ENERGY LEVELS, LIFETIMES, AND RADIATIVE DATA OF Xe XXIV**

X. M. Ren [1], L. H. Hao [2*], J. J. Liu [2]

*[1] Institute of Technology, Nanchang Jiao Tong Institute,
Nanchang, 330100, China
[2] College of Science at Hainan Tropical Ocean University,
Sanya, Hainan, 572022, China; e-mail: lhhao_1020@163.com*

The multi-configuration Dirac–Hartree-Fock method is employed to calculate the energy levels, wavelengths, transition probabilities, and line strengths for electric dipole allowed (E1) and forbidden (M1, E2, M2) lines for the $4s^2 4p$ and $4s4p^2$ configurations of Xe XXIV. From our radiative decay probabilities, we have also derived the radiative lifetimes of 10 fine-structure energy levels. The valence–valence and core–valence correlation effects, Breit interactions, as well as quantum electrodynamics (QED) effects are estimated in the subsequent relativistic configuration interaction (CI) calculations. The present results are compared with the experimental data and with the values from other calculations. In this paper, we predict new data for several radiative data where no other theoretical and/or experimental results are available.
Keywords: *energy level, wavelength, transition probability, line strength.*

УРОВНИ ЭНЕРГИИ, ВРЕМЯ ЖИЗНИ И РАДИАЦИОННЫЕ ДАННЫЕ Xe XXIV

X. M. Ren [1], L. H. Hao [2*], J. J. Liu [2]

УДК 539.194

*[1] Технологический институт, Институт Наньчан Цзяо Тун,
Наньчан, 330100, Китай
[2] Научный колледж Хайнаньского университета тропических океанов,
Санья, Хайнань, 572022, Китай; e-mail: lhhao_1020@163.com*

(Поступила 4 июня 2020)

Для расчета уровней энергии, длин волн, вероятностей переходов и сил осцилляторов для электрических дипольных разрешенных (E1) и запрещенных (M1, E2, M2) линий конфигураций $4s^2 4p$ и $4s4p^2$ Xe. XXIV применен многоконфигурационный метод Дирака—Хартри-Фока. Из вероятности радиационного распада получены радиационные времена жизни 10 тонкоструктурных уровней энергии. Эффекты корреляции валентность-валентность и ядро-валентность, взаимодействия Брейта, а также эффекты квантовой электродинамики (QED) оценены в расчетах релятивистского конфигурационного взаимодействия (CI). Результаты сравниваются с экспериментальными данными и расчетами других авторов. Предсказаны новые данные для нескольких радиационных постоянных, для которых отсутствуют другие теоретические и/или экспериментальные результаты.
Ключевые слова: *уровень энергии, длина волны, вероятность перехода, сила осциллятора.*

Introduction. The study of highly ionized atomic systems is a subject of considerable interest in atomic physics because knowledge of the structure and other properties of these systems is important in many fields of science and technology, such as laser physics, astrophysics, and plasma physics. The probabilities of electric quadrupole and magnetic dipole transitions, in particular, play an important role in plasma diagnostics. However, in many cases the experimental data about these systems are absent. In general, one has to use reliable theoretical predictions as input in other fields [1, 2].

**Full text is published in JAS V. 88, No. 4 (http://springer.com/journal/10812) and in electronic version of ZhPS V. 88, No. 4 (http://www.elibrary.ru/title_about.asp?id=7318; sales@elibrary.ru).

The interest in investigating the spectra of gallium-like ions has motivated many experimental and theoretical studies during the past several years [3]. Theoretical energy levels for the $n = 4$, 0 transitions of the ion Br V-In XIX along the gallium isoelectronic sequence were calculated using the relativistic Hartree-Fock model combined with a semi-empirical optimization of radial energy integrals (Slater parameters) [4]. The fine-structure splitting and magnetic dipole ($M1$) and electric quadrupole ($E2$) transition rates between the $4s^24p\ ^2P_{1/2}$ and $^2P_{3/2}$ levels of Ga-like ions were calculated for Ga to U^{61+} using the multiconfiguration Dirac-Fock (MCDF) method [5]. Lines of the resonance transition array $4s^24p$–$4s4p^2$ in the Ga-like ions Ru XIV, Rh XV, Pd XVI, Ag XVII, Cd XVIII, and In XIX were identified in the spectra emitted from laser-produced plasmas [6]. In particular, the spectra of gallium-like ions such as Rb VII, Sr VIII, Y IX, Zr X, Nb XI, and Mo XII emitted from sparks and laser-produced plasmas were recorded in the region 235–665 Å by Litzén [7]. Highly ionized xenon spectra (95–260 Å) excited in TFR tokamak plasmas were recorded by Breton et al. [8]. The inter-combination multiplet $4s^24p\ ^2P$–$4s4p^2\ ^4P$ in Ag XVII four lines was observed by Träbert [9, 10]. Spectra of gallium-like rare-earth atoms ($Z = 59$–70) emitted from high-temperature low-density tokamak and high-density laser plasmas have been recorded in the soft-X-ray range of 50–200 Å by Fournier et al. [11].

A little more than 10 years ago, at the Livermore Electron-Beam Ion-Trap facility, the extreme-ultraviolet spectra of highly charged Ga-like ions W XLIV [12–14], Os XLVI [15], Au IL [16], Bi LII, Th LX, and U LXII [16] were recorded. At the Berlin Electron-Beam Ion-Trap Facility Biedermann et al. investigated the radiation of highly charged xenon ions in the extreme ultraviolet wavelength in the range between 90 and 240 Å for Rb-like Xe^{17+} to Cu-like Xe^{25+} ions using a 2 m grazing incidence spectrometer and performed atomic structure calculations with the HULLAC code [17]. These experimental measurements should become simpler and more reliable using this more accurate set of theoretical analysis. On the theoretical front, the atomic data and spectral line intensities for the 11 tungsten ($Z = 74$) ions from Co-like W^{47+} to Rb-like W^{37+} in a high-temperature, low-density medium are presented using the fully relativistic *ab initio* calculations by Fournier [18]. The energies, fine-structure splitting of $4s^24p$ states, and magnetic-dipole and electric-quadrupole transition rates for the $4s^24p\ ^2P_{1/2}$–$4s^24p\ ^2P_{3/2}$ transition for Ga-like ions with the nuclear charge Z ranging from 31 to 100 were calculated using the relativistic many-body perturbation theory (MBPT) method by Safronova et al. [19]. The fine-structure energy levels, term splitting, wavelengths, and transition rates of the Gallium-like $4s^24p$–$4s4p^2$ transitions in the ions Ge II–U LXII were reported using the relativistic MCDF method by Hu et al. [20]. The energy levels, wavelengths, transition probabilities, oscillator strengths, and line strengths for the $4s^24p$–$4s4p^2$ and $4s^24p$–$4s^24d$ allowed ($E1$) transitions were calculated using the fully relativistic MCDF method in gallium-like ions from $Z = 54$ to 59 by El-Sayed [21]. The wavelengths and transition rates in the X-ray spectra of highly charged gallium-like ions from Yb XL to U LXII were presented using the multiconfiguration Dirac–Fock (MCDF) code by Quinet et al. [22].

We have used the multiconfiguration Dirac–Hartree-Fock method in the optimized level mode (OL) to calculate the $E1$ and forbidden ($M1$, $E2$, $M2$) line transition energies, fine-structure levels, wavelengths, transition probabilities, line strengths, and lifetimes in the X-ray spectra of gallium-like Xe ions. Some of the core electrons within the atom and the effects of the electron correlation are taken into account in a systematic way. The Breit interactions and QED effects are also included. This computational approach enables us to present transitions of the Xe XXIV spectra, which are useful for identifying forbidden lines in further astrophysical investigations, for an improved understanding of the origin of these effects, for the explanation of the existing results, and for making further predictions.

Calculations. The wavelengths, transition probabilities, and line strengths for the $4s^24p$–$4s4p^2$ allowed electric dipole ($E1$) transitions were calculated for Ga-like Xe ions. These calculations were performed using the fully relativistic multiconfiguration Dirac–Hartree-Fock (MCDHF) approach and the General Martrix Elements (MCDFGME) program [23, 24] of Desclaux and Indelicato. In order to account for relaxation in the transition process and different correlation effects in the initial and final atomic states, the atomic state wave functions were optimized layer by layer. To be able to compute the transition matrix elements built from independently optimized orbital sets, the biorthogonal transformation techniques introduced by Malmqvist were used [25, 26].

For the calculations of the lower-lying levels of Xe XXIV, the $4s^24p$ configuration with total angular momenta $J = 1/2$ and 3/2 and the $4s4p^2$ configuration with total angular momenta $J = 1/2$, 3/2, and 5/2 were included. In the represented computations, the ionic system was modeled as a core plus valence correlation. To build a configuration state functions (CSF) expansion, the restrictive active space methods were used. The {4s, 4p, 4d} orbitals were treated as valence subshells and the rest as the core. From the test calculations, by increasing the maximum orbital angular momentum up to g, it was found that the g orbitals were relatively unimportant for the energies, and the transition data were therefore neglected. The $4s^2 4p$ and $4s4p^2$ were included as reference configurations and the active space was systematically considered until $n = 7$, $l = 3$ so as to obtain satisfying results. First, all CSFs from the double excitations of the valence {4*s*, 4*p*, 4*d*} shell into the active set were included. We only included the valence correlation (VV) following the constraint of closed-core subshells for all CSF. In the subsequent calculations, the core plus valence correlation (CV) due to the 4*d*, 4*p*, and 4*s* orbitals was successively included. The results of these tests show that the CV correction makes significant changes to the calculations and cannot be ignored. All the levels of two different configurations were determined in the so-called extended optimal level (EOL) version. To account for the close degeneracy between $4s4p^2$ and $4s^2 4p$, the atomic state functions for $4s4p^2\ {}^2S_{1/2}$, $4s4p^2\ {}^4P_{1/2,\ 3/2,\ 5/2}$, $4s4p^2\ {}^2D_{3/2,\ 5/2}$, and $4s^2 4p\ {}^2P_{1/2,\ 3/2}$ were determined simultaneously. With a set of fixed orbitals, the core polarization from 3*p* shell to the active set was taken into account in the subsequent relativistic configuration interaction (RCI) calculations. A similar calculation procedure was previously introduced in our papers [27]. The Breit interaction as well as the QED effects (the vacuum polarization and self-energy correction) as part of the VV+CV correlations were taken into account by the RCI calculation in each step. The maximum number of the relativistic CSFs in our calculation reached up to 42009.

Results and discussion. The present results of the electric-dipole allowed (*E*1) and forbidden (*M*1, *E*2, *M*2) transitions among the low-lying levels of Xe XXIV are compiled in the following seven tables. To explain the influence of the VV and CV correlations, the QED effects, as well as the Breit interaction on the excitation energies as functions of the increasing active sets, we display some of the excitation energies obtained in different interactions in detail in Table 1. The energy contributions from the Breit interaction and the QED effects are also shown in the results. As can be seen from Table 1, the VV correlations converge when $n = 7$, whereas for core–valence (VV+CV) the principal number is limited to $n = 6$. This is because of the following. First, the addition in the 7*f* orbital was specifically optimized to represent the core polarization effects. It has a negligible effect on the energies of the system and will, therefore, be neglected in further calculations. Second, the number of the CSFs increases very rapidly when we consider the 7*f* orbitals, so it is very difficult to get convergence and accuracy in our calculation. In comparison with the VV results, a large improvement is achieved in the calculations of the excitation energies by taking the core–valence correlation into account. For example, comparing the excitation energy with and without the CV correlation for the level $4s4p^2\ {}^2D_{5/2}$, we see that the contribution from the CV correlation is more than 3200 cm^{-1}. It also can be noticed that the Breit interaction is important for the excitation energies. For example, comparing the excitation energy with and without the Breit interaction for the level $4s4p^2\ {}^2D_{5/2}$, we conclude that the contribution from the Breit interaction is greater than 1600 cm^{-1}. These results indicate that the CV correlation as well as the Breit interaction and QED effects are significant and cannot be neglected in further calculations. Moreover, as can be seen from Table 2, the results with all these effects agree well with the semiempirical [5] and theoretical values [5, 19, 21, 28]. In view of the VV+CV correlation independence just discussed, our energy and transition data are presented in the VV+CV correlation form only, and the energy contribution from the Breit interaction and QED effect are included in our calculations.

TABLE 1. The Influence of the VV and CV Correlations, the Breit Interaction, as Well as QED Effects on Some of the Excitation Energies (in cm^{-1}) for Xe XXIV

Levels	VV+Breit+QED				VV+CV			VV+CV +Breit	VV+CV+ Breit+QED
	$n = 4$	$n = 5$	$n = 6$	$n = 7$	$n = 4$	$n = 5$	$n = 6$		
$4s^2 4p\ {}^2P_{1/2}$	0	0	0	0	0	0	0	0	0
$4s^2 4p\ {}^2P_{3/2}$	138623	138726	138712	138718	140549	140940	140839	139060	139258
$4s4p^2\ {}^4P_{1/2}$	395866	396146	396212	396220	398493	399036	399125	400784	398194
$4s4p^2\ {}^4P_{3/2}$	486517	487044	487134	487162	491139	492497	492558	492691	490282
$4s4p^2\ {}^4P_{5/2}$	522653	523026	523084	523102	527545	528303	528274	528131	525755
$4s4p^2\ {}^2D_{3/2}$	584130	584242	584229	584227	587911	587689	587577	587465	585139
$4s4p^2\ {}^2P_{1/2}$	620900	620714	620627	620604	619061	618381	618202	618530	616071
$4s4p^2\ {}^2D_{5/2}$	655775	655997	656001	656015	662513	663348	663093	661459	659314
$4s4p^2\ {}^2S_{1/2}$	757704	757508	757376	757335	761061	760190	759836	758395	756163
$4s4p^2\ {}^2P_{3/2}$	768108	767883	767798	767787	767462	767284	766980	765462	763269

N o t e. *n* represents the orbital layer, i.e., the principle quantum number.

Table 2 displays the excitation energies and lifetimes for all the 10 levels of the $4s^24p$ and $4s4p^2$ configurations. The excitation energies are compared with the semiempirical data [5] and other theoretical results [5, 19, 21, 28]. For the lower-lying levels we find that our results are in good agreement with the MBPT calculations of Safronova et al. [19]. As the excitation energies increase, the match between the calculated energies and those taken from the MCDF database [21] for these transitions becomes slightly poorer, and the maximum difference for the results of the VV+CV correlation calculations is 1.26%. As can be seen from Table 2, for most levels, the deviations between the semiempirical [5] and theoretical results [5, 19, 21, 28], except for some transitions, are within 0.97% for our results. Since the lifetime is directly measurable, with very few assumptions for the observed plasma, they are also excellent test cases for experimental methods and atomic theoretical models. We calculated the lifetimes for the nine levels based on the transition rates, which are shown in Table 2. The agreement between the length and velocity gauges for the lifetimes of the nine levels is within 1–6%. This demonstrates the good quality of the results.

TABLE 2. Excitation Energies (in cm^{-1}) and Lifetimes (in s) for the 10 Low-Lying Levels in Xe XXIV; Comparison with the Semiempirical and Theoretical Results

Levels	Energy						Lifetime	
Designation	Present	MCDF [21]	MCDF [5]	SE [5]	DF [28]	RMBPT [19]	V	L
$4s^24p\ ^2P_{1/2}$	0	0						
$4s^24p\ ^2P_{3/2}$	139258	138676	139414	139057	138753	139392		4.15(–5)
$4s4p^2\ ^4P_{1/2}$	398194	398970					2.42(–10)	2.54(–10)
$4s4p^2\ ^4P_{3/2}$	490282	489664					2.01(–9)	2.10(–9)
$4s4p^2\ ^4P_{5/2}$	525755	525725					3.15(–10)	3.36(–10)
$4s4p^2\ ^2D_{3/2}$	585139	587031					2.52(–11)	2.56(–11)
$4s4p^2\ ^2P_{1/2}$	616071	623903					8.66(–12)	8.74(–12)
$4s4p^2\ ^2D_{5/2}$	659314	658505					9.77(–11)	1.03(–10)
$4s4p^2\ ^2S_{1/2}$	756163	760558					1.22(–11)	1.24(–11)
$4s4p^2\ ^2P_{3/2}$	763269	770730					6.64(–11)	6.66(–11)

N o t e. Numbers in brackets represent powers of ten.

TABLE 3. Experimental and Theoretical Wavelengths (Å) of Ga-like Xe Ions (in Å)

Transition	This work	Theory		Experiment	
		Ref. [21]	HULLAC [17]	Berlin EBIT [17]	TFR [8]
$4s^24p\ ^2P_{1/2}$–$4s4p^2\ ^4P_{1/2}$	251.13	252.47			
$4s^24p\ ^2P_{1/2}$–$4s4p^2\ ^4P_{3/2}$	203.96	205.41			
$4s^24p\ ^2P_{1/2}$–$4s4p^2\ ^2D_{3/2}$	171.08	171.15	168.00	171.092	171.60
$4s^24p\ ^2P_{1/2}$–$4s4p^2\ ^2P_{1/2}$	162.32	161.03	157.22	162.470	162.52
$4s^24p\ ^2P_{1/2}$–$4s4p^2\ ^2S_{1/2}$	132.25	131.97			
$4s^24p\ ^2P_{1/2}$–$4s4p^2\ ^2P_{3/2}$	131.02	130.21			
$4s^24p\ ^2P_{3/2}$–$4s4p^2\ ^4P_{1/2}$	386.20	388.55			
$4s^24p\ ^2P_{3/2}$–$4s4p^2\ ^4P_{3/2}$	284.88	287.26			
$4s^24p\ ^2P_{3/2}$–$4s4p^2\ ^4P_{5/2}$	258.73	260.28			
$4s^24p\ ^2P_{3/2}$–$4s4p^2\ ^2D_{3/2}$	224.28	224.42			
$4s^24p\ ^2P_{3/2}$–$4s4p^2\ ^2P_{1/2}$	209.73	207.34			
$4s^24p\ ^2P_{3/2}$–$4s4p^2\ ^2D_{5/2}$	192.29	193.38		192.084	192.40
$4s^24p\ ^2P_{3/2}$–$4s4p^2\ ^2S_{1/2}$	162.10	161.54			
$4s^24p\ ^2P_{3/2}$–$4s4p^2\ ^2P_{3/2}$	160.35	158.91		160.503	160.58

For comparison, the available theoretical and experimental results of wavelengths for lines in Ga-like Xe ions are presented in Table 3. Measurements of the radiation from Xenon ions were performed at the TFR [8] and the Lawrence Livermore National Laboratory [17] EBITs. In general, our theoretical results are in excellent agreement with the experimental wavelengths. We note that the mean ratio $\lambda_{\text{This work}}/\lambda_{\text{exp}}$ found was equal to 1±0.003, where the uncertainty represents the standard deviation of the mean. This confirms the high accuracy of our calculations. Moreover, our calculations are also generally in good agreement with the MCDF results of El-sayed [21] and the HULLAC data from Biedermann et al. [17] for Xe XXIV ions, except for some transitions with a maximum difference of approximately 3.14%. However, a more detailed comparison of the calculated and experimental energies for these transitions (Table 3) indicates that our MCDHF transition wavelengths are in better agreement with the experimental values than the MCDF results of El-sayed [21] and Biedermann et al. [17].

The *M*1 and *E*2 transition probabilities of these lines and the lifetime for the lower-lying $4s^24p$ $^2P_{3/2}$ level are compared with the available theoretical data in Table 4. The present M1 transition probabilities agree within 2.04% with the calculations of Ali [5] and Biémont et al. [29]. Meanwhile, the present *E*2 transition probability is in good agreement with the value of Ali. [5] and Biémont et al. [29]. Moreover, the present result for the lifetime of the $4s^24p$ $^2P_{3/2}$ level agrees within 1.97% with the other theoretical results [19].

TABLE 4. Comparison of *M*1, *E*2 Transition Probabilities (in s^{-1}) of the Green Coronal Line and the Lifetime (in s) for the $4s^24p$ $^2P_{3/2}$ Level of Xe XXIV in the Present Work and Other Available Values

Transition	This work	Ref. [5]	Ref. [29]
*M*1	2.41(4)	2.38(4)	2.46(4)
*E*2	2.61(2)	2.54(2)	2.71(2)
Lifetime	4.15(–5)	4.07(–5) [19]	

N o t e. Numbers in brackets represent powers of ten.

TABLE 5. MCDHF Transition Energies (ΔE in cm^{-1}), Transition Probabilities (in s^{-1}), Line Strengths (in a.u.), and the Ratios of Velocity to Length Strengths (S_v/S_l) in the Present Work for Xe XXIV for Electric Dipole (*E*1) Lines

Transition	Type	ΔE	A		S_l		S_v/S_l
		Present	Present	Ref. [21]	Present	Ref. [21]	
$4s^24p$ $^2P_{1/2}$–$4s4p^2$ $^4P_{1/2}$	*E*1	398194	3.84(9)	3.79(9)	6.00(–2)	6.02(–2)	0.953
$4s^24p$ $^2P_{1/2}$–$4s4p^2$ $^4P_{3/2}$	*E*1	490282	0.98(8)	1.02(8)	1.64(–3)	1.75(–3)	0.962
$4s^24p$ $^2P_{1/2}$–$4s4p^2$ $^2D_{3/2}$	*E*1	585139	3.70(10)	3.62(10)	3.65(–1)	3.58(–1)	0.984
$4s^24p$ $^2P_{1/2}$–$4s4p^2$ $^2P_{1/2}$	*E*1	616071	1.09(11)	1.19(11)	4.59(–1)	4.90(–1)	0.989
$4s^24p$ $^2P_{1/2}$–$4s4p^2$ $^2S_{1/2}$	*E*1	756163	4.22(9)	5.96(9)	9.63(–3)	1.35(–2)	1.044
$4s^24p$ $^2P_{1/2}$–$4s4p^2$ $^2P_{3/2}$	*E*1	763269	2.65(10)	3.63(10)	1.18(–1)	1.58(–1)	1.017
$4s^24p$ $^2P_{3/2}$–$4s4p^2$ $^4P_{1/2}$	*E*1	258936	9.60(7)	9.17(7)	5.46(–3)	5.31(–3)	1.028
$4s^24p$ $^2P_{3/2}$–$4s4p^2$ $^4P_{3/2}$	*E*1	351025	3.78(8)	3.61(8)	1.73(–2)	1.69(–2)	0.956
$4s^24p$ $^2P_{3/2}$–$4s4p^2$ $^4P_{5/2}$	*E*1	386497	2.98(9)	2.88(9)	1.53(–1)	1.51(–1)	0.939
$4s^24p$ $^2P_{3/2}$–$4s4p^2$ $^2D_{3/2}$	*E*1	445881	2.04(9)	1.87(9)	4.54(–2)	4.17(–2)	0.993
$4s^24p$ $^2P_{3/2}$–$4s4p^2$ $^2P_{1/2}$	*E*1	476813	5.73(9)	5.44(9)	5.22(–2)	4.78(–2)	0.999
$4s^24p$ $^2P_{3/2}$–$4s4p^2$ $^2D_{5/2}$	*E*1	520056	9.74(9)	9.14(9)	2.05(–1)	1.96(–1)	0.953
$4s^24p$ $^2P_{3/2}$–$4s4p^2$ $^2S_{1/2}$	*E*1	616905	7.65(10)	8.44(10)	3.22(–1)	3.51(–1)	0.985
$4s^24p$ $^2P_{3/2}$–$4s4p^2$ $^2P_{3/2}$	*E*1	624011	1.24(11)	1.31(11)	1.00	1.04	0.994

N o t e. Numbers in brackets represent powers of ten.

In order to further check the accuracy and reliability of our calculations, the calculated results for the *E*1 transition energies, transition probabilities, and line strengths from the excited levels of the $4s4p^2$ configuration to those of the $4s^24p$ configuration are shown in Table 5, together with the other available theoretical results. In comparison with the transition probabilities and line strengths involved in the table, it can be seen clearly that our results appear to be close to those of El-sayed [21]. In addition, the ratios of length to velocity strengths (S_v/S_l) are also listed in the table. It can be seen that most ratios fluctuate around 1. The nearly equal values of the length and velocity rates of the transitions can justify our present calculated results. The *E*2, *M*1, and *M*2 transition energies, transition wavelengths, transition probabilities, and line strengths among the 10 fine-structure energy levels of Xe XXIV are listed in Tables 6 and 7.

TABLE 6. Transition Energies (in cm^{-1}), Wavelengths (in Å), Transition Probabilities (in s^{-1}), and Line Strengths (in a.u.) in Different Levels of Xe XXIV for Electric Quadrupole (*E*2) Lines

Transition	Type	ΔE	λ	*A*	*S*
$4s4p^2\ ^4P_{1/2}$–$4s4p^2\ ^4P_{3/2}$	*E*2	92088	1085.91	3.72(0)	9.89(–9)
$4s4p^2\ ^4P_{1/2}$–$4s4p^2\ ^2D_{3/2}$	*E*2	186945	534.92	2.81(2)	8.40(–8)
$4s4p^2\ ^4P_{1/2}$–$4s4p^2\ ^4P_{5/2}$	*E*2	127561	783.94	1.20(2)	1.71(–7)
$4s^24p\ ^2P_{1/2}$–$4s^24p\ ^2P_{3/2}$	*E*2	139258	718.09	2.61(2)	1.91(–7)
$4s4p^2\ ^2D_{3/2}$–$4s4p^2\ ^2P_{1/2}$	*E*2	30932	3232.86	1.19(–1)	3.97(–9)
$4s4p^2\ ^4P_{3/2}$–$4s4p^2\ ^4P_{5/2}$	*E*2	35473	2819.06	1.32(–1)	8.74(–9)
$4s4p^2\ ^4P_{3/2}$–$4s4p^2\ ^2D_{5/2}$	*E*2	169032	591.61	3.12(2)	1.91(–7)
$4s4p^2\ ^2D_{3/2}$–$4s4p^2\ ^2D_{5/2}$	*E*2	74175	1348.16	2.81(0)	2.04(–8)
$4s4p^2\ ^4P_{5/2}$–$4s4p^2\ ^2D_{3/2}$	*E*2	59384	1683.96	1.67(0)	1.57(–8)
$4s4p^2\ ^4P_{5/2}$–$4s4p^2\ ^2P_{3/2}$	*E*2	237514	421.03	2.72(2)	4.01(–8)

N o t e. Numbers in brackets represent powers of ten.

TABLE 7. Transition Energies (in cm^{-1}), Wavelengths (in Å), Transition Probabilities (in s^{-1}), and Line Strengths (in a.u.) in Different Levels of Xe XXIV for Forbidden (*M*1) and (*M*2) Lines

Transition	Type	ΔE	λ	*A*	*S*
$4s4p^2\ ^4P_{1/2}$–$4s4p^2\ ^4P_{3/2}$	*M*1	92088	1085.91	1.38(4)	3.48(–5)
$4s4p^2\ ^4P_{1/2}$–$4s4p^2\ ^2D_{3/2}$	*M*1	186945	534.92	3.67(3)	1.11(–6)
$4s^24p\ ^2P_{1/2}$–$4s^24p\ ^2P_{3/2}$	*M*1	139258	718.09	2.41(4)	1.76(–5)
$4s4p^2\ ^2D_{3/2}$–$4s4p^2\ ^2P_{1/2}$	*M*1	30932	3232.86	3.53(1)	1.18(–6)
$4s4p^2\ ^4P_{3/2}$–$4s4p^2\ ^4P_{5/2}$	*M*1	35473	2819.06	5.34(2)	3.54(–5)
$4s4p^2\ ^4P_{3/2}$–$4s4p^2\ ^2D_{5/2}$	*M*1	169032	591.61	1.86(4)	1.14(–5)
$4s4p^2\ ^2D_{3/2}$–$4s4p^2\ ^2D_{5/2}$	*M*1	74175	1348.16	2.89(3)	2.10(–5)
$4s4p^2\ ^4P_{5/2}$–$4s4p^2\ ^2D_{3/2}$	*M*1	59384	1683.96	6.63(2)	6.25(–6)
$4s4p^2\ ^4P_{5/2}$–$4s4p^2\ ^2P_{3/2}$	*M*1	237514	421.03	1.16(3)	1.70(–7)
$4s^24p\ ^2P_{1/2}$–$4s4p^2\ ^4P_{3/2}$	*M*2	490282	203.96	7.71(1)	1.29(–9)
$4s^24p\ ^2P_{1/2}$–$4s4p^2\ ^2D_{3/2}$	*M*2	585139	171.08	1.39(0)	1.37(–11)
$4s^24p\ ^2P_{1/2}$–$4s4p^2\ ^2P_{3/2}$	*M*2	763269	131.02	9.20(0)	4.09(–11)
$4s^24p\ ^2P_{1/2}$–$4s4p^2\ ^4P_{5/2}$	*M*2	525755	190.20	1.14(2)	2.32(–9)
$4s^24p\ ^2P_{1/2}$–$4s4p^2\ ^2D_{5/2}$	*M*2	659314	151.67	4.46(1)	4.92(–10)
$4s^24p\ ^2P_{3/2}$–$4s4p^2\ ^4P_{1/2}$	*M*2	258936	386.20	2.00(–1)	1.14(–11)
$4s^24p\ ^2P_{3/2}$–$4s4p^2\ ^2P_{1/2}$	*M*2	476813	209.73	2.75(0)	2.50(–11)
$4s^24p\ ^2P_{3/2}$–$4s4p^2\ ^2S_{1/2}$	*M*2	616905	162.10	2.42(2)	1.02(–9)
$4s^24p\ ^2P_{3/2}$–$4s4p^2\ ^4P_{3/2}$	*M*2	351025	284.88	2.28(–1)	1.04(–11)
$4s^24p\ ^2P_{3/2}$–$4s4p^2\ ^2D_{3/2}$	*M*2	445881	224.28	2.06(0)	4.59(–11)
$4s^24p\ ^2P_{3/2}$–$4s4p^2\ ^2P_{3/2}$	*M*2	624011	160.35	9.08(1)	7.37(–10)
$4s^24p\ ^2P_{3/2}$–$4s4p^2\ ^4P_{5/2}$	*M*2	386497	258.73	1.59(0)	8.14(–11)
$4s^24p\ ^2P_{3/2}$–$4s4p^2\ ^2D_{5/2}$	*M*2	520056	192.29	2.47(2)	5.21(–9)

N o t e. Numbers in brackets represent powers of ten.

Conclusions. Large-scale calculations of the fine structure energy levels and lifetimes belonging to the $4s^24p$ and $4s4p^2$ configurations of Xe XXIV, and the *E*1, *E*2, *M*1, *M*2 transition energies, wavelengths, transition probabilities, and line strengths among them were performed using the GRASP2K package based on the MCDHF method. The valence–valence and core–valence correlations, the Breit interaction, as well as the QED effects were taken into account in a systematic way. Compared with the theoretical and experimental results, our results of the energy levels, lifetimes, wavelengths, transition rates, and line strengths are reliable and reasonable. In particular, the *E*1 transition wavelengths are in good agreement with the experimental values. We believe that our results will be useful in analyzing the existing experimental data and in planning new ones.

Acknowledgments. This work was supported in part by the Science and Technology Research Project of the Education Department of the Jiangxi Province of China under grant GJJ181488, the National Natural Science Foundation of China under grants 11565020, 11965010, and the Natural Science Foundation of the Hainan Province under grants 118MS071, 2019RC239.

REFERENCES

1. J. D. Gilaspy, *J. Phys. B: At. Mol. Opt. Phys*., **34**, R93 (2001).
2. D. A. Liedahl, in: ASP Conference Series, **247**, Eds. G. Ferland, D. W. Savin, San Francisco, 417 (2001).
3. P. Quinet, É. Biémont, P. Palmeri, E.Träbert, *At. Data Nucl. Data Tables*, **93**, 167 (2007).
4. É. Biémont, P. Qninet, J. Quant. *Spectrosc. Radiat. Transf.*, **44**, 233 (1990).
5. M. A. Ali, *Phys. Scr*., **55**, 159 (1997).
6. U. Litzén, X. T. Zeng, *Phys. Scr*., **43**, 262 (1991).
7. U. Litzén, J. Reader, *Phys. Scr.*, **39**, 73 (1989).
8. C. Breton, C. DeMichelis, W. Hecq, M. Mattioli, J. Ramette, B. Saoutic, C. Bauche-Arnoult, J. Bauche, J. F. Wyart, *Phys. Scr*., **37**, 33 (1988).
9. E. Träbert, *Nucl. Instrum. Methods B*, **43**, 362 (1989).
10. E.Träbert, G. Moller, P. H. Heckmann, A. E. Livingston, J. H. Blanke, *Phys. Scr.*, **42**, 323 (1990).
11. K. B. Fournier, W. H. Goldstein, A. Osterheld, M. Finkenthal, S. Lippmann, L. K. Huang, H. W. Moos, N. Spector, *Phys. Rev. A*, **50**, 2248 (1994).
12. S. B. Utter, P. Beiersdorfer, E. Träbert, *Can. J. Phys.*, **80**, 1503 (2002).
13. T. Pütterich, R. Neu, C. Biedermann, R. Radtke, ASDEX Upgrada Team, *J. Phys. B: At. Mol. Opt. Phys.*, **38**, 3071 (2005).
14. Y. Ralchenko, J. Reader, J. M. Pomeroy, J. N. Tan, J. D. Gillaspy, *J. Phys. B: At. Mol. Opt. Phys.*, **40**, 3861 (2007).
15. E. Träbert, P. Beiersdorfer, K. B. Fournier, M. H. Chen, *Can. J. Phys. B: At. Mol. Opt. Phys.*, **83**, 829 (2005).
16. E. Träbert, P. Beiersdorfer, K. B. Fournier, S. B. Utter, K. L. Wong, *Can. J. Phys.*, **79**, 153 (2001).
17. C. Biedermann, R. Radtke, G. Fußmann, J. L. Schwob, P. Mandelbaum, *Nucl. Instrum. Methods B*, **235**, 126 (2005).
18. K. B. Fournier, *At. Data Nucl. Data Tables*, **68**, 1 (1998).
19. U. I. Safronova, T. E. Cowan, M. S. Safronova, *Phys. Lett. A*, **348**, 293 (2006).
20. F. Hu, J. Yang, C. Wang, L. Jing, S. Chen, G. Jiang, H. Liu, L. Hao, *Phys. Rev. A*, **84**, 042506 (2011).
21. F. El-Sayed, *J. Appl. Spectrosc.*, **82**, 3 (2015).
22. P. Quinet, É. Biémont, P. Palmeri, E. Träbert, *At. Data Nucl. Data Tables*, **93**, 167 (2007).
23. J. P. Desclaux, *Comput. Phys. Commun.*, **9**, 31 (1975).
24. J. P. Desclaux, P. Indelicato, MCDFGME, a Multi-configuration Dirac Fock and General Matrix Elements program, release 2005, http://dirac.spectro.jussieu.fr/mcdf.
25. P. Å. Malmqvist, *Int. J. Quantum Chem*., **30**, 479 (1986).
26. J. Olsen, M. Godefroid, P. Jönsson, P. Å. Malmqvist, C. Froese Fischer, *Phys. Rev. E*, **52**, 4499 (1995).
27. L. H. Hao, G. Jiang, H. J. Hou, *Phys. Rev. A*, **81**, 022502 (2010).
28. L. J. Curtis, *Phys. Rev. A*, **35**, 2089 (1987).
29. É. Biémont, J. E. Hansen, *Nucl. Instrum. Methods B*, **23**, 274 (1987).