Transition probabilities and lifetimes of the low-lying levels of Fe XIV*

Fan Jian-Zhong(范建中)[a)b)], Wang Qing-Min(汪青敏)[b)],
Chang Zhi-Wei(常志伟)[b)], and Dong Chen-Zhong(董晨钟)[b)†]

[a)] *Fundamental Department, Taiyuan Normal University, Taiyuan* 030012, *China*
[b)] *Key Laboratory of Atomic and Molecular Physics and Functional Material of Gansu Province, College of Physics and Electronic Engineering, Northwest Normal University, Lanzhou* 730070, *China*

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The multi-configuration Dirac–Fock method is employed to calculate the transition energies, probabilities, and oscillator strengths for electric dipole allowed (E1) and forbidden (M1, E2, M2) lines for the $3s^23p$, $3s3p^2$, $3s^23d$, $3p^3$, and 3s3p3d configurations of Fe XIV. The lifetimes of all 40 levels of these low-lying configurations are also derived. The valence–valence and core–valence correlation effects are accounted for in a systematic way. Breit interactions and quantum electrodynamics (QED) effects are estimated in subsequent relativistic configuration interaction (CI) calculations. The present results are in good agreement with other available theoretical and experimental values, and therefore can be used for the further astrophysical investigations.

Keywords: transition probability, lifetime, Fe XIV

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1. Introduction

The study of atomic transition is a subject of considerable interest in many fields, especially in astrophysics, which plays an important role in the determination of atomic abundances. The probabilities of magnetic dipole and electric quadrupole transitions, in particular, are important in plasma diagnostics. However, the experimental determination of these quantities is difficult, accurate theoretical estimates therefore would provide valuable information.

Iron is an astrophysically abundant heavy element and a major impurity in laboratory fusion devices. In the solar corona, there are many emission lines from different ionization stages of iron, the thirteen-times ionization iron ion is abundant at a temperature of about 2×10^6 K.[1] The prominent solar coronal green line at 5305 Å (1 Å=0.1 nm) arises due to the forbidden transitions (M1, E2) in Fe XIV and it offers useful diagnostics of the solar corona. The importance of Fe XIV lines for plasma diagnostics has triggered a number of investigations. Much theoretical and experimental attention has been paid to studies of transition probabilities and radiative lifetimes of low-lying configuration levels in Fe XIV. On the experimental side, several different light sources have been used to study the spectra and energy level structures of Fe XIV. For example, the beam-foil experiments by Träbert *et al.* for the 3s3p3d ^{4}F levels of Fe XIV;[2] the Kingdon trap experiment by Moehs *et al.* on the lifetimes of the ^{2}P levels producing the coronal transitions of Fe X and Fe XIV;[3] the electron beam ion trap (EBIT) experiments by Beiersdorfer *et al.* on the transition rate of the coronal transition of Fe XIV,[4] and by Brenner *et al.* on the lifetime of the Fe XIV $3s^23p\ ^2P^o_{3/2}$ metastable level;[5] the heavy-ion storage ring experiment by Träbert for the transition rates of the coronal lines of Fe X and Fe XIV,[6] and by Träbert *et al.*[7,8] for the lifetimes and M1/E2 transition rates; the atomic lifetime of multiply charged ions were measured by Träbert.[9] On the theoretical side, there have been a large number of data sets available for Fe XIV using different approximations. For example, detailed computations were carried out by Froese Fischer *et al.*[10] for all energy levels and lifetimes within the $n = 3$ complex of Fe XIV using multiconfiguration Hartree–Fock (MCHF) wavefunctions, as well as by Fawcett

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†Corresponding author. E-mail: dongcz@nwnu.edu.cn

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on the wavelengths and oscillator strengths of the allowed transitions within the third shell for ions from Cl V to Ni XVI;[11] Huang performed (small-scale) multiconfiguration Dirac–Fock (MCDF) calculations with Breit interaction and quantum electrodynamics (QED) correction for the energy levels and transition probabilities of all the low-lying 40 levels of Fe XIV;[12] Bhatia *et al.* calculated the atomic data for a five-configuration model of Fe XIV using the SUPERSTRUCTURE (SS) code based on a scaled Thomas–Fermi model;[13,14] Storey *et al.* calculated the collision strengths and thermally averaged collision strengths for electron excitation between the forty energetically lowest levels of Fe XIV using the R-matrix method;[15] Gupta *et al.* calculated the fine-structure energy levels, oscillator strengths, and lifetimes for Fe XIV using large-scale CIV3 calculations.[16,17] In addition, Dong *et al.*[18] and Hao *et al.*[19] calculated radiative lifetimes and fine-structure levels of the ions of an aluminum isoelectronic sequence with the MCDF method, respectively. Froese Fischer *et al.* analysed relativistic energy levels, lifetimes, and transition probabilities for the sodium-like to argon-like sequences using the MCHF method.[20] Santana *et al.* calculated the energy levels and transition rates in the Al-like ions of iron group elements using the multireference Møller–Plesset perturbation theory.[21] Tayal calculated the transition rates of electric-dipole-allowed and forbidden transitions in Fe XIV based on the MCHF method.[22,23] However, most of the calculations were restricted to the energy levels and some specific electric dipole allowed (E1) and forbidden (M1, E2, M2) lines between the five configurations of Fe XIV, and many discrepancies were found between theories[15,16,18,19,20,22] and observations.[24]

Results for Fe XIV have been published by a number of authors using different approximations. However, multipole transitions have not been studied extensively. In addition, the previous calculations including the core–valence correlation were restricted on certain energy levels. In this paper, the large-scale multiconfiguration Dirac–Fock method is performed to calculate the E1, M1, E2, and M2 transition probabilities, fine-structure levels, and lifetimes of the 40 levels for Fe XIV using GRASP2K package.[25] The valence–valence (VV) and core–valence (CV) correlation effects are taken into account in a systematic way. Breit interactions and QED effects are also estimated. This computational approach enables us to present a consistent and improved data set of all important transitions of the Fe XIV spectra, which are useful for identifying forbidden lines in further astrophysical investigations.

2. Theory and computations

The MCDF method used in the calculations of the atomic structure properties is described in detail elsewhere,[25–29] so only a brief synopsis is presented here. In the MCDF method, the no-pair Dirac–Coulomb Hamiltonian for an atom with N electrons and nuclear Z, in atomic unit, is

$$H^{\mathrm{DC}} = \sum_{i=1}^{N} H_i + \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} |r_i - r_j|^{-1}, \quad (1)$$

$$H_i = c\alpha \cdot P_i + (\beta - 1)c^2 + V_{\mathrm{nucl}}(r_i). \quad (2)$$

In Eq. (1), the first term is the one-body contribution for an electron due to the kinetic energy and interaction with the nucleus. The two-body Coulomb interaction between the electrons comprises the second term. In Eq. (2), c is the velocity of light, α and β are 4×4 matrices, P_i is the momentum operator, $V_{\mathrm{nucl}}(r_i)$ is Coulomb potential of nucleus. Correspondingly the atomic state wave function (ASF) can be expanded by

$$|\Psi_\alpha(PJM)\rangle = \sum_{r=1}^{n_c} c_r(\alpha)|\gamma_r PJM\rangle, \quad (3)$$

where n_c is the number of the configuration state wave function (CSF) with the same parity P, total angular momentum J, and its z component of the atomic system, and c_r is the configuration mixing coefficient for each single CSF $|\gamma_r PJM\rangle$. These CSFs are further expressed by all possible Slater determinants in each corresponding configuration, which consist of the single electron orbitals,

$$\psi_{n\kappa\mu} = \frac{1}{r}\begin{pmatrix} P_{n,\kappa}\chi_{\kappa\mu}(\theta,\phi) \\ \mathrm{i}Q_{n,\kappa}(r)\chi_{-\kappa\mu}(\theta,\phi)\end{pmatrix}, \quad (4)$$

where $P_{n,\kappa}(r)$ and $Q_{n,\kappa}(r)$ are the large and small component radial functions, which are obtained by solving a series of radial integro-differential equations in the framework of MCDF. The $\chi_{\kappa\mu}(\theta,\phi)$ is a two-component spinor function.

The contributions from the Breit interaction, vacuum polarization, self-energy, and finite nuclear mass corrections are not included in Eq. (1) and are generally added as a first-order perturbation correction after self-consistency is obtained.[30]

According to the time-dependent perturbation theory, once the initial and final state wave functions

have been calculated, the Einstein spontaneous transition probability for the electric dipole (E1) transition can be given by Grant[31]

$$A_{\beta\alpha} = \frac{2\pi}{2j_\beta + 1} \sum_{M_\beta} \sum_{M_\alpha} |\langle \alpha(P_\alpha J_\alpha M_\alpha)| \times O^{(L)} |\beta(P_\beta J_\beta M_\beta)\rangle|^2, \quad (5)$$

where $O^{(L)}$ is the multiple moment operator, j_β is the total angular momentum of the final state β, $|\alpha(P_\alpha J_\alpha M_\alpha)\rangle$ and $|\beta(P_\beta J_\beta M_\beta)\rangle$ are the wave functions of the initial state α and final state β.

For the calculations of lower-lying levels of Fe XIV, the $3s^2 3p$ configuration with total angular momenta $J = 1/2$ and $3/2$, the $3s3p^2$ and $3s^2 3d$ configurations with total angular momenta $J = 1/2$, $3/2$, and $5/2$, and the $3p^3$ and 3s3p3d configurations with total angular momenta $J = 1/2, \ldots, 9/2$ were included. In the present computations, the ionic system was modeled as a core plus valence subshells. The full set of CSF in Eq. (3) has been obtained by applying the active space method. The {3s, 3p, 3d} orbitals were treated as valence subshells and the rest as 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 excitation energies as well as the transition rates, and were therefore neglected. The $3s^2 3p$, $3s3p^2$, $3s^2 3d$, $3p^3$, and 3s3p3d were included as reference configurations and the active set was systematically expanded until $n = 7$, $l = 3$ so as to gain the satisfied results. All CSFs from single and double excitations of the valence {3s, 3p, 3d} shell into active set were included. All the occupied orbitals were generated as spectroscopic orbitals and the others treated as correlation orbitals. The occupied orbitals were obtained from the Dirac–Fock calculation in particular parity and symmetry separately to take into account the effect of orbital relaxation. The correlation orbitals were optimized layer by layer, where an orbital layer refers to a set of orbitals with the same principal quantum number. All the levels of five different configurations were determined in extended optimal level (EOL) mode. With a set of fixed orbitals, the core polarization from 2p shell was taken into account in the subsequent relativistic configuration interaction (CI) calculations. The Breit interaction as well as the QED effects (the vacuum polarization and self-energy correction) were also estimated in this procedure. The maximum number of the relativistic CSFs in our calculation reached to 39956.

3. Results and discussion

The present results of the electric-dipole allowed and forbidden transitions among the low-lying levels of Fe XIV are compiled within the following eight tables. We assign a level number to each level in Table 1, which is used to denote individual transitions. Table 1 displays the excitation energies and lifetimes for all the 40 levels of the $3s^2 3p$, $3s3p^2$, $3s^2 3d$, $3p^3$, and 3s3p3d configurations. The excitation energies with regard to the ground state $3s^2 3p\ ^2P_{1/2}$ are compared with the experimental data[2,6,24] and other theoretical results.[18,19,20,21] For the lower-lying levels, we find that our calculation results are in good agreement with the experimental values. As the excitation energies increase, the levels become slightly less well represented in the given configuration basis. As can be seen from the table, for most levels, the deviations between theoretical and experimental results taken from the NIST database[24] are within 0.6% for our results. Comparing with other theoretical values, our results are closer to experimental data, except the values by Santana *et al.*[21] However, they did not calculate all important transition probabilities and provided the lifetimes of all the 40 levels of the Fe XIV. We calculated the lifetimes for the 40 levels based on the transition rates, which are shown in Table 1. The good agreement between the length and velocity gauges for the lifetimes of the 40 levels demonstrates the good quality of the data.

To explain the influences of the VV and CV correlations, the Breit interaction as well as QED effects on the excitation energies, we display some of the excitation energies obtained in different models in detail in Table 2. Where the results with the Breit interaction and QED effects are also shown. As can be seen from the table, 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, by comparing the excitation energy with and without CV correlation for the level 9, one can find that the contribution from the CV correlation is more than 3000 cm^{-1}. It also can be noticed that the Breit interaction is important for the excitation energies. For example, the Breit interaction accounts for 3% of the final value for the level 2. These results indicate that the core–valence correlation as well as the Breit interaction are significant and cannot be neglected in the calculations. Moreover, one

can notice that the results with all these effects agree well with the experimental values. As a result, the VV and CV correlations, the Breit interaction as well as QED effect are included in our calculations.

Table 1. Excitation energies (in cm^{-1}) and lifetimes (in s) for the 40 low-lying levels in the Fe XIV, compared to experiments and theories. Numbers in brackets represent powers of ten.

Levels			Energy					Lifetime	
No.	Designation	J^P	This work	Ref. [21]	Ref.	Ref.	NIST[24]	V	L
1	$3s^23p\ ^2P_{1/2}$	$1/2^-$	0	0	0	0	0		
2	$3s^23p\ ^2P_{3/2}$	$3/2^-$	18847	18852	18834[19]	18766[20]	18852		1.674(–2)
3	$3s3p^2\ ^4P_{1/2}$	$1/2^+$	224634	225090	224452[19]	223427[20]	225114	2.49(–8)	2.81(–8)
4	$3s3p^2\ ^4P_{3/2}$	$3/2^+$	231993	232794	232112[19]	231238[20]	232789	1.31(–7)	1.47(–7)
5	$3s3p^2\ ^4P_{5/2}$	$5/2^+$	241479	242386	241732[19]	240683[20]	242387	3.33(–8)	3.75(–8)
6	$3s3p^2\ ^2D_{3/2}$	$3/2^+$	300219	299231	300636[19]	299078[20]	299242	3.53(–10)	3.76(–10)
7	$3s3p^2\ ^2D_{5/2}$	$5/2^+$	302283	301452	302866[19]	301222[20]	301469	4.40(–10)	4.79(–10)
8	$3s3p^2\ ^2S_{1/2}$	$1/2^+$	366008	364717	366529[19]	366117[20]	364693	5.01(–11)	5.23(–11)
9	$3s3p^2\ ^2P_{1/2}$	$1/2^+$	389999	388502	390262[19]	391517[20]	388510	2.45(–11)	2.88(–11)
10	$3s3p^2\ ^2P_{3/2}$	$3/2^+$	397633	396516	389239[19]	399976[20]	396512	2.38(–11)	2.44(–11)
11	$3s^23d\ ^2D_{3/2}$	$3/2^+$	475924	473188			473223	2.27(–11)	2.23(–11)
12	$3s^23d\ ^2D_{5/2}$	$5/2^+$	477844	475185			475202	2.52(–11)	2.46(–11)
13	$3p^3\ ^2D_{3/2}$	$3/2^-$	579433	576407		578629[20]	576383	2.59(–10)	2.79(–10)
14	$3p^3\ ^2D_{5/2}$	$5/2^-$	583501	580226		582645[20]	580233	2.64(–10)	2.92(–10)
15	$3p^3\ ^4S_{3/2}$	$3/2^-$	589004	588916		591739[20]	589002	4.46(–11)	4.64(–11)
16	$3s3p(^3P)3d\ ^4F_{3/2}$	$3/2^-$	652271	644909		642145[20]		8.11(–11)	8.16(–11)
17	$3p^3\ ^2P_{1/2}$	$1/2^-$	646007	642236		645040[20]	642310	2.36(–10)	2.59(–10)
18	$3p^3\ ^2P_{3/2}$	$3/2^-$	649362	645732		643989[20]	645409	8.85(–11)	9.24(–11)
19	$3s3p(^3P)3d\ ^4F_{5/2}$	$5/2^-$	646455	645891		646381[20]	645988	5.93(–9)	5.97(–9)
20	$3s3p(^3P)3d\ ^4F_{7/2}$	$7/2^-$	652345	651824	652000[2]	652206[18]	651946	3.32(–9)	3.28(–9)
21	$3s3p(^3P)3d\ ^4F_{9/2}$	$9/2^-$	660329	660153		660390[18]	660263		2.022(–2)
22	$3s3p(^3P)3d\ ^4P_{5/2}$	$5/2^-$	691123	690300		692607[20]	690304	2.99(–10)	2.99(–10)
23	$3s3p(^3P)3d\ ^4P_{3/2}$	$3/2^-$	704776	704123		705995[20]	704209	3.55(–11)	3.49(–11)
24	$3s3p(^3P)3d\ ^4P_{1/2}$	$1/2^-$	704661	703723		705393[20]	703750	2.54(–11)	2.50(–11)
25	$3s3p(^3P)3d\ ^4D_{7/2}$	$7/2^-$	703904	703359	700675[6]	705847[18]	703393	2.51(–11)	2.48(–11)
26	$3s3p(^3P)3d\ ^4D_{1/2}$	$1/2^-$	694903	694166		696285[20]	694168	1.01(–7)	1.02(–7)
27	$3s3p(^3P)3d\ ^4D_{5/2}$	$5/2^-$	704796	704095		706197[20]	704114	3.75(–11)	3.73(–11)
28	$3s3p(^3P)3d\ ^4D_{3/2}$	$3/2^-$	693430	692673		694827[20]	692662	8.41(–11)	8.32(–11)
29	$3s3p(^3P)3d\ ^2D_{3/2}$	$3/2^-$	719760	717245		720071[20]	717195	2.31(–10)	2.29(–10)
30	$3s3p(^3P)3d\ ^2D_{5/2}$	$5/2^-$	720239	717863		720691[20]	717861	3.35(–11)	3.40(–11)
31	$3s3p(^3P)3d\ ^2F_{5/2}$	$5/2^-$	747337	744955		747392[20]	744965	3.68(–10)	3.74(–10)
32	$3s3p(^3P)3d\ ^2F_{7/2}$	$7/2^-$	762192	759833		762890[18]	759814	5.54(–11)	5.61(–11)
33	$3s3p(^3P)3d\ ^2P_{3/2}$	$3/2^-$	811650	807380		810926[20]	807113	2.41(–11)	2.36(–11)
34	$3s3p(^3P)3d\ ^2P_{1/2}$	$1/2^-$	819618	815419		818814[20]		2.39(–11)	2.35(–11)
35	$3s3p(^1P)3d\ ^2F_{7/2}$	$7/2^-$	820434	817734		823338[18]	817593	1.92(–11)	1,86(–11)
36	$3s3p(^1P)3d\ ^2F_{5/2}$	$5/2^-$	823464	820724		825450[20]	820601	6.69(–10)	6.27(–10)
37	$3s3p(^1P)3d\ ^2P_{1/2}$	$1/2^-$	842332	839475		844807[20]	839492	4.13(–11)	3.97(–11)
38	$3s3p(^1P)3d\ ^2P_{3/2}$	$3/2^-$	847085	843700		846644[20]	843656	2.67(–11)	2.60(–11)
39	$3s3p(^1P)3d\ ^2D_{3/2}$	$3/2^-$	843825	841040			840775	5.95(-11)	5.79(–11)
40	$3s3p(^1P)3d\ ^2D_{5/2}$	$5/2^-$	848074	844757		850762[20]	844477	1.07(–8)	6.61(–9)

Table 2. 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 Fe XIV. DF represents the results in the Dirac–Fock calculation, n represents the orbital layer, i.e., the principle quantum number.

		VV					VV+CV			VV+CV	VV+CV+
Level	DF	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$	$n=4$	$n=5$	$n=6$	+Breit	Breit+QED
2	19690	19279	19390	19278	19272	19272	19567	19417	19384	18847	18847
3	203347	223337	224165	224271	224290	224303	225589	224061	224355	224580	224634
8	363770	370681	368430	368105	368032	368014	368370	365845	365940	365954	366008
9	398897	395639	393987	393716	393674	393656	393519	390184	390198	389944	389999

As mentioned above, the green lines of Fe XIV are significant for diagnostics of solar coronae. Therefore, the M1 and E2 transition probabilities of these lines and the lifetime for the $3s^23p\ ^2P_{3/2}$ level are compared with available theoretical and experimental data in Table 3. The present result for the lifetime of the $3s^23p\ ^2P_{3/2}$ level agrees within 0.8% of the measured value by Beiersdorfer *et al.*,[4] and also comparable with other theoretical results in Refs. [8], [12], and [21]. Moreover, the present M1 transition probability agrees within 0.7% of the measured value by Beiersdorfer *et al.*,[4] and also agree well with the calculations of Santana *et al.*[21] and Huang.[12] Meanwhile, the present E2 transition probability is in good agreement with the value of Santana *et al.*[21]

In Table 4, some calculated results of the lifetimes are compared with the available experimental data and other theoretical values. With regard to the lifetimes of the $J = 7/2$ and $9/2$ high angular momentum levels, the lifetime of the $3s3p(^3P)3d\ ^4F_{7/2}$ level is mainly determined by the fast E1 decay into some of the $J = 5/2$ levels of the $3s3p^2$ and $3s^23d$ configurations, and only the $^4F_{9/2}$ level is a metastable state which decays via magnetic dipole (M1) and electric quadrupole transitions (E2) to the lower-lying levels of the same parity, or via magnetic quadrupole transitions (M2) to the lower-lying levels of the even parity. Compared with other theoretical values of the lifetime of the $^4F_{7/2}$ level,[2,18] the present results (in length gauge) is closer to the measurement by Träbert *et al.*[2] One can notice that the calculated lifetime of the $^4F_{9/2}$ level is slightly longer than the result in Refs. [8], [18], and [21], the differences are 1.8%, 2.9%, and 1.8%, respectively. However, our results are closer to the measurement,[8] which attributes to the more accurate calculations of the related transition probabilities.

Table 3. Comparison of M1, E2 transition probabilities (in s^{-1}) of the green coronal line and the lifetime (in ms) for the $3s^23p\ ^2P_{3/2}$ level of Fe XIV in the present work and other available values. Numbers in brackets represent powers of ten.

	This work	Experiment			Theory				
		Ref. [3]	Ref. [4]	Ref. [7]	Ref. [10]	Ref. [12]	Ref. [14]	Ref. [21]	Ref. [8]
M1	59.79	57.80±1.05	59.7±0.4		50.5	60.04	46.77	60.16	
E2	1.46(–2)							1.466(–2)	
Lifetime	16.74	17.52±0.29	16.74±0.12	18.0±1.2	19.8	16.66	21.38	16.62	16.62

Table 4. Comparison of the lifetimes (in s) for the five $J = 7/2$ and $9/2$ levels of the 3s3p3d configuration of Fe XIV in the present work and other available values. Numbers in brackets represent powers of ten.

No.	Level	This work		Ref. [18]		Refs. [8] and [21]	Experiment
		V	*L*	*V*	*L*	*L*	
20	$3s3p(^3P)3d\ ^4F_{7/2}$	3.32(-9)	3.28(–9)	3.31(–9)	3.46(–9)		2.8±0.2(–9)[2]
21	$3s3p(^3P)3d\ ^4F_{9/2}$		2.022(–2)		1.96(–2)	1.895(–2)	2.5(–2)[8]
25	$3s3p(^3P)3d\ ^4D_{7/2}$	2.51(–11)	2.48(–11)	2.27(–11)	2.38(–11)		
32	$3s3p(^3P)3d\ ^2F_{7/2}$	5.54(–11)	5.61(–11)	5.07(–11	5.18(–11)		
35	$3s3p(^1P)3d\ ^2F_{7/2}$	1.92(–11)	1.86(–11)	1.83(–11)	1.88(–11)		

In order to further check the reliability and accuracy of our calculations, the calculated results for E1 transition probabilities (in the length gauge) from the excited levels of the $3s3p^2$ configuration to those of the $3s^23p$ configuration are shown in Table 5, together with other available theoretical results. In comparison with the data involved in the table, it can be seen clearly that our results appear to be close to those by Hao *et al.*[19] and Froese Fischer *et al.*,[20] and Santana *et al.*[21] In addition, some of the E1, E2, M1, and M2 transition probabilities for the $3s3p(^3P)3d\ ^4F_{7/2}$ and $3s3p(^3P)3d\ ^4F_{9/2}$ levels are also listed in the table. For the $^4F_{7/2}$ level, the contributions from dipole-forbidden transitions are completely negligible for its lifetime and are not displayed in this table. The strongest decay path is the spin-allowed $3s3p^2\ ^4P_{5/2}$–$3s3p(^3P)3d\ ^4F_{7/2}$ (5–20) transition, while the transition rate is higher than that of the $3s3p^2\ ^2D_{5/2}$–$3s3p(^3P)3d\ ^4F_{7/2}$ (7–20) and $3s^23d\ ^2D_{5/2}$–$3s3p(^3P)3d\ ^4F_{7/2}$ (12–20) intercombina-

tion lines by almost 2 orders of magnitude. It can be seen that our three E1 transition rates are in better agreement with the previous results. As discussed before, the decay of the 3s3p3d $^4F_{9/2}$ level may follow several E1 forbidden paths. Compared with the M1 and M2 lines, the possible E2 decay paths into the $J = 7/2$ and $5/2$ levels appear too small to be negligible. A comparison between the present M2 transition rates and the other theoretical values reveals that the maximum difference is less than 3%.[18,21] Besides, the M1 and E2 transition rates are also consistent with the results in these calculations.

Table 5. Comparison of some of the E1, E2, M1, and M2 transition probabilities (in s^{-1}) (in length gauge) in the present work and other available values. Numbers in brackets represent powers of ten.

Emission lines		A				
Transition	Type	This work	Ref. [18]	Ref. [19]	Ref. [20]	Ref. [21]
1–3	E1	2.59(+7)		2.59(+7)	2.62(+7)	2.23(+7)
1–9	E1	1.34(+10)		1.27(+10)	1.51(+10)	
1–10	E1	7.47(+9)		7.36(+9)	7.90(+9)	
2–4	E1	6.19(+6)		5.90(+6)	5.91(+6)	5.46(+6)
1–6	E1	2.57(+9)		2.55(+9)	2.46(+9)	
2–5	E1	2.66(+7)		2.43(+7)	2.49(+7)	2.25(+7)
12–20	E1	6.73(+6)	5.81(+6)			
7–20	E1	1.30(+6)	1.09(+6)			
5–20	E1	2.93(+8)	2.82(+8)			
20–21	M1	1.34(+1)	1.46(+1)			1.54(+1)
20–21	E2	1.56(–4)				1.72(-4)
7–21	M2	3.25(+1)	3.33(+1)			3.37(+1)
5–21	M2	3.28	3.28			3.36

The E1, E2 transition energies, transition probabilities, and oscillator strengths (both in velocity and length gauges) among the 40 fine-structure energy levels belonging to the five low-lying configurations are listed in Tables 6 and 7, respectively. As can be seen, the transition probabilities and the oscillator strengths for the length and velocity gauges agree well with each other. The M1, M2 transition energies, transition probabilities, and oscillator strengths among the 40 fine-structure energy levels are listed in Table 8. One can see that the M2 transition probabilities are slightly smaller than the M1 transition probabilities.

Table 6. Transition energies (in cm^{-1}), wavelengths (in Å), transition probabilities (in s^{-1}), and oscillator strengths (gf) in different levels of Fe XIV for electric dipole (E1) lines. Numbers in brackets represent powers of ten.

Emission lines				A		gf	
Transition	Type	Energy/cm^{-1}	Wavelength/Å	V	L	V	L
1–3	E1	224634	445.16	2.91(+7)	2.59(+7)	1.72(–3)	1.53(–3)
1–8	E1	366008	273.21	1.86(+10)	1.79(+10)	4.17(–1)	4.00(–1)
1–9	E1	389999	256.41	1.38(+10)	1.34(+10)	2.71(–1)	2.63(–1)
2–3	E1	205787	485.94	1.09(+7)	9.55(+6)	7.71(–4)	6.71(–4)
2–8	E1	347160	288.05	1.23(+9)	1.15(+9)	3.04(–2)	2.86(–2)
2–9	E1	371152	269.43	2.21(+10)	2.12(+10)	4.79(–1)	4.61(–1)
1–6	E1	300219	333.09	2.73(+9)	2.57(+9)	1.81(1)	1.70(–1)
1–10	E1	397633	251.48	7.63(+9)	7.47(+9)	2.88(–1)	2.82(–1)
2–4	E1	213146	469.16	6.96(+6)	6.19(+6)	9.13(–4)	8.12(–4)
2–6	E1	281372	355.40	9.21(+7)	8.50(+7)	6.95(–3)	6.41(–3)
2–10	E1	378786	264.00	3.43(+10)	3.33(+10)	1.43	1.39
2–5	E1	222632	449.17	3.00(+7)	2.66(+7)	5.41(–3)	4.80(–3)
2–7	E1	283436	352.81	2.27(+9)	2.08(+9)	2.53(–1)	2.32(–1)
1–11	E1	475924	210.11	3.53(+10)	3.62(+10)	9.36(–1)	9.58(–1)

Table 6. (*Continued*)

Emission lines				A		gf	
Transition	Type	Energy/cm^{-1}	Wavelength/Å	V	L	V	L
2–11	E1	457077	218.78	8.20(+9)	8.43(+9)	2.35(–1)	2.42(–1)
2–12	E1	458997	217.86	3.96(+10)	4.06(+10)	1.69	1.73
3–13	E1	354799	281.84	4.73(+8)	4.58(+8)	2.24(–2)	2.17(–2)
3–15	E1	364370	274.44	6.20(+9)	6.01(+9)	2.79(–1)	2.70(–1)
8–13	E1	213425	468.54	4.81(+8)	4.22(+8)	6.31(–2)	5.54(–2)
8–18	E1	283354	352.91	2.03(+9)	1.80(+9)	1.51(–1)	1.34(–1)
9–13	E1	189434	527.88	5.89(+8)	5.25(+8)	9.79(–2)	8.73(–2)
8–17	E1	279999	357.14	1.48(+8)	1.014(+8)	5.64(–3)	3.86(–3)
9–17	E1	256008	390.61	4.06(+9)	3.72(+9)	1.85(–1)	1.69(–1)
3–16	E1	427637	233.84	2.43(+8)	2.41(+8)	7.97(–3)	7.91(–3)
8–16	E1	286263	349.33	1.72(+9)	1.77(+9)	1.26(–1)	1.29(–1)
5–13	E1	337954	295.89	1.28(+9)	1.22(+9)	6.70(–2)	6.39(–2)
5–15	E1	347525	287.75	1.61(+10)	1.54(+10)	7.79(–1)	7.63(–1)
5–18	E1	407883	245.16	1.41(+8)	1.33(+8)	5.09(–3)	4.79(–3)
7–13	E1	277150	360.81	1.02(+9)	9.53(+8)	7.98(–2)	7.41(–2)
7–15	E1	286721	348.77	6.46(+7)	5.66(+7)	4.68(–3)	4.11(–3)
7–18	E1	347079	288.11	9.04(+9)	8.79(+9)	4.48(–1)	4.36(–1)
5–14	E1	342022	292.37	1.15(+8)	1.06(+8)	8.85(–3)	8.18(–1)
7–14	E1	281218	355.59	3.66(+9)	3.30(+9)	4.15(–1)	3.74(–1)
5–20	E1	410866	243.38	2.93(+8)	2.98(+8)	2.08(–2)	2.12(–2)
7–20	E1	350062	285.66	7.35(+5)	1.30(+6)	7.19(–5)	1.27(–4)
12–20	E1	174501	573.06	6.73(+6)	6.21(+6)	2.63(–3)	2.43(–3)
5–16	E1	410792	243.43	2.22(+8)	2.22(+8)	7.87(–3)	7.89(–3)
7–16	E1	349988	285.72	1.01(+10)	1.00(+10)	4.94(–1)	4.88(–1)
5–19	E1	404976	246.92	8.64(+7)	8.70(+7)	4.73(–3)	4.77(–3)
7–19	E1	344172	290.55	8.20(+7)	8.02(+7)	6.22(–3)	6.09(–3)
3–23	E1	480142	208.27	2.72(+10)	2.77(+10)	7.44(–1)	7.58(–1)
8–33	E1	445642	224.39	4.06(+10)	4.15(+10)	1.22	1.25
9–38	E1	457086	218.77	3.69(+10)	3.81(+10)	1.07	1.11
9–39	E1	453826	220.34	1.07(+10)	1.10(+10)	3.07(–1)	3.17(–1)
3–24	E1	480027	208.32	3.92(+10)	3.99(+10)	5.32(–1)	5.41(–1)
5–25	E1	462425	216.25	3.94(+10)	3.99(+10)	2.21	2.23
7–32	E1	459909	217.43	1.53(+10)	1.52(+10)	8.72(–1)	8.66(–1)
5–28	E1	451951	221.26	1.17(+10)	1.19(+10)	3.28(–1)	3.32(–1)
5–27	E1	463317	215.83	2.66(+10)	2.69(+10)	1.11	1.12
7–30	E1	417956	239.25	2.97(+10)	2.93(+10)	1.53	1.51

Table 7. Transition energies (in cm^{-1}), wavelengths (in Å), transition probabilities (in s^{-1}), and oscillator strengths (gf) in different levels of Fe XIV for electric quadrupole (E2) lines. Numbers in brackets represent powers of ten.

Emission lines				A		gf	
Transition	Type	Energy/cm^{-1}	Wavelength/Å	V	L	V	L
1–13	E2	579433	172.58	1.92(+5)	1.93(+5)	3.41(–6)	3.44(–6)
1–18	E2	649362	153.99	6.71(+4)	6.81(+4)	9.51(–7)	9.65(–7)
2–13	E2	560586	178.38	7.89(+4)	7.94(+4)	1.50(–6)	1.50(–6)
2–15	E2	570157	175.39	1.80(+4)	1.81(+4)	3.30(–7)	3.33(–7)
2–18	E2	630515	158.60	1.93(+5)	1.95(+5)	2.90(–6)	2.94(–6)
1–14	E2	583501	171.38	7.90(+4)	7.97(+4)	2.08(–6)	2.09(–6)
2–17	E2	627160	159.44	2.59(+5)	2.62(+5)	1.96(–6)	1.99(–6)
2–14	E2	564654	177.09	2.03(+5)	2.04(+5)	5.70(–6)	5.74(–6)
1–16	E2	652271	153.31	9.68(+4)	9.61(+4)	1.35(–6)	1.35(–6)
2–16	E2	633424	157.87	2.55(+5)	2.54(+5)	3.80(–6)	3.78(–6)
2–40	E2	829227	120.59	1.57(+6)	1.58(+6)	2.05(–5)	2.06(–5)
1–2	E2	18847	5305.79	1.43(–2)	1.46(–2)	2.43(–10)	2.47(–10)
20–21	E2	7984	12525.05	1.56(–4)	1.29(–4)	3.68(–11)	3.07(–11)

Table 8. Transition energies (in cm^{-1}), wavelengths (in Å), transition probabilities (in s^{-1}), oscillator strengths (gf) in different levels of Fe XIV for forbidden (M1) and (M2) lines. Numbers in brackets represent powers of ten.

Transition	Type	Energy/cm^{-1}	Wavelength/Å	A	gf
1–2	M1	18847	5305.79	5.97(+1)	1.01(–6)
3–6	M1	75585	1323.01	2.09(+1)	2.11(–8)
3–10	M1	172999	578.03	2.31(+1)	4.63(–9)
4–8	M1	134015	746.18	9.58(+2)	1.59(–7)
8–10	M1	31625	3162.05	6.20(+1)	3.72(–7)
4–9	M1	158006	632.88	2.82(+2)	3.39(–8)
6–9	M1	89780	1113.83	7.43(+1)	2.76(–8)
7–11	M1	173641	575.90	1.17(+2)	2.34(–8)
7–12	M1	175561	569.60	1.75(+3)	5.14(–7)
4–11	M1	243931	409.95	3.47(+1)	3.51(–9)
6–11	M1	175705	569.13	2.88(+2)	5.63(–8)
10–11	M1	78291	1277.28	5.01(+1)	4.97(–8)
4–12	M1	245851	406.75	2.03(+1)	3.03(–9)
6–12	M1	177625	562.98	4.24(+1)	1.21(–8)
20–21	M1	7984	12525.05	1.34(+1)	3.17(–6)
2–8	M2	347161	288.05	4.78	1.18(–10)
2–9	M2	371152	269.43	1.05(+1)	2.29(–10)
1–4	M2	231993	431.04	2.16	2.39(–10)
1–5	M2	241479	414.11	1.41	2.16(–10)
1–7	M2	302283	330.81	5.98	5.86(–10)
2–5	M2	222632	449.17	1.64	2.96(–10)
2–7	M2	283436	352.81	1.01(+1)	1.13(–9)
5–20	M2	410866	243.38	7.00	4.97(–10)
7–20	M2	350062	285.66	2.52	2.47(–10)
5–21	M2	418850	238.74	3.27	2.80(–10)
7–21	M2	358046	279.29	3.25(+1)	3.80(–9)

4. Conclusion

In this paper, large-scale calculations of the fine-structure energy levels and lifetimes belonging to the five low-lying configurations of Fe XIV, and the E1, E2, M1, M2 transition rates, oscillator strengths among them have been performed using the GRASP2K package based on the MCDF method. The valence–valence and core–valence correlations, Breit interaction, and QED effects were taken into account in a systematic way. Compared with the theoretical and experimental results, it is found that our results of the energy levels, lifetimes, and transition rates are reliable and reasonable. Especially, the M1 transition probability of the green coronal line and the lifetimes for the $3s^2 3p\ ^2P_{3/2}$ level are in good agreement with the experimental values. This computational approach enables us to present a consistent and clearly improved data set of all the important transitions of the Fe XIV spectrum which might be useful in further astrophysical investigations, and the present results are expected to be helpful for most astrophysical and laboratory applications.

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