s)_1 2p_{1/2})_{1/2} 2p_{3/2}]_1$	20930	20928		0.45	0.46	0.47		
Li8	$[((1s2s)_1 2p_{1/2})_{3/2} 2p_{3/2}]_2$	20953	20950		3.34	3.43	3.45		
	$[((1s2s)_1 2p_{1/2})_{3/2} 2p_{3/2}]_0$	20981			0.01	0.00			
Li9	$[((1s2s)_1 2p_{1/2})_{3/2} 2p_{3/2}]_1$	20981	20977		1.74	1.75	1.82		
Li10	$[((1s2s)_0 2p_{1/2})_{1/2} 2p_{3/2}]_1$	21005	21005		0.12	0.28	0.23		
Li11	$[((1s2s)_0 2p_{1/2})_{1/2} 2p_{3/2}]_2$	21011	21012		2.69	2.92	3.07		
Li12	$[(1s2s)_1(2p_{3/2})^2_2]_3$	21260	21263		3.02	2.76	2.84		
Li13	$[(1s2s)_1(2p_{3/2})^2_2]_2$	21325	21329		1.11	1.51	1.51		
Li14	$[(1s2s)_1(2p_{3/2})^2_0]_1$	21352	21355		0.71	0.64	0.68		

Table 1. (*Continued*).

		Resonant energy/eV			Resonant strength/10^{-20} cm^2·eV				
Label	State	present	Yao[17]	Expt. [10]	C+B	C	Yao[17]	Nilsen[29]	Chen
Li15	$[(1s2s)_1(2p_{3/2})^2_2]_1$	21379	21381		0.42	0.62	0.63		
Li16	$[(1s2s)_0(2p_{3/2})^2_2]_2$	21388	21395		1.42	1.37	1.45		
	$[(1s2s)_0(2p_{3/2})^2_0]_0$	21429			0.27	0.24			
Be1	$[1s2s^2(2p_{1/2})^2]_{1/2}$	20721	20715	20715(5)	0.91	0.89	0.91		0.95[b]
	$[(1s2s^22p_{1/2})_12p_{3/2}]_{3/2}$	21067			0.01	0.02			0.01[b]
Be2	$[(1s2s^22p_{1/2})_12p_{3/2}]_{5/2}$	21080	21076	21077(4)	5.62	5.96	6.10		5.82[b]
	$[(1s2s^22p_{1/2})_12p_{3/2}]_{1/2}$	21099			0.12	0.03			0.12[b]
Be3	$[(1s2s^22p_{1/2})_02p_{3/2}]_{3/2}$	21117	21112	21117(5)	4.95	5.47	5.54		5.05[b]
Be4	$[1s2s^2(2p_{3/2})^2_2]_{5/2}$	21452	21444		3.76	3.49	3.59		3.86[b]
Be5	$[1s2s^2(2p_{3/2})^2_2]_{3/2}$	21493	21485		1.46	2.11	2.16		1.47[b]
Be6	$[1s2s^2(2p_{3/2})^2_0]_{1/2}$	21513	21510		1.19	1.06	1.04		1.22[b]
B1	$[1s2s^2(2p_{1/2})^22p_{3/2}]_2$	21232	21231	21231(4)	2.75	2.97	3.09		2.98[c]
B2	$[1s2s^2(2p_{1/2})^22p_{3/2}]_1$	21268	21266	21270(5)	2.51	2.65	2.64		2.61[c]
B3	$[(1s2s^22p_{1/2})_1(2p_{3/2})^2_2]_2$	21577	21577		1.69	1.57	1.59		1.78[c]
B4	$[(1s2s^22p_{1/2})_1(2p_{3/2})^2_2]_3$	21595	21594		1.93	1.76	1.79		2.05[c]
B5	$[(1s2s^22p_{1/2})_1(2p_{3/2})^2_2]_1$	21616	21615		0.52	0.75	0.76		0.54[c]
B6	$[(1s2s^22p_{1/2})_0(2p_{3/2})^2_2]_2$	21638	21638		0.89	1.28	1.28		0.92[c]
B7	$[(1s2s^22p_{1/2})_1(2p_{3/2})^2_0]_1$	21646	21643		0.80	0.72	0.71		0.83[c]
B8	$[(1s2s^22p_{1/2})_0(2p_{3/2})^2_0]_0$	21651	21648		0.26	0.23	0.23		0.27[c]
C1	$[1s2s^2(2p_{1/2})^2(2p_{3/2})^2_2]_{5/2}$	21725	21730	21728(5)	3.44	3.07	2.96		
C2	$[1s2s^2(2p_{1/2})^2(2p_{3/2})^2_2]_{3/2}$	21767	21771	21772(6)	1.39	1.98	1.94		
C3	$[1s2s^2(2p_{1/2})^2(2p_{3/2})^2_0]_{1/2}$	21784	21785	21796(10)	0.80	0.70	0.82		
N1	$[1s2s^2(2p_{1/2})^2(2p_{3/2})^3_{3/2}]_2$	21901	21904	21092(4)	1.75	1.64	1.63		
N2	$[1s2s^2(2p_{1/2})^2(2p_{3/2})^3_{3/2}]_1$	21933	21936	21933(4)	0.81	0.96	0.97		
O1	$[1s2s^2(2p_{1/2})^2(2p_{3/2})^4]_{1/2}$	22081	22083	22082(4)	0.79	0.82	0.81		

[a] Ref. [30], [b] Ref. [31], [c] Ref. [32]

From this table, it can be seen that the present calculated resonant energies accord very well with the experimental results[10] except for Li2, Be1, and C3, for which the present resonant energies are slightly outside of the experimental uncertainties. The differences in resonant energy between our results and Yao's[17] are less than 3 eV for most intermediate doubly excited states. The largest difference is 8 eV for Be4 and Be5. This good agreement of the present energy calculations with the experimental results indicates that our wave functions are accurate enough. Using these wave functions, we further calculate the radiative decay and the autoionization rates, and then obtain the DR resonant strengths.

The present calculated DR resonant strengths with and without the inclusion of the Breit interaction into the autoionization rate calculation are listed in columns C+B and C, respectively. For comparison, the available previous calculations from Yao *et al.*,[17] Nilsen,[29] and Chen *et al.*[30–32] are also listed in the Table 1. Yao's results were calculated by using the FAC code, in which the Breit interaction was not included in the autoionization rate calculation.[17] The DR resonant strengths of the He-like xenon are obtained by using the present resonant energies and the decay rates (autoionization and radiative rates) from Nilsen[29] and from Chen *et al.*[30] respectively. The ones for the Be-like and the B-like ions are from Chen *et al.*[31] and Chen *et al.*[32] It is worth noting that Nilson and Chen have also included the Breit interaction into their calculations of the autoionization rates.

By systematically comparing the theoretical resonant strengths shown in Table 1, we can draw the following conclusions. (i) For the results without the inclusion of the Breit interaction into the autoionization rate calculations, i.e., the results in columns C and Yao, most of them are nearly identical except for He1, Li3, Li10, and C3, in which discrepancies larger than 10% are found. Especially for Li3, our result is 36% smaller than Yao's.[17] The reason why the large discrepancy occurs at Li3 is still unclear at present.

(ii) There are several different situations for the results with the inclusion of the Breit interaction into the autoionization rate calculations. For the He-like DR resonant strengths, it can be found that Nilsen's results including the Breit interaction accord much better with Yao's results without the inclusion of the Breit interaction than with our results with the Breit interaction, except for He6, He8, and He11. Compared with Nilson's results, our results with the inclusion of the Breit interaction are well consistent with those of Chen's work.[30] For example, Chen's results are very close to ours but are one sixth and one half of Nilsen's results for He2 and He5, respectively. A good agreement can also be found between our results and Chen's[31,32] for the Be-like and the B-like ions. Of course, we also note that there are some small differences between the results with the inclusion of the Breit interaction. These differences indicate that the Auger rate can sensitively depend on the electron correlation and the detail of the atomic wave function, as pointed out first by Kelly.[33] (iii) By comparing the results with and without the inclusion of the Breit interaction, i.e., the results in columns C+B and C, we find that the Breit interaction can affect significantly the DR resonant strengths for some intermediate doubly excited states. For example, the contributions of the Breit interaction to the DR resonant strengths are over 30% for the double states of He2, He4, He5, He10, Li1, Li10, Li15, Be5, B5, B6, and C3. Particularly, the Breit interaction reduces the DR resonant strength of state He2 for about 88%. In addition, for the doubly excited states, such as $[(1s2s)_1 2p_{1/2}]_{1/2}$, $[(1s2s)_1 2p_{3/2}]_{5/2}$, $[(1s2p_{1/2})_1 2p_{3/2}]_{1/2}$, $[((1s2s)_1 2p_{1/2})_{3/2} 2p_{3/2}]_0$, and $[(1s2s^2 2p_{1/2})_1 2p_{3/2}]_{1/2}$, the DR processes are almost forbidden for the Coulomb interaction and are dominated by the Breit interaction. Whereas for the other states, such as He6, He7, $[(1s2s)_0(2p_{1/2})^2]_0$, Li3, Li6, Li7, Li8, Li9, and Be1, the influence of the Breit interaction is less important, and the contribution is within 3%. Therefore, the contribution of the Breit interaction is very state-dependant. It is generally impossible to anticipate to what extent the Breit interaction can affect the DR resonant strength before actually carrying out the detailed computation.

In order to make a comparison with the available experimental results, we list some DR resonant strengths for several intermediate doubly excited states in Table 2. The notations are the same as those used in Table 1. The differences between the results in columns C and Yao[17] are less than 4% except for He1, Li1, and Li2, for which the differences are more than 7%. In general, the experimental results agree better with those of column C except for He1 and Li1. The situation is similar when we compare Yao's results calculated by the FAC code with the experimental results. However, when we compare the results with the inclusion of the Breit interaction shown in column C+B with the experimental results, we find that the results including the Breit interaction are in poor agreement with the experimental results except for He1 and Li1, whose values are closer to the experimental results after the inclusion of the Breit interaction. For example, the DR resonant strengths of states He9, Li4+Li5+Li6, B6+B7+B8, and C2+C3 are within the experimental uncertainties before the inclusion of the Breit interaction. However, all of them are outside of the experimental uncertainties after the inclusion of the Breit interaction. The results for states He3, Li10+Li11, Li15+Li16, Li15+Li16, and Be5+Be6, which are outside of the experimental uncertainties before the inclusion of the Breit interaction, are still outside of the error bars after the Breit interaction has been included. A possible reason for the worse agreement with the experimental results after the inclusion of the Breit interaction in the calculation is that the Breit interaction is not included in the calculation of the angular correction factor, which is needed for experimentally acquiring the DR resonant strength (see expression (6) in Ref. [17]). For example, the angular correction factor for intermediate state $[1s2s^2 2p_{1/2}]_1$ decaying to $[1s^2 2s^2]_0$ is 0.76 obtained by Yao *et al.*,[17] which also can be obtained by us without the inclusion of the Breit interaction. However, it becomes 0.87 with the inclusion of the Breit interaction. It means that the contribution of the Breit interaction to this angular correction factor can approach 14%. From expression (6) in Ref. [17], we can see that if the angular correction factor increases, the experimentally obtained DR resonant strength will decrease correspondingly. It will result in a good agreement between the experimental strength and the present theoretical calculated one with the inclusion of the Breit interaction. In the future, we will more systematically and comprehensively calculate the angular correction factors in order to assist the experimental determination of the resonant strengths.

Table 2. Comparison between theoretical and experimental results for state resolved and unresolved *KLL* DR resonant strengths of He-like to O-like xenon ions. Experimental uncertainties are listed in the parentheses. Results are in the unit of 10^{-20} cm^2·eV.

Ion	State	C+B	C	Yao[17]	Nilson[29]	Chen	Expt. [17]
He-like	He1	2.52	2.25	2.57	2.62		2.72(0.26)
	He3	4.18	3.27	3.24	3.27	4.52[a)]	3.70(0.36)
	He9	4.85	4.40	4.35	4.48		4.25(0.41)
Li-like	Li1	2.08	1.53	1.43			2.56(0.24)
	Li2	0.36	0.38	0.41			0.43(0.04)
	Li4+Li5+Li6	4.02	4.27	4.38			4.57(0.43)
	Li7+Li8+Li9	5.53	5.64	5.74			5.83(0.54)
	Li10+Li11	2.81	3.20	3.31			3.98(0.37)
	Li13+Li14	1.82	2.14	2.19			2.66(0.25)
	Li15+Li16	1.84	1.99	2.08			2.91(0.27)
Be-like	Be2+Be3	10.57	11.43	11.64		10.87[b)]	11.43(1.03)
	Be4	3.76	3.49	3.59		3.86[b)]	3.61(0.32)
	Be5+Be6	2.65	3.17	3.20		2.69[b)]	3.81(0.34)
B-like	B3+B4+B5	4.14	4.08	4.14		4.37[c)]	4.05(0.36)
	B6+B7+B8	1.95	2.23	2.22		2.02[c)]	2.27(0.20)
C-like	C1	3.44	3.07	2.96			3.26(0.30)
	C2+C3	2.19	2.68	2.76			2.96(0.27)
N-like	N1+N2	2.56	2.60	2.60			2.46(0.23)
O-like	O1	0.79	0.82	0.81			0.86(0.08)

[a)]Ref. [30], [b)]Ref. [31], [c)]Ref. [32]

In Table 3, the total *KLL* DR strengths of the He-like to the O-like xenon ions from the experimental results and the calculations are listed. The comparison of the experimental results with the calculations shows that our results without the Breit interaction and the previous calculations are fully within the experimental error bars, except for the case of the Li-like ions. After the inclusion of the Breit interaction into the autoionization rate calculations, the total *KLL* DR strengths all decrease, but the changes are small. As pointed out by Yao *et al.*,[17] the Breit interaction does not affect the total resonant strength in a pronounced way. However, for the case of Li-like xenon ions, the calculated resonant strengths shown in columns C+B, C, and Yao are smaller than the experimental results by about 19%, 17%, and 14%, respectively. It means that the difference becomes larger after the inclusion of the Breit interaction. In the case of the Li-like iodine ions, which are next to xenon in the periodic table, our calculated result with the Breit interaction[14] is smaller than Watanabe's[11] experimental result by about 20%, while is only smaller than Kavanagh's[12] experimental result by about 7.7%. Recently, the experimental results of Watanabe *et al.*[11] were corrected by Zhang *et al.*[34] The corrected results accord very well with our results.[14] The reason why such large differences appear in the case of the Li-like xenon ions has not been clear until now. We also call for further theoretical and experimental work on the Li-like xenon to check our calculations.

Table 3. Total *KLL* DR resonant strengths (in the unit of 10^{-20} cm^2·eV) of He-like to O-like xenon ions. Experimental uncertainties are listed in the parentheses.

	Theory				Experiment	
Ion	C+B	C	Yao[1]	others	Ref. [1]	others
He-like	32.51	33.47	33.54	32.86[b)]	31.42(3.02)	
Li-like	22.45	22.87	23.74		27.51(2.56)	
Be-like	18.00	19.03	19.5	18.51[c)]	19.79(1.78)	19.22(3.54)[a)]
B-like	11.36	11.93	12.09	11.98[d)]	11.93(1.06)	
C-like	5.64	5.77	5.74		6.22(0.57)	6.52(1.27)[a)]
N-like	2.56	2.60	2.60		2.48(0.23)	
O-like	0.79	0.82	0.81		0.86(0.08)	

[a)]Ref. [10], [b)]Ref. [29], [c)]Ref. [31], [d)]Ref. [32]

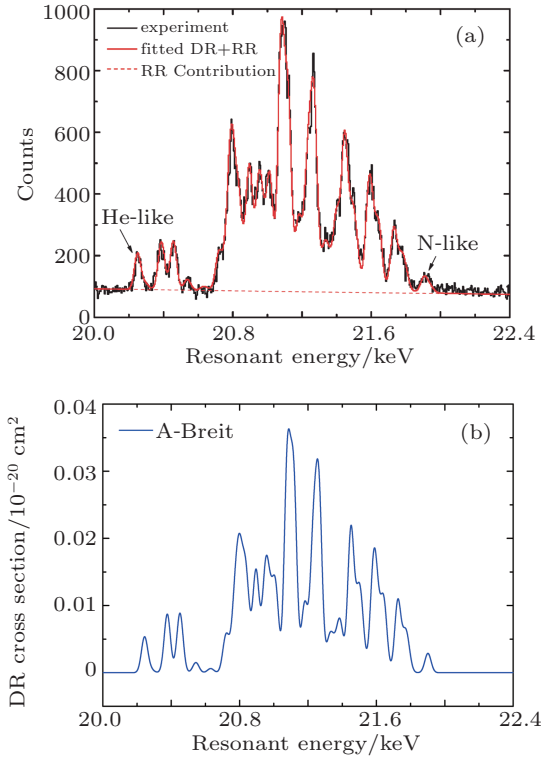


Fig. 1. (colour online) (a) Excitation function from experiment A, where the solid line denotes the fitting result, and the dashed line denotes the contribution of the n=2RR.[17] (b) Theoretical *KLL* DR spectra of He-like to O-like xenon ions.

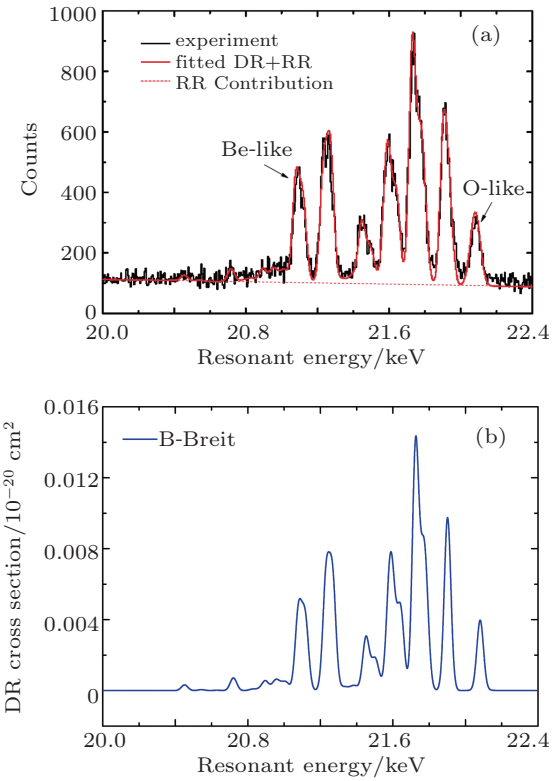


Fig. 2. (colour online) (a) Excitation function from experiment B, where the solid line denotes the fitting result, and the dashed line denotes the contribution of the n=2RR.[17] (b) Theoretical *KLL* DR spectra of He-like to O-like xenon ions.

In order to obtain the theoretical DR spectra, the calculated resonant strengths multiplied by the fitted ion abundance $f_q(\%)$ from experiments A and B in Ref. [17] are convoluted using a Gaussian distribution with an experimental energy resolution of 42.8 eV. Here the DR resonant strengths are taken from the results with the Breit interaction. Figures 1 and 2 show the theoretical DR spectra corresponding to the conditions of experiments A and B, respectively. For comparison, the experimental DR spectra are also shown.[17] A good agreement for the position of the peak, the relative amplitude of the cross section, and the line shape can be found between the present calculated DR spectra and the experimental spectra. However, we also notice that the relative strengths of the three small peaks in the range from 20.8 keV to 21.0 keV slightly disaccord with the experimental results.

4. Conclusion

In this work, the *KLL* DR processes of highly charged He-like to O-like xenon ions are studied systematically. The effect of the Breit interaction on the *KLL* DR resonant strength is especially emphasized. It is found that the Breit interaction can affect the DR resonant strengths very strongly for some intermediate doubly excited states. However, we also find that the DR resonant strengths calculated with the inclusion of the Breit interaction into the calculation of the autoionization rate further deviate from the experimental results compared with the results without the inclusion of the Breit interaction. We hope that more accurate theoretical and state resolved experimental work can be done in the near future to further clarify the effect. In addition, the theoretical DR spectra are obtained in the *KLL* region and are compared with the latest experimental results obtained in the Shanghai EBIT. A good agreement is found.

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