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# Spectra and oscillator strengths of $d$–$d$ and $d$–$p$ transitions for cobalt-like $Cd^{21+}$ ion

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**Abstract.** We calculate the spectra and oscillator strengths for highly ionized cobalt-like $Cd^{21+}$ ions $3p^63d^9$–$3p^53d^{10}$ , $3p^63d^9$–$3p^63d^84p$ transitions by using multi-configuration self-consistent field method program together with fitting formula proposed by us. The calculations have a good agreement with observations.

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**Key words**: highly ionized, energy level, fitting formula

## 1 Introduction

The proposition of Soft-X-Ray laser theory, which laser work material is cobalt-like $Au^{52+}$ was verified by TIAP instrument [1]. It renewed the interest of research for highly ionized cobalt-like ions. Ions of the cobalt isoelectronic sequence have the ground configuration $3p^63d^9$. At the beginning of the sequence the lowest configuration with odd parity is $3p^63d^84p$. However, from $Rb^{10+}$ on, the $3p^53d^{10}$ configuration takes its place. The correction between $3p^63d^9/^2D$ and $3p^53d^{10}/^2P$ gives rise to configuration combination.

Experimentally, these configuration transitions of cobalt-like ions were first observed by Edlén for Rb, Sr, Y, Zr, Mo, Pd, Ag, Cd, In, and Sn, although no wavelengths were reported [2]. Edlén's observed wavelengths can be inferred from the wave numbers given in his monograph, which also gives values for Br and Sb [3]. Later, Alexander reported wavelengths for these transitions in Y, Zr, Nb, and Mo [4]. Two of these transitions were observed by Burkhalter *et al.* for $Sn^{23+}$ in a laser-produced plasma [5] . Burkhalter *et al.* [6] reported new wavelength values for $Mo^{15+}$. The same transitions in $Sr^{11+}$ were given by Acquista and Reader [7] and revised values for $Sr^{11+}$, $Y^{12+}$, $Zr^{13+}$, $Nb^{14+}$, and $Mo^{15+}$ by Ryabtsev and Reader [8]. The $3p^63d^9$–$3p^53d^{10}$ transitions of $Ba^{29+}$, $La^{30+}$, $Nd^{33+}$, $Sm^{35+}$, $Gd^{37+}$, $Dy^{39+}$, $Er^{41+}$, and $Yb^{43+}$

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were reported by Reader [9]. New wavelengths for these transitions in $Ag^{20+}$, $Cd^{21+}$, $In^{22+}$, and $Sn^{23+}$ were given by Kononov [10]. The magnetic-dipole transition between the levels of the $3p^6 3d^9/{}^2D$ ground term has been observed in three cobalt-like ions: the magnetic-dipole transitions of $Zr^{13+}$ and $Mo^{15+}$ were observed in the PLT tokamak by Suckewer [11]; that of $Nb^{14+}$ was observed in an electron cyclotron resonance ion source by Prior [12]. Ekberg *et al.* [13] gave new measurements for $3p^6 3d^9$–$3p^5 3d^{10}$ transitions of the ions from $Sr^{11+}$ to $Au^{52+}$ in laser-produced plasmas.

In this paper, we have theoretically calculated the wavelengths and oscillator strengths for highly ionized cobalt-like $Cd^{21+}$ ions $3p^6 3d^9$–$3p^5 3d^{10}$, $3p^6 3d^9$–$3p^p 3d^8 4p$ transitions using multi-configuration self-consistent field method [14] together with the fitting formula proposed by us. The calculations have a good agreement with observations.

## 2 Fitting formulas

Up to the present day, it is difficult to solve a HFR equation of polyelectron system accurately. However, our real purpose is calculating accurately the known energy levels of atoms and predicting the unknown those, which can be achieved by using multi-configuration self-consistent field method together with fitting formula. So it is important to find a better fitting formula. Because the difference values $\Delta E$ between experimental measuring values and theoretical calculated values of multi-configuration self-consistent field method change smoothly along the isoelectronic sequence, we can achieve the least square fitting and find the fitting formula between $\Delta E$ and $Z_c$. In 1987, Wyart proposed a fitting formula [15]

$$E_{\rm fit} = -98751.4 + 55078 \times Z_c + 5618.86 \times Z_c^2 + 7.6414 \times Z_c^3 + Z_c^4. \tag{1}$$

In 1991, Matsushima *et al.* proposed another fitting formula [16]

$$E_{\rm fit} = A + BZ_c + \frac{CZ_c^2}{10} + \frac{DZ_c^3}{100} + \frac{EZ_c^4}{1000} + \frac{FZ_c^5}{1000000}. \tag{2}$$

According to the quantum electrodynamics effect of high-Z ions proposed by Gould *et al.* [17], which can move the energy levels of the isoelectronic sequence, we find that the quantum electrodynamics effect of high-Z ions is not considered in the formulas (1) and (2). So we have proposed a better formula, in which the quantum electrodynamics effect of high-Z ions is included, and it is expressed as

$$\Delta E = A + BZ_c + CZ_c^2 + DZ_c^3 + EZ_c^4 + FZ_c^5 + GZ_c^6 + HZ_c^7 + \text{ higher order terms}, \tag{3}$$

where $Z_c$,$Z_c^2$,$Z_c^3$, and $Z_c^4$ constant term is used for eliminating high order relativistic effect, remnant correlation energy and radiative corrections; $Z_c^5$ is used for eliminating high order Breit effect as in the formula (1) and (2). $Z_c^6$, $Z_c^7$, and higher order terms is used for eliminating the quantum electrodynamics effect of high-Z ions, which is proposed by us. All of above-mentioned effects are not considered by the multi-configuration self-consistent field