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Transition spectral parameters of In-like Ba, La and Ce ions

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Abstract

The spectral parameters (energy levels, wavelengths, transition probabilities, line strengths and oscillator strengths) of resonance lines for Ba VIII, La IX and Ce X have been performed using the multiconfiguration Dirac-Hartree-Fock method, the contributions of quantum electrodynamics and Breit interactions correction are taken into considered. The calculated results of energy levels and wavelengths are in good agreement with experimental values and other calculation. The number of energy levels and wavelengths considered is larger than that of any other experiment values and other calculations. The transition probabilities, line strengths and oscillator strengths are also calculated where no other theoretical results and experimental values are available.

Keywords: multiconfiguration Dirac-Hartree-Fock, wavelengths, energy levels, transition probabilities, core-valence correlations.

1. Introduction

Ions of Indium isoelectronic sequence have three valence electrons outside a closed core [Kr] 4d¹⁰ and provide a model for studying the effects of the strong correlation on closely spaced levels in heavy atoms [1]. The spectral parameters (energy levels, wavelengths, oscillator strengths and line strengths) can be obtained by calculating EI transitions, and the accurate spectral parameters is not only an significant basis data for precision physic, but also required in energy source, isotope identification, defense construction, materials physics, component analysis and so on. However, theoretical predictions of In-like ions are not sufficiently complete presently.

In the experiment, the spectra of In-like Xe, Cs, Ba, and La were produced with a high-voltage spark discharge were observed photographically with the National Bureau of Standards 10.7 m normal and grazing-incidence spectrographs by Kaufman [2]. The 5s²5p ²P-5s5p² ⁴P inter combination lines of Indium-like ions were investigated tend from Sb III to La IX by Tauheed [3].

In terms of theoretical calculations, the transition array of the complex La IX were calculated using least-squares-fitting parametric Hartree-Fock calculation by Churilov [4]. The transition parameters of 4*f* and 5*p* valence orbitals of the Indium isoelectronic sequence (*N* = 49) were calculated using Dirac-Fock method in the V^{N-1} approximation by Berengut [5]. The transition rates, energy levels and atomic lifetimes of In-like ions have been calculated by using the relativistic linearized coupled-cluster method that includes all single, double, and partial triple excitations of Dirac-Fock wavefunction by Safronova [6]. The energy levels and transition properties of In-like ions of Cs VII - Pm XIII were investigated by using the multi-configuration Dirac-Hartree-Fock (MCDHF) method [7]. However, due to the

scarcity of theoretical data on the ions of Ba VIII, La IX and Ce X, so the calculations of Ba VIII, La IX and Ce X are carried out in this article.

2. Method

The GRASP2K package [8-10] was used in this work, which is based on the multiconfiguration Dirac-Hartree-Fock (MCDHF) method [11], it has particular advantage in dealing with highly charged ions with several valence electrons. Details about the theoretical method can be discovered everywhere [12-17]. Here we only give a general description.

An atomic state functions (ASF) ψ is fabricated by the linear combination of configuration state functions (CSFs) ϕ for a many electron atomic system.

$$\psi(\gamma P J M_J) = \sum_i^{n_c} c_i \phi(\gamma_i P J M_J) \quad (1)$$

In Eq. (1) γ represents other appropriate labeling of the CSF. c_i is the mixing coefficient for the state of i . P is the parity, J and M_J are total angular momentum and magnetic quantum number, respectively. n_c is the number of CSFs.

In the CSFs, ϕ is constructed as an antisymmetrized linear combination of products of one-electron Dirac orbitals. The orbital is of the form:

$$\phi(r) = \frac{1}{r} \begin{pmatrix} P_{n\kappa}(r) \chi_{\kappa m}^{\text{V}}(r) \\ i Q_{n\kappa}(r) \chi_{-\kappa m}^{\text{V}}(r) \end{pmatrix} \quad (2)$$

In Eq. (2), n , κ and m are the principal quantum number, the relativistic angular quantum number and the magnetic quantum number respectively. $P_{n\kappa}(r)$ and $Q_{n\kappa}(r)$ are the large and small components of one-electron radial wavefunctions.

$\chi_{\kappa m}^{\text{V}}(r)$ is the spinor spherical harmonic in a LSJ -coupling scheme.

$$A_{\beta \rightarrow \alpha} = [j_{\beta}]^{-1} \sum_{m_{\alpha}, m_{\beta}} 2\pi |M_{\alpha\beta}|^2 \quad (3)$$

In Eq. (3), $A_{\beta \rightarrow \alpha}$ is the transition probability from β to α , β , α are Initial and final states, j_{β} is angular momentum, $M_{\alpha\beta}$ is magnetic moment.

All the expanded configurations are generated by the method of active space approach in this article. The CSFs are increased systematically to guarantee the convergence of the atomic parameters calculated. Here, we refer to the $\{1s, 2s, 2p, \dots, 3s, 3p, 3d\}$ set of orbitals as $n=3$ orbital layer and $\{1s, 2s, 2p, \dots, 4s, 4p, 4d, 4f\}$ as

$n=4$, etc. To improve the calculations effectively and ensure the accuracy of calculated results, we have chosen the active space set with the principal quantum number $n \leq 1\sim 7$ and $l \leq g$. The active space is defined as follows:

$$ASl = \{4s, 4p, 4d, 4f\} \tag{4}$$

Then the active sets were increased as follows:

$$AS(i+1) = AS(i) + \{(i+4)s, (i+4)p, (i+4)d, (i+4)f, (i+4)g\} \tag{5}$$

Where $i = (1 \dots, 3)$, and $n = (i+4)$. For In-like Ba, La and Ce ions, the core-valence (CV) correlations were taken into account. The $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10}$ are core electrons, the $5s^2 5p$ are valence electrons, the reference configurations were divided into odd and even parities in the calculations, which are the configurations of $5s^2 5p$ and $5s 5p^2$, $5s^2 5d$, the energy levels were calculated as functions of increasing active sets with double (SD) excitations.

3. Results and discussion

Table 1. Comparisons of the energy levels (cm⁻¹) calculated with available experimental values and other calculations [4] of In-like Ba, La, Ce ions.

Ba VIII			La IX				Ce X	
level	this work	Exp.[2, 3]	level	this work	Exp.[2, 3]	Ref.[4]	level	this work
5s ² 5p ² P _{1/2}	0	0	5s ² 5p ² P _{1/2}	0	0	0	5s ² 5p ² P _{1/2}	0
5s ² 5p ² P _{3/2}	23406	23613.9	5s ² 5p ² P _{3/2}	28075.49	28269	28266	5s ² 5p ² P _{3/2}	33217.76
5s5p ² 4P _{1/2}	115108	115922	5s5p ² 4P _{1/2}	127163.59	127671	127701	4f5s ² 2F _{5/2}	64045.81
5s5p ² 4P _{3/2}	127543	128564	5s5p ² 4P _{3/2}	142596.99	143357	143441	5s5p ² 4P _{1/2}	138757.62
5s5p ² 4P _{5/2}	136734	137739	5s5p ² 4P _{5/2}	152915.78	153630	153522	5s5p ² 4P _{3/2}	157653.66
4f5s ² 2F _{5/2}	146173		5s5p ² 2D _{3/2}	174027.45	168929	174732	5s5p ² 4P _{5/2}	168833.21
5s5p ² 2D _{3/2}	157026	155218	5s5p ² 2D _{5/2}	184372.58	185134	184687	5s5p ² 2D _{3/2}	189037.99
5s5p ² 2D _{5/2}	164917	165800	5s5p ² 2P _{1/2}	190417.07	191313	191097	4f5s5p ⁴ G _{5/2}	189272.68
5s5p ² 2P _{1/2}	173473	174781	5s5p ² 2S _{1/2}	220050.09	220463	220501	4f5s5p ⁴ F _{3/2}	196323.55
5s5p ² 2S _{1/2}	198321	199035	5s5p ² 2P _{3/2}	220338.20	221735	221846	4f5s5p ⁴ F _{5/2}	196646.13
5s5p ² 2P _{3/2}	198553	200243	4f5s5p ⁴ G _{5/2}	223733.69			5s5p ² 2D _{5/2}	200538.48
5s ² 5d ² D _{3/2}	229994		4f5s5p ⁴ F _{3/2}	228180.26			5s5p ² 2P _{1/2}	207137.93
5s ² 5d ² D _{5/2}	233848		4f5s5p ⁴ F _{5/2}	229957.15			5s5p ² 2D _{5/2}	208345.61
4f5s5p ⁴ G _{5/2}	251230		4f5s5p ⁴ F _{5/2}	237597.30			4f5s5p ⁴ D _{5/2}	224389.00
4f5s5p ⁴ F _{3/2}	256322		5s ² 5d ² D _{3/2}	251783.02			4f5s5p ⁴ D _{3/2}	227453.16
4f5s5p ⁴ F _{5/2}	256923		4f5s5p ⁴ D _{5/2}	252708.90			4f5s5p ⁴ D _{1/2}	229375.05
4f5s5p ² F _{5/2}	264034		4f5s5p ⁴ D _{3/2}	257235.51			5s5p ² 2P _{3/2}	239655.93
4f5s5p ⁴ D _{3/2}	279992		4f5s5p ⁴ D _{1/2}	258205.58			5s5p ² 2S _{1/2}	241719.90
4f5s5p ⁴ D _{1/2}	281364						5s5p ² 2P _{3/2}	243839.19

The calculated energy levels, experimental values [2, 3] and other theoretical calculations [4] are listed in table 1. The experimental values [2] of In-like Ba, La, ions were obtained using the electrically triggered low-inductance spark by Kaufman and the experimental values [3] were obtained using beam-foil instrument by Tauheed.

The other theoretical calculations [4] were obtained in the frame of the Hartree-Fock method with relativistic correction by using the Cowan computer Code and least-squares-fitting. As can be seen from Table 1, for the ions of Ba VIII and La IX, the energy levels calculated are in good agreement with the values of experiment [2, 3] and the values of reference [4]. The maximum discrepancy between our calculated energy levels and experimental values is less than 0.8%. The number of calculated energy levels is more than that of any other experiments and theoretical calculations.

Figure 1: Differences between theoretical calculations and experimental values of the Ba VIII and La IX ions, and the differences between theoretical calculations and the other calculated values.

Fig.1 shows the differences between theoretical calculations and experimental values of the Ba VIII and La IX ions, and the differences between theoretical calculations and the other calculated values. It is clear from the Fig. 1 that our calculated values are in good agreement with the experimental values and the theoretical values calculated by others. The maximum discrepancy is the state of $5s5p^2 \ ^2D_{3/2}$ of Ba VIII and La IX ions, about to achieve 3%.

Therefore, it is conclude that the configuration interactions considered are enough to describe the system of the Ba VIII and La IX ions. The energy levels of Ce X are also calculated and listed in table 1. For these excited states, there are no other theoretical results and experimental values so far. Based on the previous analysis, we can sure that our results are accurate and reasonable. For the ions of Ba VIII, La IX and Ce X, there are some energy levels of $4f$ orbital in the lower excited states, that maybe because the level crossings occur among the angular momentum $p-f$. And with the increase of nuclear charge Z , the energy levels of $4f5s^2$ is closer to the ground state $5s^25p \ ^2P_{1/2}$.

Table 2. Transition dates for E1 from excitation states to ground states of In-like Ba ions: wavelengths λ (in Å), transition probabilities A (length gauge and velocity gauge) in s^{-1} . The oscillator strengths and the line strengths (S_l) in length gauge.

low level	up level	λ (Å)	Exp.[2,3]	A_l	A_v	gf	S
$5s^25p \ ^2P_{1/2}$	$5s5p^2 \ ^4P_{1/2}$	868.75	862.68	1.427E+08	1.332E+08	3.231E-02	9.241E-02
$5s^25p \ ^2P_{1/2}$	$5s5p^2 \ ^4P_{3/2}$	784.05		2.905E+06	2.654E+06	1.071E-03	2.764E-03
$5s^25p \ ^2P_{3/2}$	$5s5p^2 \ ^4P_{1/2}$	1090.48	1083.06	1.371E+07	1.052E+07	3.754E-03	1.347E-02
$5s^25p \ ^2P_{3/2}$	$5s5p^2 \ ^4P_{3/2}$	960.27	952.63	1.955E+07	1.940E+07	1.081E-02	3.418E-02
$5s^25p \ ^2P_{3/2}$	$5s5p^2 \ ^4P_{5/2}$	882.39	876.05	1.369E+08	1.313E+08	9.593E-02	2.786E-01

$5s^25p\ ^2P_{1/2}$	$5s5p^2\ ^2P_{1/2}$	576.46	572.14	1.185E+10	1.154E+10	1.181E+00	2.242E+00
$5s^25p\ ^2P_{1/2}$	$5s5p^2\ ^2P_{3/2}$	503.64	499.36	3.255E+09	3.206E+09	4.951E-01	8.209E-01
$5s^25p\ ^2P_{3/2}$	$5s5p^2\ ^2P_{1/2}$	666.37		5.168E+08	5.484E+08	6.881E-02	1.509E-01
$5s^25p\ ^2P_{3/2}$	$5s5p^2\ ^2P_{3/2}$	570.95	566.16	1.285E+10	1.267E+10	2.512E+00	4.721E+00
$5s^25p\ ^2P_{1/2}$	$5s5p^2\ ^2D_{3/2}$	636.84	644.26	2.378E+09	2.309E+09	5.785E-01	1.212E+00
$5s^25p\ ^2P_{3/2}$	$5s5p^2\ ^2D_{3/2}$	748.39	759.85	4.567E+07	4.777E+07	1.533E-02	3.779E-02
$5s^25p\ ^2P_{3/2}$	$5s5p^2\ ^2D_{5/2}$	706.66	703.30	9.394E+08	9.048E+08	4.219E-01	9.816E-01
$5s^25p\ ^2P_{1/2}$	$5s5p^2\ ^2S_{1/2}$	504.23		5.481E+08	5.971E+08	4.178E-02	6.937E-02
$5s^25p\ ^2P_{3/2}$	$5s5p^2\ ^2S_{1/2}$	571.71	570.06	8.412E+09	8.004E+09	8.244E-01	1.551E+00
$5s^25p\ ^2P_{1/2}$	$5s^25d\ ^2D_{3/2}$	434.79	422.92	1.948E+10	1.864E+10	2.209E+00	3.162E+00
$5s^25p\ ^2P_{3/2}$	$5s^25d\ ^2D_{3/2}$	484.05	469.84	4.720E+09	4.558E+09	6.632E-01	1.056E+00
$5s^25p\ ^2P_{3/2}$	$5s^25d\ ^2D_{5/2}$	475.19	463.20	2.032E+10	1.959E+10	4.127E+00	6.456E+00
$5s^25p\ ^2P_{1/2}$	$4f5s5p\ ^4F_{3/2}$	390.13		6.222E+08	6.206E+08	5.679E-02	7.294E-02
$5s^25p\ ^2P_{3/2}$	$4f5s5p\ ^4F_{3/2}$	429.34		1.417E+08	1.409E+08	1.566E-02	2.214E-02
$5s^25p\ ^2P_{3/2}$	$4f5s5p\ ^4F_{5/2}$	428.23		2.338E+08	2.414E+08	3.857E-02	5.438E-02
$5s^25p\ ^2P_{1/2}$	$4f5s5p\ ^4D_{1/2}$	355.41		3.915E+04	6.376E+04	1.482E-06	1.735E-06
$5s^25p\ ^2P_{1/2}$	$4f5s5p\ ^4D_{3/2}$	357.15		5.236E+07	5.361E+07	4.005E-03	4.709E-03
$5s^25p\ ^2P_{3/2}$	$4f5s5p\ ^4D_{1/2}$	387.66		1.574E+04	2.598E+04	7.096E-07	9.056E-07
$5s^25p\ ^2P_{3/2}$	$4f5s5p\ ^4D_{3/2}$	389.73		1.068E+07	1.057E+07	9.736E-04	1.249E-03
$5s^25p\ ^2P_{1/2}$	$4f5s5p\ ^2D_{3/2}$	338.64		1.266E+09	1.229E+09	8.708E-02	9.708E-02
$5s^25p\ ^2P_{3/2}$	$4f5s5p\ ^2D_{3/2}$	367.79		3.041E+08	2.948E+08	2.466E-02	2.986E-02
$5s^25p\ ^2P_{3/2}$	$4f5s5p\ ^2F_{5/2}$	415.58		2.832E+08	2.670E+08	4.400E-02	6.020E-02
$5s^25p\ ^2P_{3/2}$	$4f5s5p\ ^4G_{5/2}$	438.94		1.540E+08	1.498E+08	2.669E-02	3.857E-02

Wavelengths, transition probabilities, oscillator strengths and line strengths of In-like Ba, La and Ce ions were calculated and listed in Table 2, 3 and table 4, other experimental values of wavelengths [2, 3] were also displayed to illustrate the accuracy of the calculated results. The transition probabilities are show in both length gauge and velocity gauge, for oscillator strengths and line strengths only show the calculated results in length gauge. In table 2 and table 3, for the ions of Ba VIII and La VII, the wavelengths calculated are in good agreement with the values of experiment [2, 3]. The maximum discrepancy between the calculated energy levels and experimental values is less than 0.8% for most of transitions. The slight difference because it is impossible that all the configuration interactions are taken into account in calculations using the MCDHF method, and the limited configuration selection results in inadequately considered configuration interaction. But for the transitions of $5s^25p\ ^2P - 5s^25d\ ^2D$ of Ba VIII, the maximum discrepancy is reach about 3%, the reason for such discrepancy may be the calculated energy levels of $5s^25p\ ^2P$ are less than the experimental values and the calculated energy levels of $5s^25d\ ^2D$ are more than the experimental values.

Table 3. Transition dates for E1 from excitation states to ground states of In-like La ions: wavelengths λ (in Å), transition probabilities A (length gauge and velocity gauge) in s^{-1} . The oscillator strengths and the line strengths (S_l) in length gauge.

low level	up level	$\lambda(\text{\AA})$	Exp.[2, 3]	A_l	A_v	gf	S
5s ² 5p ² P _{1/2}	5s5p ² ⁴ P _{1/2}	786.39	783.27	2.189E+08	2.040E+08	4.060E-02	1.051E-01
5s ² 5p ² P _{1/2}	5s5p ² ⁴ P _{3/2}	701.28		4.716E+06	4.352E+06	1.390E-03	3.211E-03
5s ² 5p ² P _{3/2}	5s5p ² ⁴ P _{1/2}	1009.20	1006.00	1.754E+07	1.313E+07	5.358E-03	1.780E-02
5s ² 5p ² P _{3/2}	5s5p ² ⁴ P _{3/2}	873.20	868.88	2.805E+07	2.775E+07	1.282E-02	3.687E-02
5s ² 5p ² P _{3/2}	5s5p ² ⁴ P _{5/2}	801.02	797.70	2.152E+08	2.032E+08	1.242E-01	3.275E-01
5s ² 5p ² P _{1/2}	5s5p ² ² D _{3/2}	574.62	591.96	3.196E+09	3.105E+09	6.329E-01	1.197E+00
5s ² 5p ² P _{3/2}	5s5p ² ² D _{3/2}	685.16		7.646E+07	7.884E+07	2.152E-02	4.855E-02
5s ² 5p ² P _{3/2}	5s5p ² ² D _{5/2}	639.81	637.49	1.260E+09	1.189E+09	4.641E-01	9.775E-01
5s ² 5p ² P _{1/2}	5s5p ² ² P _{1/2}	525.16	522.70	1.414E+10	1.375E+10	1.169E+00	2.022E+00
5s ² 5p ² P _{1/2}	5s5p ² ² P _{3/2}	453.85	450.99	3.620E+09	3.563E+09	4.471E-01	6.681E-01
5s ² 5p ² P _{3/2}	5s5p ² ² P _{1/2}	615.99		6.453E+08	6.835E+08	7.342E-02	1.488E-01
5s ² 5p ² P _{3/2}	5s5p ² ² P _{3/2}	520.12	516.88	1.548E+10	1.524E+10	2.511E+00	4.300E+00
5s ² 5p ² P _{1/2}	5s5p ² ² S _{1/2}	454.44		6.116E+08	6.642E+08	3.787E-02	5.666E-02
5s ² 5p ² P _{3/2}	5s5p ² ² S _{1/2}	520.90	520.30	9.933E+09	9.455E+09	8.081E-01	1.385E+00
5s ² 5p ² P _{1/2}	4f5s5p ⁴ F _{3/2}	438.25		4.043E+08	3.675E+08	4.657E-02	6.719E-02
5s ² 5p ² P _{3/2}	4f5s5p ⁴ F _{3/2}	499.74		2.881E+07	2.573E+07	4.315E-03	7.100E-03
5s ² 5p ² P _{3/2}	4f5s5p ⁴ F _{5/2}	495.34		8.136E+07	7.284E+07	1.795E-02	2.928E-02
5s ² 5p ² P _{1/2}	4f5s5p ⁴ D _{1/2}	387.29		9.407E+04	1.391E+05	4.231E-06	5.394E-06
5s ² 5p ² P _{1/2}	4f5s5p ⁴ D _{3/2}	388.75		2.091E+09	2.007E+09	1.895E-01	2.425E-01
5s ² 5p ² P _{3/2}	4f5s5p ⁴ D _{1/2}	434.54		4.625E+04	6.602E+04	2.618E-06	3.745E-06
5s ² 5p ² P _{3/2}	4f5s5p ⁴ D _{3/2}	436.38		4.759E+08	4.582E+08	5.434E-02	7.807E-02
5s ² 5p ² P _{3/2}	4f5s5p ⁴ D _{5/2}	445.17		1.762E+09	1.750E+09	3.142E-01	4.604E-01
5s ² 5p ² P _{1/2}	4f5s5p ² D _{3/2}	362.64		5.940E+09	5.625E+09	4.684E-01	5.592E-01
5s ² 5p ² P _{3/2}	4f5s5p ² D _{3/2}	403.75		1.548E+09	1.479E+09	1.514E-01	2.012E-01
5s ² 5p ² P _{3/2}	4f5s5p ² F _{5/2}	477.28		9.193E+07	9.900E+07	2.028E-02	3.187E-02
5s ² 5p ² P _{3/2}	4f5s5p ⁴ G _{5/2}	511.10		8.410E+06	8.368E+06	1.976E-03	3.325E-03

From the table 2-4, it is obvious that the agreement between length gauge (l) and velocity gauge (v) of transition probabilities is remarkably good for the In-like Ba, La and Ce ions. The ratio of A_l/A_v is around 1.0. There are large differences

between A_l and A_v of transition probabilities such as the transitions 5s²5p ²P - 4f5s5p ⁴D of Ba VIII, La IX and Ce X, that is because the transitions 5s²5p ²P - 4f5s5p ⁴D of Ba VIII, La IX and Ce X are weak transitions (the oscillator strengths f_l are less than 0.1) being sensitive to mixing. So the large differences between A_l and A_v of transition probabilities might be due to the small oscillator strengths f_l sensitive to cancelation effects [18].

For the ions of Ce X, there are no other theoretical results and experimental values. So far, our calculated results (wavelengths, transition probabilities, oscillator strengths and line strengths) can supplement the atom databases of Ce X.

Table 4. Transition dates for E1 from excitation states to ground states of In-like Ce ions: wavelengths λ (in Å), transition probabilities A (length gauge and velocity gauge) in s^{-1} . The oscillator strengths and the line strengths (S_l) in length gauge.

low level	up level	λ (Å)	A_l	A_v	gf	S
5s ² 5p ² P _{1/2}	5s5p ² ⁴ P _{1/2}	720.68	3.152E+08	2.946E+08	4.908E-02	1.164E-01
5s ² 5p ² P _{1/2}	5s5p ² ⁴ P _{3/2}	634.30	8.033E+06	7.416E+06	1.938E-03	4.047E-03
5s ² 5p ² P _{3/2}	5s5p ² ⁴ P _{1/2}	947.51	2.003E+07	1.505E+07	5.391E-03	1.681E-02
5s ² 5p ² P _{3/2}	5s5p ² ⁴ P _{3/2}	803.63	3.863E+07	3.799E+07	1.496E-02	3.958E-02
5s ² 5p ² P _{3/2}	5s5p ² ⁴ P _{5/2}	737.38	3.242E+08	3.045E+08	1.585E-01	3.849E-01
5s ² 5p ² P _{1/2}	5s5p ² ² S _{1/2}	413.70	7.149E+08	7.755E+08	3.668E-02	4.996E-02
5s ² 5p ² P _{3/2}	5s5p ² ² S _{1/2}	479.61	1.138E+10	1.080E+10	7.851E-01	1.239E+00
5s ² 5p ² P _{1/2}	5s5p ² ² P _{1/2}	482.77	1.637E+10	1.589E+10	1.143E+00	1.818E+00
5s ² 5p ² P _{1/2}	5s5p ² ² P _{3/2}	417.26	5.621E+08	5.639E+08	5.869E-02	8.062E-02
5s ² 5p ² P _{3/2}	5s5p ² ² P _{1/2}	574.98	7.972E+08	8.324E+08	7.903E-02	1.495E-01
5s ² 5p ² P _{3/2}	5s5p ² ² P _{3/2}	484.41	7.680E+09	7.540E+09	1.080E+00	1.723E+00
5s ² 5p ² P _{1/2}	5s5p ² ² D _{3/2}	528.99	3.450E+09	3.318E+09	5.790E-01	1.008E+00
5s ² 5p ² P _{3/2}	5s5p ² ² D _{3/2}	641.77	6.155E+07	6.467E+07	1.520E-02	3.211E-02
5s ² 5p ² P _{3/2}	5s5p ² ² D _{5/2}	597.65	7.360E+08	7.075E+08	2.364E-01	4.653E-01
5s ² 5p ² P _{1/2}	4f5s5p ⁴ F _{3/2}	509.36	6.164E+08	6.171E+08	9.591E-02	1.608E-01
5s ² 5p ² P _{3/2}	4f5s5p ⁴ F _{3/2}	613.10	6.292E+07	6.138E+07	1.418E-02	2.863E-02
5s ² 5p ² P _{3/2}	4f5s5p ² F _{5/2}	611.89	7.876E+07	6.868E+07	2.652E-02	5.343E-02
5s ² 5p ² P _{1/2}	4f5s5p ⁴ D _{1/2}	435.97	5.856E+05	6.580E+05	3.337E-05	4.790E-05
5s ² 5p ² P _{1/2}	4f5s5p ⁴ D _{3/2}	439.65	5.514E+04	1.515E+02	6.391E-06	9.250E-06
5s ² 5p ² P _{3/2}	4f5s5p ⁴ D _{1/2}	509.79	4.959E+04	2.828E+04	3.864E-06	6.485E-06
5s ² 5p ² P _{3/2}	4f5s5p ⁴ D _{3/2}	514.84	3.550E+07	3.460E+07	5.642E-03	9.564E-03
5s ² 5p ² P _{3/2}	4f5s5p ⁴ D _{5/2}	523.09	4.640E+06	3.965E+06	1.142E-03	1.966E-03
5s ² 5p ² P _{1/2}	4f5s5p ² D _{3/2}	380.43	3.183E+09	2.803E+09	2.762E-01	3.460E-01
5s ² 5p ² P _{3/2}	4f5s5p ² D _{3/2}	435.46	1.194E+09	1.099E+09	1.358E-01	1.947E-01

4. Conclusion

The energy levels, wavelengths, transition probabilities, oscillator strengths and line strengths of Ba VIII, La VII and Ce X have investigated using the method of MCDHF. The calculated results are in good agreement with the experimental values, then the configuration wavefunctions selected can be correctly describe the states of Ba VIII, La VII and Ce X. Some other energy levels, wavelengths, transition probabilities, oscillator strengths and line strengths for the ions of Ba VIII, La VII and Ce X have also obtained in this article, which were unpublished previously. We hope that the calculated results will be helping in analyzing previous experiments and make experiments simpler.

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