Volume 9, Number 2
1009-1963/2000/09(02)/0100-08
CHINESE PHYSICS
February, 2000
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FULLY RELATIVISTIC CALCULATIONS OF THE ENERGIES, OSCILLATOR STRENGTHS AND EINSTEIN COEFFICENTS OF THE FORBIDDEN TRANSITIONS FOR Ne-LIKE SEQUENCES*

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(Received 3 May 1999; revised manuscript received 3 August 1999)

We provide systematic calculations about the energy levels, Einstein coefficients and oscillator strengths for electric quadrupole (E2) and magnetic quadrupole (M2) transitions between n=3 and n=2 of Ne-like systems by using the fully relativistic multi-configuration Dirac-Fock method. The oscillator strengths of the E2 transitions under Coulomb and Babshkin gauges are compared with each other and show the differences from 1.2 to 12 percent. We also found that the M2 line (0.37429 nm) with the biggest oscillator strengths in Ne-like Ag^{37+} mixes with the line $(2p^5_{3/2}3s_{1/2}3d_{5/2})_{3/2} \rightarrow$gs (0.37427 nm) emitted by the Na-like Ag^{36+}.

PACC: 3207; 3320; 3200; 3000

I. INTRODUCTION

The electric dipole forbidden lines—electric quadruple (E2) and magnetic quadruple (M2) transitions—were first observed in the coronal spectrum.[1−3] With the development of the experiments in plasmas and spectroscopy, the forbidden lines now can be obtained in laboratory.[3−7] The observation of E2 transitions in the Ne-like systems has been reported for the first time from beam-foil experiment. The observation of the magnetic quadruple (M2) transitions between the $(2p^5_{3/2}3s_{1/2})_{J=2}$ upper state and the ground state has been found from tokamak discharges in the Princeton Large Tours.[3] Due to its small decay rate the M2 transition cannot be observed in beam-foil experiments, nor can it be observed in high-density laser produced or z-pinch plasmas because of the collisional deexcitation of the $(2p^5_{3/2}3s_{1/2})_{J=2}$ level. This line provides additional information on intrashell transitions, and has been of interest in astrophysics. The magnetic dipole (M1) lines in Ne-like ions between n=3 and n=2 are still not observed up to now.

In recent two decades, based on the observation of these forbidden lines, much work has been done in theory and experiment.[8−11] One of the prominent works done in this field is the measurement of the wavelengths of these forbidden lines. Commonly speaking, the experimental accuracy for the measurement of wavelength can be achieved in 0.01 to 0.1m nm in highly stripped Ne-like systems.[3,7] Another satisfactory work is the theoretical calculations for the transition wavelengths. In much work using multi-configuration Dirac-Fock (MCDF) method the calculation discrepancies (for the Ne-like systems) can be in the range of $-2.6 \rightarrow 2.6$ eV[7] and our calculations are even more accurate by using the orbital polarization.[12] For a special case in our calculation of Ne-like ions from the elements ranging from $Z = 47$ to $Z = 63$, the discrepancies between our calculations and experiments fall in $-0.4 \rightarrow 0.9$ eV.

The uses of these forbidden lines are in many aspects. It is well known that the line intensities and ratios provide excellent diagnostics for temperature and density and consequently for element abundance.[6,13,14] For instance, the E2 transitions in Ne-like Ag^{37+} and Mo^{32+} are found to be sensitive to the electron density. Young et al.[6] have test the density dependence of E2 transitions by comparing experimental to theoretical lines intensity ratios as a function of the measured electron density. To perform such a calculation reliably accurate data for energy levels, oscillator strengths and electron excitation rates are required. Because a direct measurement of the 3→3 transitions of Ne-like ions is very difficult due to the presence of many lines of nearly identical wavelengths which have much higher intensity and which result from $\Delta n = 0$ transitions in Na-like, Mg-like and Al-like charge state.[3] So together with the electric dipole transitions of the type 3s→2p, the electric quadrupole lines can be used to determine the energies of $\Delta n = 0$

*Project supported by the Science Foundation of China Academy of Engineering Physics (Grant No. 98020207).
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transitions within the n=3 shell. These transitions, in particular the transitions $(2p^5_{1/2}3p_{3/2})_{J=2}\rightarrow(2p^5_{1/2}3s_{1/2})_{J=1}$ and $(2p^5_{3/2}3p_{3/2})_{J=2}\rightarrow(2p^5_{3/2}3s_{1/2})_{J=1}$, are of interest in collisionally pumped soft X-ray laser schemes. The research of forbidden transitions also can extend the spectra fine structure and promote further studying in theoretical calculation.

In the research of highly stripped ions, the experimental transition probability and oscillator strength for forbidden lines are scarce. It is therefore to rely upon theoretical values. The only way to check theoretical method consists therefore in comparing the results deduced from the theory with any other measurable quantity which might be available (mostly the observed energies) and in comparing the results obtained by different calculation method.

In this paper, we report our systematic relativistic calculations of oscillator strengths and Einstein coefficients of the forbidden lines E2 and M2 for the neon isoelectronic sequences. Due to the lack of both experimental and other theoretical values of oscillator strengths and Einstein coefficients, one way to check our calculated results is to deduce from the comparison of our calculated wavelengths with the experimental values. We also compare the oscillator strengths and Einstein coefficients of the E2 transitions under Coulomb gauge and Babushkin gauge. The differences between the two gauges range from 1.2 to 12 percent and show close relation with the atomic number and the type of transitions.

Ⅱ. RELATIVISTIC RADIATIVE TRANSITION PROBABILITY

Calculations of relativistic radiative transition probabilities have either been based on the Coulomb gauge, or following Babushkin, on another gauge leading to a different formula.[14] The oscillator strength for the transition from atomic state function (ASF) Γ_i to Γ_j induced by a multipole radiation field operator $\widehat{O}^{(L)}_{\rm m}$ of order L is

$$f_{i\rightarrow j}=\frac{\pi c}{(2L+1)\omega^2}|\langle\Gamma_iP_iJ_i\|\widehat{O}^{(L)}\|\Gamma_jP_jJ_j\rangle|^2, \quad (1)$$

where we use the Brink and Satchler definition of the reduced matrix element. This, in turn, can be expressed in terms of configuration state function (CSF) matrix elements as

$$\langle\Gamma_iP_iJ_i\|\widehat{O}^{(L)}\|\Gamma_jP_jJ_j\rangle = \sum_{r,s}c_{r\Gamma_i}c_{r\Gamma_j}\langle\gamma_rP_rJ_r\|\widehat{O}^{(L)}\|\gamma_sP_sJ_s\rangle, \quad (2)$$

which in turn, is a sum of single electron transition integral defined as

$$\langle\gamma_rP_rJ_r\|\widehat{O}^{(L)}\|\gamma_sP_sJ_s\rangle = \sum_{a,b}d^L_{ab}(rs)\langle n_a\kappa_a\|\widehat{O}^{(L)}\|n_b\kappa_b\rangle, \quad (3)$$

where d^L_{ab} is related to the configuration coupling coefficients. Allowing for the fact that we are now using Brink-and-Satchler type of reduced matrix elements, we have

$$\langle n_a\kappa_a|\hat{o}^{(L)}|n_b\kappa_b\rangle=\left(\frac{(2j_b+1)\omega}{\pi c}\right)^2(-1)^{j_a-1/2}\left(\begin{array}{ccc} j_a & L & j_b \\ 1/2 & 0 & -1/2\end{array}\right)_{\overline{M}_{ab}}, \quad (4)$$

where $\overline{M}_{ab}$ is one of the radiative transition integrals defined by Grant

$$\overline{M}_{ab}=\begin{cases}\overline{M}^{\rm e}_{ab}+G\overline{M}^{1}_{ab} & \text{for electron multipole transitions;} \quad (5)\\ \overline{M}^{\rm m}_{ab} & \text{for magnetic multipole transitions.} \quad (6)\end{cases}$$

Explicitly, for magnetic type multipoles

$$\overline{M}^{\rm m}_{ab}=\mathrm{i}^{l+1}\frac{2L+1}{[L(L+1)]^{1/2}}(\kappa_b+\kappa_b)I^+_L(\omega); \quad (7)$$

whereas for electric type multipoles, the value depends linearly on the gauge parameter

$$\overline{M}^{\rm e}_{ab}=\mathrm{i}^L\left[\left(\frac{L}{L+1}\right)^{1/2}[(\kappa_a-\kappa_b)I^+_{L+1}+(L+1)I^-_{L+1}]-\left(\frac{L+1}{L}\right)^{1/2}[(\kappa_a-\kappa_b)I^+_{L-1}-LI^-_{L-1}]\right], \quad (8)$$

$$\overline{M}^{\rm l}_{ab}=\mathrm{i}^L\{[(\kappa_a-\kappa_b)I^+_{L+1}+(L+1)I^-_{L+1}]+[(\kappa_a-\kappa_b)I^+_{L-1}-LI^-_{L-1}]+(2L+1)J_L\}, \quad (9)$$

$$I^{\pm}_L=\int_0^\infty {\rm d}rj_L(\omega r/c)(P_{n_a\kappa_a}(r)Q_{n_b\kappa_b}(r)\pm Q_{n_a\kappa_a}(r)P_{n_b\kappa_b}(r)), \quad (10)$$

$$J_L=\int_0^\infty {\rm d}rj_L(\omega r/c)(P_{n_a\kappa_a}(r)P_{n_b\kappa_b}(r)+Q_{n_a\kappa_a}(r)Q_{n_b\kappa_b}(r)), \quad (11)$$

In Eq.(5) G is the gauge parameter. It takes the value 0 in the Coulomb gauge and $[(L+1)/L]^{1/2}$ in the Bubushkin gauge. In the nonrelativistic limit $G=0$ gives the velocity form of radiation matrix elements, while $G=[(L+1)/L]^{1/2}$ gives the length form. The detailed discussion about gauge invariance and radiative transitions can refer to Ref.[15] and the transition selection rule for E2 and M2 can refer to Refs.[16,17]. The matrix element M_{ab}, as an observable quantity should be invariant under gauge transformation. The spontaneous emission propability per unit time ($\tau_0 = h^3/8\pi^3 me^4$) for the transition $b \to a$ is given, according to the usual rules of time-dependent perturbation theory, by

$$A_{b\to a} = [j_b]^{-1} \sum_{M_a}\sum_{M_b} 2\pi |M_{ab}|^2 = 2\alpha\omega \frac{[j_a]}{[L]} \begin{pmatrix} j_b & L & j_a \\ 1/2 & 0 & -1/2 \end{pmatrix} |\overline{M}_{ab}|^2, \quad (12)$$

where $\alpha = c^{-1}$ (in atomic units). Let the degree of degeneracy (statistical weights) of states b and a be g_b and g_a. For processes of spontaneous or induced emission, the initial states are the states b, and for absorption the states a. Assuming in each case that all g_a and g_b initial states are equally probable, we have $g_a B_{a\to b} = g_b B_{b\to a} = g_b A_{b\to a}\pi c^3/\hbar\omega$.

Based on the discussion above, we employ the fully relativistic MCDF method (programmed by Grant et al.) and take the QED effect (including vacuum polarization (VP) and self-energy (SE)) and Breit correction into account. In the course of our calculation, we choose the Fermi nucleus model and the extended average level calculation procedure. And finally, we use the orbital polarization correction. After careful choice of configurations, we calculate the forbidden transition energies, Einstein coefficients and oscillator strengths of the Ne-like ions between n=3 and n=2. The results are listed in Tables 1 and 2. The data in the brackets, except the brackets in the column of experimental wavelength which express the errors in experiment, indicate the exponents.

Table 1. The E2 transitions between n=3 and n=2 for Ne-like systems. The Einstein coefficients A and gB and the weighted oscillator strengths gf are given in Coulomb gauge (the upper row) and Babushkin gauge (the lower row). The ratio is $gf_{\rm Babushkin}/gf_{\rm Coulomb}$.

Element	Upper level	Wavelength λ/nm	A/S^{-1}	$gB/M^3S^{-2}J^{-1}$	gf	Ratio
Ge	$(2p^5_{3/2}3p_{1/2})_{J=2}$	0.96677	2.6489(9)	4.5152(15)	1.8558(–4)	1.12
			2.9623(9)	5.0494(15)	2.0753(–4)	
	$(2p^5_{3/2}3p_{3/2})_{J=2}$	0.95923	2.6826(9)	4.4665(15)	1.8502(–4)	1.12
			3.0170(9)	5.0233(15)	2.0808(–4)	
	$(2p^5_{1/2}3p_{1/2})_{J=2}$	0.93733	3.0782(9)	4.7821(15)	2.0272(–4)	1.129
			3.4760(9)	5.4001(15)	2.2892(–4)	
	$(2s_{1/2}3d_{3/2})_{J=2}$	0.80621	4.2169(8)	4.1685(14)	2.0545(–5)	0.965
			4.0676(8)	4.0209(14)	1.9817(–5)	
	$(2s_{1/2}3d_{5/2})_{J=2}$	0.80211	4.5373(10)	4.4171(16)	2.1882(–3)	0.964
			4.3782(10)	4.2623(16)	2.1115(–3)	
Se	$(2p^5_{3/2}3p_{1/2})_{J=2}$	0.83440	4.2196(9)	4.6243(15)	2.2021(–4)	1.107
			4.6709(9)	5.1189(15)	2.4376(–4)	
	$(2p^5_{3/2}3p_{3/2})_{J=2}$	0.82723	4.2388(9)	4.5266(15)	2.1743(–4)	1.113
			4.7190(9)	5.0394(15)	2.4206(–4)	
	$(2p^5_{1/2}3p_{1/2})_{J=2}$	0.80566	4.8188(9)	4.7539(15)	2.3446(–4)	1.118
			5.3882(9)	5.3157(15)	2.6217(–4)	
	$(2s_{1/2}3d_{3/2})_{J=2}$	0.69971	9.9466(8)	6.4278(14)	3.6503(–5)	0.968
			9.6306(8)	6.2236(14)	3.5343(–5)	
	$(2s_{1/2}3d_{5/2})_{J=2}$	0.69623	6.9944(10)	4.4531(16)	2.5414(–3)	0.978
			6.7728(10)	4.3120(16)	2.4609(–3)	
Zr	$(2p^5_{3/2}3p_{1/2})_{J=2}$	0.56747	1.4091(10)	4.8576(15)	3.4014(–4)	1.088
			1.5339(10)	5.2880(15)	3.7027(–4)	
	$(2p^5_{3/2}3p_{3/2})_{J=2}$	0.56095	1.3983(10)	4.6564(15)	3.2984(–4)	1.095
			1.5313(10)	5.0991(15)	3.6120(–4)	
	$(2p^5_{1/2}3p_{1/2})_{J=2}$	0.54026	1.5687(10)	4.6665(15)	3.4322(–4)	1.007
			1.7267(10)	5.1366(15)	3.7779(–4)	
	$(2s_{1/2}3d_{3/2})_{J=2}$	0.48022	8.8518(9)	1.8492(15)	1.5301(–4)	0.975
			8.6324(9)	1.8033(15)	1.4922(–4)	
	$(2s_{1/2}3d_{5/2})_{J=2}$	0.47793	2.1579(11)	4.4439(16)	3.6947(–3)	0.975
			2.1038(11)	4.3325(16)	3.6021(–3)	
Rh	$(2p^5_{3/2}3p_{1/2})_{J=2}$	0.43299	3.2537(10)	4.9828(15)	4.5727(–4)	1.072
			3.4892(10)	5.3434(15)	4.9036(–4)	
	$(2p^5_{3/2}3p_{3/2})_{J=2}$	0.42673	3.2108(10)	4.7066(15)	4.3827(–4)	1.079

Table 1. (*Continued*)

Element	Upper level	Wavelength λ/nm	A/S^{-1}	$gB/M^3S^{-2}J^{-1}$	gf	Ratio
			3.4652(10)	5.0795(15)	4.7299(–4)	
	$(2p^5_{1/2}3p_{1/2})_{J=2}$	0.40651	3.6039(10)	4.5671(15)	4.4642(–4)	1.086
			3.9142(10)	4.9603(15)	4.8485(–4)	
	$(2s_{1/2}3d_{3/2})_{J=2}$	0.36618	3.8065(10)	3.5257(15)	3.8259(–4)	0.97
			3.7247(10)	3.4500(15)	3.7437(–4)	
	$(2s_{1/2}3d_{5/2})_{J=2}$	0.36441	4.7338(11)	4.3214(16)	4.7121(–3)	0.98
			4.6304(11)	4.2271(16)	4.6092(–3)	
Ag	$(2p^5_{3/2}3p_{1/2})_{J=2}$	0.39242	4.4076(10)	5.0242(15)	5.0875(–4)	1.067
		0.39250[a]	4.7051(10)	5.3634(15)	5.4310(–4)	
	$(2p^5_{3/2}3p_{3/2})_{J=2}$	0.38620	4.3421(10)	4.7183(15)	4.8546(–4)	1.074
		0.38627[a]	4.6659(10)	5.0701(15)	5.2166(–4)	
	$(2p^5_{1/2}3p_{1/2})_{J=2}$	0.36615	4.8841(10)	4.5229(15)	4.9083(–4)	1.081
		0.36611[a]	5.2843(10)	4.8935(15)	5.3105(–4)	
	$(2s_{1/2}3d_{3/2})_{J=2}$	0.33131	6.3210(10)	4.3364(15)	5.2009(–4)	0.98
			6.1912(10)	4.2473(15)	5.0940(–4)	
	$(2s_{1/2}3d_{5/2})_{J=2}$	0.32968	6.2868(11)	4.2497(16)	5.1220(–3)	0.98
			6.1555(11)	4.1609(16)	5.0150(–3)	
Sb	$(2p^5_{3/2}3p_{1/2})_{J=2}$	0.32689	7.7350(10)	5.0969(15)	6.1956(–4)	1.058
			8.1861(10)	5.3941(15)	6.5569(–4)	
	$(2p^5_{3/2}3p_{3/2})_{J=2}$	0.32075	7.5981(10)	4.7297(15)	5.8594(–4)	1.065
			8.0981(10)	5.0409(15)	6.2449(–4)	
	$(2p^5_{1/2}3p_{1/2})_{J=2}$	0.30097	8.6022(10)	4.4243(15)	5.8411(–4)	1.074
			9.2423(10)	4.7535(15)	6.2757(–4)	
	$(2s_{1/2}3d_{3/2})_{J=2}$	0.27445	1.5602(11)	6.0847(15)	8.8094(–4)	0.98
			1.5304(11)	5.9685(15)	8.6413(–4)	
	$(2s_{1/2}3d_{5/2})_{J=2}$	0.2703	1.0631(12)	4.0817(16)	5.9404(–3)	0.98
			1.0424(12)	4.0023(16)	5.8249(–3)	
Xe	$(2p^5_{3/2}3p_{1/2})_{J=2}$	0.28794	1.1432(11)	5.1484(15)	7.1048(–4)	1.057
		0.28799(1)[b]	1.2083(11)	5.4419(15)	7.5098(–4)	
	$(2p^5_{3/2}3p_{3/2})_{J=2}$	0.28182	1.1212(11)	4.7341(15)	6.6749(–4)	1.065
		0.28186(1)[b]	1.1939(11)	5.0412(15)	7.1079(–4)	
	$(2p^5_{1/2}3p_{1/2})_{J=2}$	0.26225	1.2773(11)	4.3464(15)	6.5854(–4)	1.074
		0.26221(2.5)[b]	1.3718(11)	4.6679(15)	7.0726(–4)	
	$(2s_{1/2}3d_{3/2})_{J=2}$	0.24045	2.8274(11)	7.4150(15)	1.2253(–3)	0.98
			2.7756(11)	7.2793(15)	1.2029(–3)	
	$(2s_{1/2}3d_{5/2})_{J=2}$	0.23913	1.5291(12)	3.9445(16)	6.5543(–3)	0.98
		0.23941(1)[b]	1.5005(12)	3.8708(16)	6.4319(–3)	
La	$(2p^5_{3/2}3p_{1/2})_{J=2}$	0.25575	1.6462(11)	5.1950(15)	8.0713(–4)	1.054
		0.25580(1)[b]	1.7343(11)	5.4732(15)	8.5035(–4)	
	$(2p^5_{3/2}3p_{3/2})_{J=2}$	0.24963	1.6122(11)	4.7313(15)	7.5311(–4)	1.062
			1.7119(11)	5.0238(15)	7.9967(–4)	
	$(2p^5_{1/2}3p_{1/2})_{J=2}$	0.23022	1.8498(11)	4.2585(15)	7.3498(–4)	1.072
		0.23019(2)[b]	1.9827(11)	4.5642(15)	7.8775(–4)	
	$(2s_{1/2}3d_{3/2})_{J=2}$	0.21205	4.8286(11)	8.6858(15)	1.6275(–3)	0.98
			4.7431(11)	8.5321(15)	1.5987(–3)	
	$(2s_{1/2}3d_{5/2})_{J=2}$	0.21081	2.1536(12)	3.8064(16)	7.1746(–3)	0.98
		0.21108(1.5)[b]	2.1147(12)	3.7376(16)	7.0449(–3)	
Nd	$(2p^5_{3/2}3p_{1/2})_{J=2}$	0.22878	2.3193(11)	5.2394(15)	9.0998(–4)	1.051
			2.4365(11)	5.5044(15)	9.5600(–4)	
	$(2p^5_{3/2}3p_{3/2})_{J=2}$	0.22264	2.2693(11)	4.7245(15)	8.4320(–4)	1.059
			2.4038(11)	5.0046(15)	8.9319(–4)	
	$(2p^5_{1/2}3p_{1/2})_{J=2}$	0.20337	2.6236(11)	4.1633(15)	8.1343(–4)	1.07
			2.8078(11)	4.4555(15)	8.7053(–4)	
	$(2s_{1/2}3d_{3/2})_{J=2}$	0.18809	7.8477(11)	9.8511(15)	2.0811(–3)	0.98
			7.7123(11)	9.6810(15)	2.0452(–3)	
	$(2s_{1/2}3d_{5/2})_{J=2}$	0.18691	2.9815(12)	3.6727(16)	7.8078(–3)	0.98
			2.9289(12)	3.6078(16)	7.6700(–3)	
Eu	$(2p^5_{3/2}3p_{1/2})_{J=2}$	0.20597	3.2045(11)	5.2823(15)	1.0190(–3)	1.048
			3.3583(11)	5.5358(15)	1.0679(–3)	
	$(2p^5_{3/2}3p_{3/2})_{J=2}$	0.19979	3.1341(11)	4.7147(15)	9.3770(–4)	1.057
			3.3132(11)	4.9842(15)	9.9131(–4)	
	$(2p^5_{1/2}3p_{1/2})_{J=2}$	0.18064	3.6523(11)	4.0609(15)	8.9331(–4)	1.069
			3.9047(11)	4.3416(15)	9.5504(–4)	
	$(2s_{1/2}3d_{3/2})_{J=2}$	0.16768	1.2239(12)	1.0884(16)	2.5794(–3)	0.98
			1.2032(12)	1.0700(16)	2.5357(–3)	
	$(2s_{1/2}3d_{5/2})_{J=2}$	0.16654	4.0691(12)	3.5460(16)	8.4604(–3)	0.98
			3.9986(12)	3.4846(16)	8.3137(–3)	

a: Experimental wavelengths from Ref.[3]. b: Experimental wavelengths from Ref.[7].

Table 2. The M2 transitions between n=3 and n=2 for Ne-like systems. The last colum shows the oscillator strengths normalized to the transition $(2p^5_{3/2}3s_{1/2})_{J=2}$. $W_{\rm expt}$ is the experimental wavelength of M2.

Element	Upper level	Wavelength λ/nm	$W_{\rm exp.}$	A/S^{-1}	gB/M^{3}S^{-2}J^{-1}	gf	
Ge	$(2p^5_{3/2}3s_{1/2})_{J=2}$	0.100298		1.9816(6)	1.1511(26)	1.4942(−7)	1
	$(2p^5_{3/2}3d_{5/2})_{J=2}$	0.91972		4.3881(7)	2.5491(27)	2.7823(−6)	18.62
	$(2p^5_{3/2}3d_{3/2})_{J=2}$	0.91768		1.6666(7)	9.6815(26)	1.0520(−6)	7.04
	$(2p^5_{1/2}3d_{3/2})_{J=2}$	0.89824		2.2399(6)	1.3012(26)	1.3547(−7)	0.907
	$(2p^5_{1/2}3d_{5/2})_{J=2}$	0.89716		5.8274(6)	3.3852(26)	3.5159(−7)	2.353
	$(2s_{1/2}3p_{3/2})_{J=2}$	0.83735		6.0718(6)	3.5272(26)	3.1912(−7)	2.136
Se	$(2p^5_{3/2}3s_{1/2})_{J=2}$	0.86377		3.5185(6)	2.0439(26)	1.9677(−7)	1
	$(2p^5_{3/2}3d_{5/2})_{J=2}$	0.79507		7.1249(7)	4.1390(27)	3.3761(−6)	17.157
	$(2p^5_{3/2}3d_{3/2})_{J=2}$	0.79352		3.7521(7)	2.1796(27)	1.7709(−6)	8.999
	$(2p^5_{1/2}3d_{3/2})_{J=2}$	0.77426		3.5574(6)	2.0665(26)	1.5985(−7)	0.812
	$(2p^5_{1/2}3d_{5/2})_{J=2}$	0.77321		1.2289(7)	7.1393(26)	5.5075(−7)	2.799
	$(2s_{1/2}3p_{3/2})_{J=2}$	0.72517		1.1365(7)	6.6022(26)	4.4800(−7)	2.277
Zr	$(2p^5_{3/2}3s_{1/2})_{J=2}$	0.58446		1.6166(7)	9.3915(26)	4.1395(−7)	1
	$(2p^5_{3/2}3d_{3/2})_{J=2}$	0.54226		1.7047(8)	9.9030(27)	3.7574(−6)	9.077
	$(2p^5_{3/2}3d_{5/2})_{J=2}$	0.54137		3.3588(8)	1.9512(28)	7.3790(−6)	17.826
	$(2p^5_{1/2}3d_{3/2})_{J=2}$	0.52270		1.3093(7)	7.6059(26)	2.6814(−7)	0.648
	$(2p^5_{1/2}3d_{5/2})_{J=2}$	0.52164		7.7195(7)	4.4843(27)	1.5745(−6)	3.804
	$(2s_{1/2}3p_{3/2})_{J=2}$	0.49508		5.8230(7)	3.3826(27)	1.0698(−6)	2.584
Rh	$(2p^5_{3/2}3s_{1/2})_{J=2}$	0.44461		4.7247(7)	2.7446(27)	7.0011(−7)	1
	$(2p^5_{3/2}3d_{3/2})_{J=2}$	0.41402		1.9096(8)	1.1093(28)	2.4536(−6)	3.505
	$(2p^5_{3/2}3d_{5/2})_{J=2}$	0.41317		1.2981(9)	7.5412(28)	1.6611(−5)	23.727
	$(2p^5_{1/2}3d_{3/2})_{J=2}$	0.39493		3.5110(7)	2.0396(27)	4.1048(−7)	0.586
	$(2p^5_{1/2}3d_{5/2})_{J=2}$	0.39384		2.6345(8)	1.5304(28)	3.0633(−6)	4.375
	$(2s_{1/2}3p_{3/2})_{J=2}$	0.37625		1.8600(8)	1.0805(28)	1.9738(−6)	2.819
Ag	$(2p^5_{3/2}3s_{1/2})_{J=2}$	0.40254	4.0253	7.0130(7)	4.0739(27)	8.5182(−7)	1
	$(2p^5_{3/2}3d_{3/2})_{J=2}$	0.37518		1.8911(8)	1.0985(28)	1.9953(−6)	2.342
	$(2p^5_{3/2}3d_{5/2})_{J=2}$	0.37429		2.0190(9)	1.1729(29)	2.1203(−5)	24.892
	$(2p^5_{1/2}3d_{3/2})_{J=2}$	0.35621		5.0970(7)	2.9609(27)	4.8479(−7)	0.569
	$(2p^5_{1/2}3d_{5/2})_{J=2}$	0.35513		4.0927(8)	2.3775(28)	3.8691(−6)	4.542
	$(2s_{1/2}3p_{3/2})_{J=2}$	0.34003		2.8377(8)	1.6484(28)	2.4593(−6)	2.887
Sb	$(2p^5_{3/2}3s_{1/2})_{J=2}$	0.33476		1.4681(8)	8.5284(27)	1.2332(−6)	1
	$(2p^5_{3/2}3d_{3/2})_{J=2}$	0.31229		1.8484(8)	1.0737(28)	1.3512(−6)	1.096
	$(2p^5_{3/2}3d_{5/2})_{J=2}$	0.31134		4.4110(9)	2.5624(29)	3.2050(−5)	25.989
	$(2p^5_{1/2}3d_{3/2})_{J=2}$	0.29352		1.0353(8)	6.0147(27)	6.6866(−7)	0.542
	$(2p^5_{1/2}3d_{5/2})_{J=2}$	0.29243		9.2238(8)	5.3582(28)	5.9126(−6)	4.794
	$(2s_{1/2}3p_{3/2})_{J=2}$	0.28109		6.2298(8)	3.6189(28)	3.6899(−6)	2.992
Xe	$(2p^5_{3/2}3s_{1/2})_{J=2}$	0.29455	2.9449	2.4856(8)	1.4439(28)	1.6165(−6)	1
	$(2p^5_{3/2}3d_{3/2})_{J=2}$	0.27479		1.8537(8)	1.0768(28)	1.0492(−6)	0.649
	$(2p^5_{3/2}3d_{5/2})_{J=2}$	0.27379		7.4934(9)	4.3530(29)	4.2105(−5)	26.046
	$(2p^5_{1/2}3d_{3/2})_{J=2}$	0.25617		1.7172(8)	9.9759(27)	8.4475(−7)	0.523
	$(2p^5_{1/2}3d_{5/2})_{J=2}$	0.25508		1.6227(9)	9.4270(28)	7.9147(−6)	4.896
	$(2s_{1/2}3p_{3/2})_{J=2}$	0.24593		1.0691(9)	6.2107(28)	4.8471(−6)	2.998
La	$(2p^5_{3/2}3s_{1/2})_{J=2}$	0.26139	2.6133	4.0711(8)	2.3650(28)	2.0850(−6)	1
	$(2p^5_{3/2}3d_{3/2})_{J=2}$	0.24373		1.8773(8)	1.0906(28)	8.3596(−7)	0.401
	$(2p^5_{3/2}3d_{5/2})_{J=2}$	0.24267		1.2220(10)	7.0991(29)	5.3946(−5)	25.872
	$(2p^5_{1/2}3d_{3/2})_{J=2}$	0.22521		2.7768(8)	1.6131(28)	1.0556(−6)	0.506
	$(2p^5_{1/2}3d_{5/2})_{J=2}$	0.22411		2.7491(9)	1.5970(29)	1.0350(−5)	4.964
	$(2s_{1/2}3p_{3/2})_{J=2}$	0.21662		1.7789(9)	1.0334(29)	6.2573(−6)	3.001
Nd	$(2p^5_{3/2}3s_{1/2})_{J=2}$	0.23364	2.3359	6.5092(8)	3.7813(28)	2.6635(−6)	1
	$(2p^5_{3/2}3d_{3/2})_{J=2}$	0.21763		1.9212(8)	1.1161(28)	6.8211(−7)	0.256
	$(2p^5_{3/2}3d_{5/2})_{J=2}$	0.21653		1.9323(10)	1.1225(30)	6.7912(−5)	25.497
	$(2p^5_{1/2}3d_{3/2})_{J=2}$	0.19919		4.3963(8)	2.5539(28)	1.3075(−6)	0.491
	$(2p^5_{1/2}3d_{5/2})_{J=2}$	0.19811		4.5194(9)	2.6254(29)	1.3295(−5)	4.992
	$(2s_{1/2}3p_{3/2})_{J=2}$	0.19192		2.8733(9)	1.6691(29)	7.9332(−6)	2.978
Eu	$(2p^5_{3/2}3s_{1/2})_{J=2}$	0.21020	2.1015	1.0186(9)	5.9176(28)	3.3739(−6)	1
	$(2p^5_{3/2}3d_{3/2})_{J=2}$	0.19549		1.9808(8)	1.1506(28)	5.6747(−7)	0.168
	$(2p^5_{3/2}3d_{5/2})_{J=2}$	0.19436		2.9762(10)	1.7289(30)	8.4276(−5)	24.979
	$(2p^5_{1/2}3d_{3/2})_{J=2}$	0.17713		6.8275(8)	3.9662(28)	1.6057(−6)	0.476
	$(2p^5_{1/2}3d_{5/2})_{J=2}$	0.17605		7.2388(9)	4.2051(29)	1.6818(−5)	4.985
	$(2s_{1/2}3p_{3/2})_{J=2}$	0.17091		4.5189(9)	2.6251(29)	9.8946(−6)	2.933

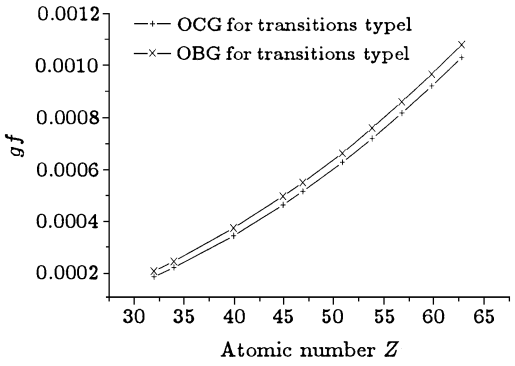


Fig.1. gf vs atomic number curve.

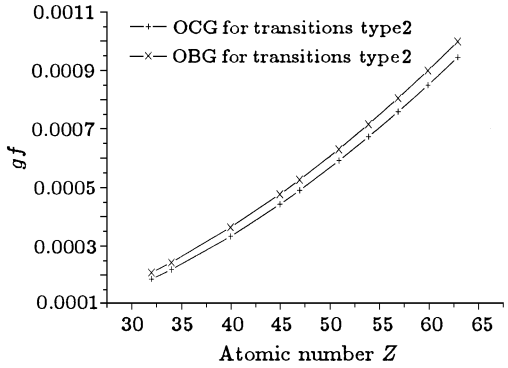


Fig.2. gf vs atomic number curve.

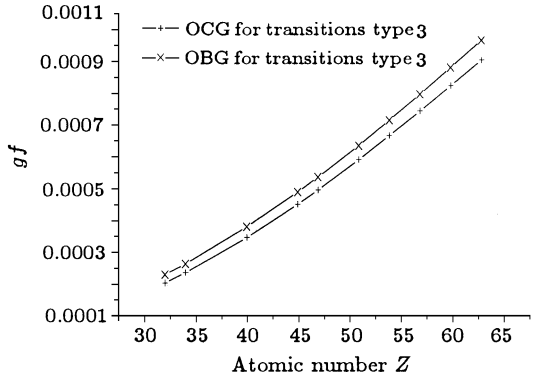


Fig.3. gf vs atomic number curve.

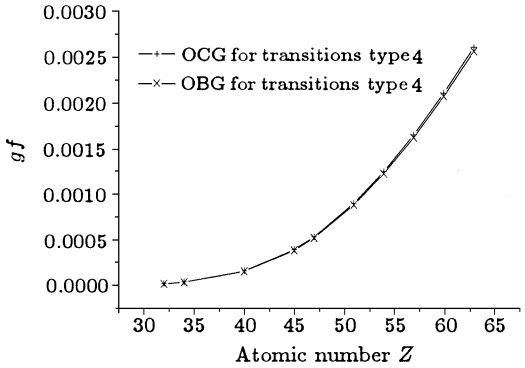


Fig.4. gf vs atomic number curve.

From Figs.1 to 5, OCG represents oscillator strengths of E2 under Coulomb gauge and OBG is under Babushkin gauge.

Transition type 1 is $(2p^5_{3/2}3p_{1/2})_{J=2}\rightarrow$gs, Transition type 2 is $(2p^5_{3/2}3p_{3/2})_{J=2}\rightarrow$gs, Transition type 3 is $(2p^5_{1/2}3p_{1/2})_{J=2}\rightarrow$gs, Transition type 4 is $(2s_{1/2}3d_{3/2})_{J=2}\rightarrow$gs, Transition type 5 is $(2s_{1/2}3d_{5/2})_{J=2}\rightarrow$gs.

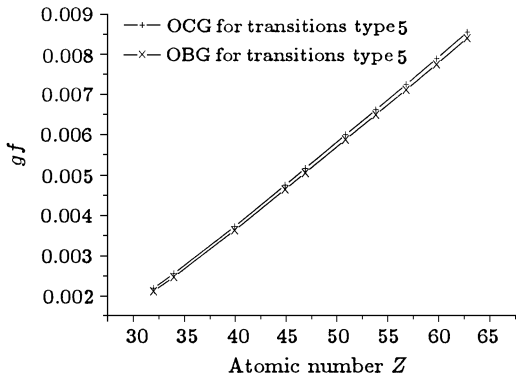


Fig.5. gf vs atomic number curve.

Ⅲ. RESULTS AND DISCUSSION

1. Table 1 shows that the E2 transition with the biggest oscillator strength for each element is $(2s_{1/2}3d_{5/2})_{J=2}$ to ground state (gs). The strength is about eight to ten times that of other E2 transitions. But from the references available for us, we only found the experimental wavelength for $(2s_{1/2}3d_{5/2})_{J=2}\rightarrow$gs in Xe^{44+} and La^{47+} and our calculation discrepancies for this line are relatively larger than our calculation discrepancies for other lines. The errors may come from the fact that the 3d electron in $(2s_{1/2}3d_{5/2})_{J=2}$ is an Auger electron. So it will interact strongly with the continuum states. But in our calculation we ignore the interaction with the continuum states. For other elements the results of our calculation for the wavelengths of E1[12], E2 and M2 are in excellent agreement with the experimental results. So we think our wave function sets obtained from our calculation are fundamentally correct, and the oscillator strengths calculated are reliable.

From other point of view, the two kinds of gauges for oscillator strength will be the same when the exact wave functions are used. Since all of the calculations for multi-electron systems use the approaching wave functions, the oscillator strengths under the two gauges will be different if improper wave functions are chosen. From Figs.1 to 5 we can see that the oscillator strengths under Coulomb gauge and Babushkin gauge are a little different and the two kinds of oscillator strength show the same rule for the same type of transitions. At the same time, we can also deduce from Figs.1 to 5 that the relative intensities of the

lines will be the same no matter which kind of oscillator strength are used.

Table 1 lists the ratios of oscillator strengths between Coulomb gauge and Babushkin gauge. For Ge^{22+} and Se^{24+} the ratios are deviated by 10% to 12% for the transitions $(2p^5_{3/2}3p_{1/2})_{J=2}$, $(2p^5_{3/2}3p_{3/2})_{J=2}$, $(2p^5_{1/2}3p_{3/2})_{J=2}$ to the ground state and by 1.2% to 2% for the transitions $(2s_{1/2}3d_{3/2})_{J=2}$ and $(2s_{1/2}3d_{5/2})_{J=2}$ to the ground state between the two gauges. For the other Ne-like ions the ratios are deviated by 6% to 8% for transitions $(2p^5_{3/2}3p_{1/2})_{J=2}$, $(2p^5_{3/2}3p_{3/2})_{J=2}$ and $(2p^5_{1/2}3p_{3/2})_{J=2}$ to the ground state and by 1.2% to 2% for transitions $(2s_{1/2}3d_{3/2})_{J=2}$ and $(2s_{1/2}3d_{5/2})_{J=2}$ to the ground state between the two gauges. We think these differences come partly from the insufficient estimate of configuration interaction, especially the interaction with the continuum states. We cannot choose all of the configurations in our calculation. So we ignore the contributions from other configurations we did not choose. These differences come also partly from the insufficient estimate of QED effect, especially the estimate of self-energies. We also found from Table 1 that for E2 transition the ratios, $(gf_{\text{transition type5}})/(gf_{\text{transition type4}})$, decrease with the increase of atomic number. Figures 1 to 5 show that the values of gf not only depend on the atomic number and the transition energy, but also depend on the type of transition for E2 and M2 separately.

2. For the M2 transitions the experiments give one M2 line for Ag^{37+}, La^{47+}, Nd^{50+}, Xe^{44+} and Eu^{53+} separately. The agreement of wavelengths obtained by our calculations and experiments is also excellent. This is partly because the levels involved in our calculation are all metastable states, so that there are little interactions with the continuum states. But we can see from our results that the only one M2 transition observed in experiment for each element is not the M2 transition with the biggest oscillator strength. The M2 transition with the biggest oscillator strength is $(2p^5_{3/2}3d_{5/2})_{J=2}$ to the ground state for all elements we have chosen. But we have not found the report about the observation of the $(2p^5_{3/2}3d_{5/2})_{J=2}$ to ground state M2 line. In some of the experiments the transition $(2p^5_{3/2}3d_{5/2})_{J=2}$ to the ground state (M2) fall into the observable ranges. In the case of Ag^{37+} the experimentally observable ranges are from 0.34004 to 0.40245 nm and the calculation wavelength of the transition $(2p^5_{3/2}3d_{5/2})_{J=2}$ to the ground state are 0.37429 nm. It is clear that the line is in the experimentally observable range. The oscillator strength of the line $(2p^5_{3/2}3d_{5/2})_{J=2}$ to the ground state is about 24 times that of the line $(2p^5_{3/2}3s_{1/2})_{J=2}$ to the ground state observed in each experiment. So, theoretically, we should observe the line $(2p^5_{3/2}3d_{5/2})_{J=2}$ to the ground state in the experiment. The reason for the experiments not to observe this line may lie in the mixing with the E1 line and some satellite lines emitted from the low charge state of silver, such as Na-like silver (Ag^{36+}), Mg-like silver (Ag^{35+}) and Al-like silver (Ag^{34+}), etc. We have looked over Ref.[3] and we found that the transition $(2p^5_{3/2}3s_{1/2}3d_{5/2})_{3/2}\rightarrow$gs of Na-like silver ($Ag^{37+}$) have the experimental wavelength 0.37427 nm and have the biggest gf value over the other lines observed in this experiment. So we deduce that the line $(2p^5_{3/2}3d_{5/2})_{J=2}\rightarrow$gs of Ne-like silver ($Ag^{37+}$) must have mixed with the line $(2p^5_{3/2}3s_{1/2}3d_{5/2})_{3/2}\rightarrow$gs of Na-like silver ($Ag^{36+}$). When the experimental conditions (such as temperature and density) change, the ratios of abundance between Ne-like silver (Ag^{37+}) and Na-like silver (Ag^{36+}) in plasmas will change. So the line 0.37427 nm should belong to $(2p^5_{3/2}3s_{1/2})_{3/2}\rightarrow$gs of Na-like silver ($Ag^{36+}$) or $(2p^5_{3/2}3d_{5/2})_{J=2}\rightarrow$gs of Ne-like silver ($Ag^{37+}$) or cannot be separated. In the case of Nd^{50+} and Eu^{53+} all of the E2 lines and part of M2 lines are out of the experimentally observable range. So there exist no experimental reports of these lines.

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