**Atomic properties and transition parameters of highly
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Atomic properties and transition parameters of highly charged Sb-like isoelectronic ions

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Abstract. The atomic properties and transition parameters of Sb-like Cs^{4+} , Ba^{5+} , La^{6+} , Ce^{7+} , Pr^{8+} , Nd^{9+} , Pm^{10+} and Sm^{11+} ions were first calculated using the GRASP2K package. This method is based on the multi-configuration Dirac-Hartree-Fock (MCDHF) method. In this calculation, the contributions of Breit and QED corrections were taken into consideration. By comparison, our results were in good agreement with the NIST values for Cs^{4+} and Ba^{5+} . It revealed that our calculations are dependable. Meanwhile, it also showed that these ions have high sensitivity to the fine-structure constant α and long-lived metastable states. Especially Pm^{10+} and Sm^{11+} had very long-lived metastable states with transitions within the optical transition. These ions are useful for the research of ultra-accurate atomic clocks and fundamental physics.

1. Introduction

In recent years, the great progress has been made in the study of the accuracy and stability of optical frequency standards. The most precise study in experiment was 5.2×10^{-17} from the frequency ratio of Al^+ and Hg^+ optical atomic clocks [1]. The most accurate trapped-ion clocks were two Al^+ clocks which have the fractional frequency uncertainty of 8.6×10^{-18} [2], the accuracy of an optical lattice clock based on Sr atoms has been reported with an inaccuracy of 1.5×10^{-16} [3]. The more accurate frequency standard is essential for further study of the fine-structure constant α . Recent researches have found that the fractional uncertainty of the transition rate in the atomic clocks which based on highly charged ions (HCIs) can be smaller than 10^{-19} , the sensitivity to the variation of α is assessed as up to $10^{-20} \text{ year}^{-1}$ [4,5]. Hence the highly charged ions can be the candidates for atomic clocks, search for variation of fine-structure constant, and quantum information. These ions must have the optical transition so that they can be excited by available lasers. And they should have metastable states with long lifetimes so that they can be made atomic clocks. Therefore it is necessary to study the energy levels, transition rates and lifetimes of these ions [6]. And furthermore, the research about Sb-isoelectronic sequence ions are lacking and our research can add the database and offer a reference. Meanwhile, the Sb-like ions belong to multiple electron system and our results can provide a reference for other scientific research in this respect.

There were many scholars and research institutes have made studies on this subject. M. S. Safronova and S. G. Porsev et al. have researched it in depth, they studied atomic properties of Cd-like and Sn-like ions for the development of

frequency standards and researched the variation of the fine-structure constant in 2014 [7]. In 2014, they studied the energies, transition wavelengths and lifetimes of Ag-like and In-like ions [6]. J. C. Berengut and V. A. Dzuba investigated an optical frequency standard according to the electric-octupole reference transition in a single trapped $^{171}\text{Yb}^+$ ion in experiment in 2012 [8].

There are studies found out that transitions near level crossings in HCIs can provide higher sensitivity to α variation than any other optical transitions seen in atomic systems [9, 10]. The level crossing refers to the energies of some orbitals which have larger principal quantum number are smaller than orbitals which have smaller principal quantum number, it is because that the filling order of electron shells in neutral atoms depends on the Madelung rule but changes to the Coulomb rule with the increasing of ion charge, Z_{ion} . Most level crossings occur at a relatively low ion stage, the interesting cases are those that occur in HCIs with $Z_{\text{ion}} \geq 5$, the crossing of $4f - 5s$ occurs at a relatively higher degree of ionization [11].

In this work, we calculated the atomic properties and transition parameters of Sb-like Cs^{4+} , Ba^{5+} , La^{6+} , Ce^{7+} , Pr^{8+} , Nd^{9+} , Pm^{10+} and Sm^{11+} ions using the GRASP2K package. This package is based on the multi-configuration Dirac-Hartree-Fock (MCDHF) method. We analyzed the level crossing and transition parameters of these ions in section 3. Breit and quantum electrodynamics (QED) corrections were included into the energies. Because we were focused on the ions near level crossing, we just discussed the transition rates and lifetimes of La^{6+} , Ce^{7+} , Pr^{8+} , Nd^{9+} , Pm^{10+} and Sm^{11+} ions. There are just Sb-like Cs^{4+} and Ba^{5+} ions which have been studied before and we can examine the accuracy of our study by compared the results of Cs^{4+} and Ba^{5+} with NIST [12].

2. Method

In our work, the package of GRASP2K was used to calculate the energy levels and transition parameters, it is based on the multi-configuration Dirac-Hartree-Fock (MCDHF) method. The theoretical basis of this approach has been discussed in many reports [13–16]. So we gave a brief summarization of the MCDHF method in this paper. For a given N electronic system, the configuration state functions (CSFs) $\langle \Gamma P J M |$ are composed by a linear combination of Slater determinants of the single electron Dirac orbitals. The atomic state functions (ASFs) $|\gamma_r P J M\rangle$ are obtained by a linear combination of CSFs with the same magnetic quantum number M , parity and total angular momentum J :

$$\langle \Gamma P J M | = \sum_{r=1}^{n_c} c_{r\Gamma} |\gamma_r P J M\rangle \quad (1)$$

Where $c_{r\gamma}$ is the configuration mixing coefficient for each state γ .

The Dirac–Coulomb Hamiltonian of the system is

$$\hat{H}^{DC} = \sum_{i=1}^N \hat{H}_i + \sum_{i<j}^N \left| r_i - r_j \right|^{-1} \quad (2)$$

Where the second item is the coulomb interaction between two electrons in an instant, the first $\hat{H}_i$ is the Hamiltonian of the single electron i expressed in

$$\hat{H}_i = c\alpha \cdot \hat{P}_i + (\beta - 1)c^2 + V_{nuc.}(r_i) \quad (3)$$

So the Dirac–Coulomb Hamiltonian can be given in

$$\hat{H}^{DC} = \sum_{i=1}^N \left[c\alpha \cdot \hat{P}_i + (\beta - 1)c^2 + V_{nuc.}(r_i) \right] + \sum_{i<j}^N \left| r_i - r_j \right|^{-1} \quad (4)$$

Where $\hat{P}_i$ is momentum operator, $V_{nuc.}(r_i)$ is Nuclear potential field, α and β are 4×4 Dirac matrices. The V is the monopole part of the electron-nucleus Coulomb interaction. In the relativistic self-consistent field procedure, the Configuration mixing coefficients and radial parts of the Dirac orbitals were optimized to self-consistency. Some important high order effects should be considered in the process of calculation. In this work, the transverse photon interaction (Breit) and the quantum electrodynamics (QED) corrections including self-energy and vacuum polarization were considered as perturbative corrections. The wavelength of the transition is obtained according to

$$E = hc/\lambda \quad (5)$$

The lifetime of energy levels is the reciprocal of the sum of all transition rates from this level to other low levels:

$$\tau_i = \frac{1}{\sum_j A_{ij}} \quad (6)$$

In the MCDHF theory, the configuration state functions (CSFs) are generated by restrictive active space methods, it means that electrons are limited to be active between specified orbitals. We do this by exciting electrons from the reference configurations to a set of orbitals called the active set (AS). Then we expand the configuration space by increasing the principal quantum number systematically.

In this work, we calculated the energy levels of Sb-like Cs^{4+} , Ba^{5+} , La^{6+} , Ce^{7+} , Pr^{8+} , Nd^{9+} , Pm^{10+} and Sm^{11+} ions and the transition rates, wavelength and lifetimes of La^{6+} , Ce^{7+} , Pr^{8+} , Nd^{9+} , Pm^{10+} and Sm^{11+} . The ground state of Sb I is $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 5s^2 5p^3$, we included valence-valence correlations by keeping the core $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10}$ closed and common to all calculations. The CSFs are generated by triplet substitutions from the reference configuration to an active set of orbitals. In the first step of the calculation, we set the ground state as the reference configuration and the 5s, 5p were active. And then we

added the 5d, 5f and 5g shells to our active set. For the $n = 6$ orbitals, we still use a complete VV space approach and add the $n = 6$ (with $l \leq 4$) orbitals to the active set.

3. Results and discussion

3.1. Energy levels

As mentioned earlier, the noteworthy cases are those that occur in HCIs with $Z_{\text{ion}} \geq 5$ and the crossing of Sb-like ions occurs at a relatively higher degree of ionization [11]. Hence we infer that the level crossing may happen in Ce^{7+} or Pr^{8+} , but there are few reference about these ions so we calculate the Cs^{4+} and Ba^{5+} to verify the veracity of our result. Table I presents the energy levels of Sb-like isoelectronic ions, along with NIST experimental values for Cs^{4+} and Ba^{5+} . The energy levels without any corrections are presented in the column E, the contributions of Breit and QED corrections are given separately in columns Breit and QED. The final energy levels are exhibited in the column Final. From the results we know that the contribution of Breit correction is significant while the influence of QED correction is neglected for it is smaller than 0.1%. The relative error with experiment is given in the column Diff. The atomic data for Sb-like isoelectronic ions is fragmentary, only Cs^{4+} and Ba^{5+} have been researched before experimentally [16], all of the relative error are smaller than 2%, so we judge that our results are in good agreement with data from NIST. Because all calculated ions belong to Sb-like isoelectronic ions, thus we can indicate that our calculations about La^{6+} , Ce^{7+} , Pr^{8+} , Nd^{9+} , Pm^{10+} and Sm^{11+} ions are credible.

The 5p-4f level crossing in the Sb isoelectronic sequence occurs for Pr^{8+} - Sm^{11+} ions, the order of these levels in previous ions like Cs^{4+} , Ba^{5+} , La^{6+} and Ce^{7+} is $5p^3$, $4f5p^2$, $4f^25p$ and $4f^3$, there are only $5p^3$ levels in table I for Cs^{4+} , Ba^{5+} , La^{6+} and Ce^{7+} because the energy difference between $5p^3$ and $4f5p^2$ is too large so we just present several lowest levels. The order of these levels changes from Pr^{8+} , the ground state is still $5p^3$ but other low-lying levels belonging to either $4f5p^2$ or $5p^3$ configurations cause the energy of some 4f orbitals are smaller than some 5p orbitals so that these $4f5p^2$ levels go to front of some $5p^3$ levels, as the $4f5p^2\ ^4G_{5/2}$ and $5p^3\ ^2D_{3/2}$ in Table I. For Nd^{9+} , the ground state changes to $4f5p^2$ with other low-lying levels belonging to either $4f5p^2$ or $4f^25p$ configurations. And the $4f^25p$ becomes the ground state for Pm^{10+} with other low-lying levels belonging to either $4f^3$ or $4f^25p$ configurations. For Sm^{11+} , the ground state and several lowest levels are all $4f^3$, the order of these levels changes to $4f^3$, $4f^25p$, $4f5p^2$ and $5p^3$. The energy differences between $5p^3$ and $4f5p^2$, $4f5p^2$ and $4f^25p$ or $4f^25p$ and $4f^3$ are getting smaller and smaller near the level crossing. Further, the energy differences between the ground state and several low excited states are small enough to be excited by lasers.

Table I. The level energies (in cm^{-1}) of Sb-like Cs^{4+} , Ba^{5+} , La^{6+} , Ce^{7+} , Pr^{8+} , Nd^{9+} , Pm^{10+} ions, the energy levels without any corrections calculated by MCDHF are presented in columns E, the

influence of Breit and QED corrections are given respectively in columns Breit and QED, the final energy levels taking account of Breit corrections are presented in the column Final. The relative error with experiment is given in the column Diff (in %).

	CSFs	Term	E	Breit	QED	Final	NIST ^a	Diff.%
Cs ⁴⁺	5p ³	⁴ S _{3/2}	0	0	0	0	0	0
	5p ³	² D _{3/2}	15392	-73	8	15319	15077	1.6
	5p ³	² D _{5/2}	20658	-137	13	20521	20373	0.7
	5p ³	² P _{1/2}	32692	-140	9	32552	31951	1.8
	5p ³	² P _{3/2}	42571	-309	28	42261	42273	0.02
Ba ⁵⁺	5p ³	⁴ S _{3/2}	0	0	0	0	0	0
	5p ³	² D _{3/2}	17493	-117	11	17376	17260	0.6
	5p ³	² D _{5/2}	23812	-182	18	23630	23547	0.3
	5p ³	² P _{1/2}	36959	-184	14	36775	36155	1.7
	5p ³	² P _{3/2}	49934	-397	37	49537	49621	0.1
La ⁶⁺	5p ³	⁴ S _{3/2}	0	0	0	0		
	5p ³	² D _{3/2}	18518	-128	14	18390		
	5p ³	² D _{5/2}	25256	-190	20	25066		
	5p ³	² P _{1/2}	38741	-196	20	38545		
	5p ³	² P _{3/2}	53392	-416	46	52976		
Ce ⁷⁺	5p ³	⁴ S _{3/2}	0	0	0	0		
	5p ³	² D _{3/2}	22866	-252	25	22614		
	5p ³	² D _{5/2}	30561	-324	30	30237		
	5p ³	² P _{1/2}	46632	-307	26	46325		
	5p ³	² P _{3/2}	66723	-637	53	66086		
Pr ⁸⁺	5p ³	⁴ S _{3/2}	0	0	0	0		
	4f5p ²	⁴ G _{5/2}	18946	-560	-36	18386		
	5p ³	² D _{3/2}	24752	-404	32	24348		
	4f5p ²	⁴ D _{7/2}	25847	-862	-42	24985		
	5p ³	² D _{5/2}	32343	-591	18	31751		
Nd ⁹⁺	4f5p ²	⁴ G _{5/2}	0	0	0	0		
	4f5p ²	⁴ D _{7/2}	6513	-345	3	6168		

	4f5p ²	² G _{7/2}	24389	-749	24	23640
	4f5p ²	⁴ G _{5/2}	27102	-459	47	26643
	4f ² 5p	² D _{3/2}	29973	-611	30	29362
	4f5p ²	⁴ G _{7/2}	31113	-785	37	30328
	4f ² 5p	⁴ G _{5/2}	32348	-957	6	31391
	4f5p ²	⁴ F _{3/2}	34980	-654	31	34326
	5p ³	⁴ S _{3/2}	40829	-61	45	40768
Pm ¹⁰⁺	4f ² 5p	⁴ I _{9/2}	0	0	0	0
	4f ³	⁴ I _{9/2}	6262	-966	-13	5296
	4f ² 5p	⁴ H _{7/2}	5612	-19	5	5593
	4f ³	⁴ I _{11/2}	6753	-544	2	6209
	4f ² 5p	⁴ H _{9/2}	7792	-321	-5	7471
	4f ² 5p	⁴ I _{11/2}	9115	-1104	-9	8011
	4f ² 5p	⁴ G _{5/2}	9438	11	2	9449
	4f ² 5p	² D _{3/2}	11706	-26	3	11680
	4f5p ²	⁴ G _{5/2}	73744	682	63	74426
	5p ³	⁴ S _{3/2}	163424	1929	75	165353
Sm ¹¹⁺	4f ³	⁴ I _{9/2}	0	0	0	0
	4f ³	⁴ I _{11/2}	3397	-337	3	3063
	4f ³	⁴ I _{13/2}	6983	-692	4	6296
	4f ³	⁴ I _{15/2}	10679	-1051	6	9633
	4f ³	⁴ F _{3/2}	19834	62	1	19867
	4f ³	⁴ F _{5/2}	21767	-189	2	21578
	4f ² 5p	² D _{3/2}	71903	-1208	8	73111
	4f5p ²	⁴ G _{5/2}	171337	229	77	171566
	5p ³	⁴ S _{3/2}	371140	3073	97	374213

^aValues from Ref. [13]

Table II. Transition energies ΔE (in cm^{-1}), transition rates A (in s^{-1}), wavelengths λ (in nm) and lifetimes τ (in sec) in Sb-like ions. All of these are obtained from final energy values given by Table I. The numbers in brackets represent powers of 10.

Ion	Upper	lower		ΔE	λ	A	τ
La^{6+}	$5p^3\ ^2D_{3/2}$	$5p^3\ ^2S_{3/2}$	M1	18390	544.2	9.12287[+01]	1.1[-02]
	$5p^3\ ^2D_{5/2}$	$5p^3\ ^2S_{3/2}$	M1	25066	399.2	1.36860[+01]	5.9[-02]
			E2	25066	399.2	1.02636	
		$5p^3\ ^2D_{3/2}$	M1	6676	1499	2.19404	
Ce^{7+}	$5p^3\ ^2D_{3/2}$	$5p^3\ ^2S_{3/2}$	M1	22614	442.6	2.16603[+02]	0.005
	$5p^3\ ^2D_{5/2}$	$5p^3\ ^2S_{3/2}$	E2	30237	331	1.90040	0.024
			M1	30237	331	3.65461[+01]	
		$5p^3\ ^2D_{3/2}$	M1	7623	1312.7	3.029670	
	$5p^3\ ^2P_{1/2}$	$5p^3\ ^2S_{3/2}$	E2	46325	216	8.71302	0.002
			M1	46325	216	4.36211[+02]	
		$5p^3\ ^2D_{3/2}$	E2	23711	422	2.02959	
			M1	23711	422	1.90667[+01]	
Pr^{8+}		$5p^3\ ^2D_{5/2}$	E2	16088	6220.01	3.17776[-01]	
	$4f5p^2\ ^4G_{5/2}$	$5p^3\ ^4S_{3/2}$	M1	18386	544.27	3.89334[+01]	2.57[-02]
	$5p^3\ ^2D_{3/2}$	$5p^3\ ^4S_{3/2}$	E2	24348	411	2.61488[-01]	3.3[-03]
		$5p^3\ ^4S_{3/2}$	M1	24348	411	3.02414[+02]	
		$4f5p^2\ ^4G_{5/2}$	E2	5962	1678.45	6.21771[-06]	
	$4f5p^2\ ^4D_{7/2}$	$5p^3\ ^4S_{3/2}$	E2	24985	400.52	1.48869[-01]	2.48[-01]
Nd^{9+}		$4f5p^2\ ^4G_{5/2}$	M1	6599	1516.43	3.88650[+00]	
	$4f5p^2\ ^4D_{7/2}$	$4f5p^2\ ^4G_{5/2}$	M1	6168	1622.39	3.58614[+00]	2.79[-01]
	$4f5p^2\ ^2G_{7/2}$	$4f5p^2\ ^4G_{5/2}$	E2	23640	423.30	3.15546[-03]	2.75[-02]
		$4f5p^2\ ^4G_{5/2}$	M1	23640	423.30	3.14261[+01]	
		$4f5p^2\ ^4D_{7/2}$	E2	18113	552.47	5.09213[-03]	
		$4f5p^2\ ^4D_{7/2}$	M1	18113	552.47	4.88835[+00]	
	$4f5p^2\ ^2G_{5/2}$	$4f5p^2\ ^4G_{5/2}$	M1	26643	375.59	2.91850[+02]	3.37[-03]
		$4f5p^2\ ^4D_{7/2}$	M1	20474	488.76	4.25268[+00]	
		$4f5p^2\ ^2G_{7/2}$	M1	3002	3333.42	9.82796[-02]	
	$4f^25p^2\ D_{3/2}$	$4f5p^2\ ^4G_{5/2}$	E2	29362	340.81	1.34959[-02]	1.13[-02]
		$4f5p^2\ ^4G_{5/2}$	M1	29362	340.81	8.82127[+01]	

		$4f5p^2\ ^4D_{7/2}$	E2	23194	431.44	2.61054[-02]	
		$4f5p^2\ ^2G_{5/2}$	M1	2720	3679.01	1.40089[-01]	
Pm ¹⁰⁺	$4f^3\ ^4I_{9/2}$	$4f^25p\ ^4I_{9/2}$	M1	5296	1889.52	2.84553[-02]	35.14
	$4f^25p\ ^4H_{7/2}$	$4f^25p\ ^4I_{9/2}$	M1	5593	1789.19	2.01045[-01]	4.97
	$4f^3\ ^4I_{11/2}$	$4f^25p\ ^4I_{9/2}$	M1	6209	1611.68	5.81502[+00]	0.17
	$4f^25p\ ^4H_{9/2}$	$4f^25p\ ^4I_{9/2}$	M1	7471	1339.43	1.94216[-01]	2.66
		$4f^3\ ^4I_{9/2}$	M1	2175	4600.88	2.69243[-03]	
		$4f^25p\ ^4H_{7/2}$	M1	1878	5328.5	1.70346[-01]	
		$4f^3\ ^4I_{11/2}$	M1	1262	7929.41	8.90877[-03]	
	$4f^3\ ^4I_{11/2}$	$4f^25p\ ^4I_{9/2}$	M1	8011	1249.15	1.39465[+00]	0.48
		$4f^3\ ^4I_{9/2}$	M1	2714	3687.15	6.73103[-01]	
		$4f^3\ ^4I_{11/2}$	M1	1802	5553.23	2.37105[-03]	
Sm ¹¹⁺	$4f^3\ ^4I_{11/2}$	$4f^3\ ^4I_{9/2}$	M1	3063	3267	1.20119[+00]	0.83
	$4f^3\ ^4I_{13/2}$	$4f^3\ ^4I_{9/2}$	M3	6296	1589.41	4.57536[-23]	0.61
		$4f^3\ ^4I_{11/2}$	M1	3233	3095.24	1.62660[+00]	
	$4f^3\ ^4I_{15/2}$	$4f^3\ ^4I_{9/2}$	M3	9633	1038.82	3.21145[-22]	0.84
		$4f^3\ ^4I_{13/2}$	M1	3337	2998.78	1.19054[+00]	

3.2 Transition parameters

Because transitions near level crossings in HClIs can provide higher sensitivity to α variation than others [9,10], we focused on La⁶⁺, Ce⁷⁺, Pr⁸⁺, Nd⁹⁺, Pm¹⁰⁺ and Sm¹¹⁺ ions according to our results. The transition rates A (in s⁻¹), wavelengths λ (in nm) and lifetimes τ (in sec) are showed in Table II. The numbers in brackets represent powers of 10. There is no any reference to be compared, but we can use the energy reference to estimate the uncertainties of the transition parameters calculations. It is remarkable that these ions have strong electric quadrupole ($E2$) or magnetic dipole ($M1$) transitions hence they have long-lived metastable states. Especially Pm¹⁰⁺ and Sm¹¹⁺, which have metastable states with very long lifetimes. For Pm¹⁰⁺, the lowest metastable state $4f^3\ ^4I_{9/2}$ has a very long lifetime with 35.14 s and its wavelength to the ground state is 1889.52 nm which can be excited by existing laser. The next two levels $4f^25p\ ^4H_{7/2}$ and $4f^3\ ^4I_{11/2}$ also have optical transitions to the ground state and they have long lifetimes with 4.97 s and 0.17 s. The low-lying levels of Nd¹³⁺ ion, transitions and the radiative lifetimes are shown in Fig. 1. The transitions between some low excited states are ignored because that the transition rates are too small. It is

more intuitive to show the transitions between these low-lying levels and the long lifetimes.

FIG. 1. Transitions(color online), energy levels and radiative lifetimes of low-lying levels of Sb-like Pm^{10+} .

The several low-lying levels, transitions and our calculation of the radiative lifetimes of Sm^{11+} ion are given in Fig. 2. The lowest metastable state $4f^3 \text{ } ^4\text{I}_{11/2}$ for Sm^{11+} have the strong M1 transition in the optical range to the ground state with a long lifetime 0.83 s, the next two low excited states $4f^3 \text{ } ^4\text{I}_{13/2}$ and $4f^3 \text{ } ^4\text{I}_{15/2}$ also have appropriate transition wavelength to the ground state and long lifetimes but the transitions to the ground state are too weak. Compared with Nd^{13+} ions, the lifetimes of the Sm^{13+} levels are smaller (less than 1 s), whereas the advantage of smaller lifetimes is that it can make locate the transitions simpler, hence it can be used as a development object.

FIG.2. Transitions(color online), energy levels and radiative lifetimes of low-lying levels of Sb-like Sm^{11+} .

4. Summary

In this work, the atomic properties and transition parameters of Sb-like Cs^{4+} , Ba^{5+} , La^{6+} , Ce^{7+} , Pr^{8+} , Nd^{9+} , Pm^{10+} and Sm^{11+} ions were performed by GRASP2K which based on multi-configuration relativity Dirac-Hartree-Fock (MCDHF) method.

The Breit and QED correlations were considered in the calculation of energy levels, only the contribution of Breit correlation was taken into account in final results because that it is more dominant than QED. Our results about energy levels of Cs^{4+} and Ba^{5+} agreed well with the previous experimental value. The level crossing of Sb-like isoelectronic ions occurs from Pr^{8+} to Sm^{11+} . The transition energies from low excited states to the ground state are relatively small near the level crossing. Particularly Pm^{10+} and Sm^{11+} which the suitable transitions within the optical range, and they have long-lived metastable states. These highly charged ions are very important for researches of variation of α and the atomic clocks. The researches about Sb-like La^{6+} , Ce^{7+} , Pr^{8+} , Nd^{9+} , Pm^{10+} and Sm^{11+} ions are lacking and our results can add the database and provide a reference for further research.

Author contribution statement

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