



Energy Levels and Transition Data of Cs XI[†]

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Abstract

Previously reported atomic data for Cs XI, including spectral lines, wavelengths, energy levels, and transition probabilities, were collected and systematically analyzed. The present theoretical investigation was supported by extensive calculations performed for Cs XI using the pseudo-relativistic Hartree–Fock (HFR) method with configuration interaction, as implemented in Cowan’s codes. In this work, all previously reported energy levels and their allowed transition assignments were confirmed. A critically evaluated dataset is presented, including optimized energy levels with their uncertainties, observed and Ritz wavelengths with their corresponding uncertainties, and theoretical transition probabilities with estimated uncertainties.

Keywords: atomic spectra; cesium; energy levels; spectral lines; wavelengths; transition probabilities

1. Introduction

In general, accurate transition probabilities (gA-values) are essential for interpreting astrophysical spectra and modeling radiative processes in high-temperature plasmas, as they determine spectral line intensities and enable plasma diagnostics such as electron temperature, density, and elemental abundances. For highly charged ions such as Cs XI, reliable A-values are particularly important in the extreme ultraviolet (EUV) and vacuum ultraviolet (VUV) regions, where strong configuration interaction effects can significantly influence transition probabilities. Therefore, accurate theoretical calculations are required to provide reliable atomic data for astrophysical plasma modeling and spectroscopic databases.

From an experimental standpoint, the first detailed analysis of this spectrum was carried out by Van Kleef and Joshi [1], who reported the energy levels of the $4d^9$ and $4d^85p$ configurations. The cesium spectrum was photographed using a 10.7 m grazing-incidence spectrograph with a triggered spark source. In total, thirty-six energy levels were established on the basis of forty-seven observed lines in the 117–140 Å wavelength region. Subsequently, Gayasov and Joshi [2] classified the ten strongest lines of the $4d^9$ – $4d^84f$ transition array in the 103–109 Å region and established the six highest levels of the $4d^84f$ configuration. In 2005, Churilov et al. [3] re-examined the spectrum and confirmed the previously reported levels, introducing corrections to five levels of the $4d^85p$ configuration. They further extended the analysis by incorporating the $4p^54d^{10}$ configuration. A total of 103 spectral lines of the $4d^9$ – $\{4d^85p + 4d^84f + 4p^54d^{10}\}$ transition array were classified,



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leading to the determination of 77 (including 40 new) energy levels for the configurations involved. The spectrograms used in this analysis were recorded with a 10.7 m grazing-incidence spectrograph at NIST (Gaithersburg, MD, USA) and the 3 m grazing-incidence spectrograph at ISAN (Troitsk, Russia). All of these revisions were incorporated into the comprehensive compilation of cesium and its ions (Cs I–LV) by Sansonetti [4]. Subsequently, the updated results were included in the NIST Atomic Spectra Database (ASD) [5].

In the compilation by Sansonetti [4], observed wavelengths (with uncertainties), line intensities, and associated energy levels with roughly estimated uncertainties (nearly constant) were tabulated, and gA -values were listed for some spectra, though without any uncertainty estimates. The method of energy-level optimization was not specified—however, it was likely performed using the “ECALC” code [6]—and Ritz wavelengths with uncertainties were not reported. Therefore, a more rigorous and systematic analysis—similar to recent critical evaluations [7]—is desirable. We have previously performed such analyses for the Cs VI–VII spectra [8,9]. In the present work, we aim to provide an extensive and critically evaluated atomic dataset for the Cs XI spectrum by comparing it with the existing literature.

2. HFR Method

To support the present experimental results, theoretical calculations were performed within the pseudo-relativistic Hartree–Fock (HFR) framework including configuration interaction, using Cowan’s suite of codes [10]. The Windows version developed by Kramida [11] was employed. The computational procedure followed Ref. [12]. The present work focuses on the $4d^9 - \{4d^8 5p + 4d^8 4f + 4p^5 4d^{10}\}$ transition arrays of Cs XI, which were previously investigated experimentally in [3] with their gA -values reported. Further details of the calculations are given in the Theoretical Calculations and Transition Probabilities Section.

3. Results

The primary results of our work on Cs XI are given in Table 1, in which all observed lines are listed along with their evaluated radiative transition parameters. Another important result on the optimized energy levels along with their theoretical LS-composition vectors for Cs XI spectrum is supplemented in Appendix A. The LS-composition vectors were obtained from theoretical calculations using Cowan’s codes. Further details of the analysis are presented in the following sections.

Table 1. Classified lines of Cs XI.

$\lambda_{Obs.}^a$ (arb. u.)	$\lambda_{Obs.}^b$ (Å)	σ^b (cm ^{−1})	Classification	λ_{Ritz}^b (Å)	$\delta\lambda_{O-R}^c$ (mÅ)	gA^d (s ^{−1})	CF ^d	Acc. ^e	gA_{Prev}^f (s ^{−1})
4	103.374(3)	967,360(30)	$4d^9 \ ^2D_{3/2} - 4p^5 4d^{10} \ ^2P_{1/2}^o$	103.374(3)	0	4.04×10^{12}	0.73	D+	4.49×10^{12}
15m	104.085(6)	960,750(60)	$4d^9 \ ^2D_{5/2} - 4d^8(^3F)4f \ ^2F_{5/2}^o$	104.084(3)	1	1.06×10^{11}	0.03	D	9.70×10^{10}
13	104.980(3)	952,560(30)	$4d^9 \ ^2D_{5/2} - 4d^8(^3F)4f \ ^2D_{3/2}^o$	104.9806(21)	−1	3.46×10^{11}	0.06	D	3.23×10^{11}
49	106.033(3)	943,100(30)	$4d^9 \ ^2D_{5/2} - 4d^8(^1G)4f \ ^2P_{3/2}^o$	106.0341(21)	−1	7.06×10^{12}	0.70	D+	8.13×10^{12}
60	106.193(3)	941,680(30)	$4d^9 \ ^2D_{5/2} - 4d^8(^3F)4f \ ^2F_{7/2}^o$	106.193(3)	0	1.52×10^{13}	0.69	D+	1.72×10^{13}
54	106.213(3)	941,500(30)	$4d^9 \ ^2D_{3/2} - 4d^8(^3F)4f \ ^2F_{5/2}^o$	106.213(3)	0	1.12×10^{13}	0.69	D+	1.27×10^{13}
55	106.923(3)	935,250(30)	$4d^9 \ ^2D_{5/2} - 4d^8(^3F)4f \ ^2D_{5/2}^o$	106.9227(21)	0	9.75×10^{12}	0.65	D+	1.17×10^{13}
44	107.147(3)	933,300(30)	$4d^9 \ ^2D_{3/2} - 4d^8(^3F)4f \ ^2D_{3/2}^o$	107.1465(22)	1	6.33×10^{12}	0.65	D+	7.55×10^{12}
12	108.245(3)	923,830(30)	$4d^9 \ ^2D_{3/2} - 4d^8(^1G)4f \ ^2P_{3/2}^o$	108.2441(22)	1	2.09×10^{11}	0.04	D	2.33×10^{11}
5	109.170(3)	916,000(30)	$4d^9 \ ^2D_{3/2} - 4d^8(^3F)4f \ ^2D_{5/2}^o$	109.1703(22)	0	4.73×10^{10}	0.02	D	5.60×10^{10}
28	117.482(3)	851,194(22)	$4d^9 \ ^2D_{5/2} - 4d^8(^1S)5p \ ^2P_{3/2}^o$	117.4800(21)	2	2.85×10^{10}	0.11	D+	3.10×10^{10}
5	117.595(3)	850,376(22)	$4d^9 \ ^2D_{5/2} - 4d^8(^1S)4f \ ^2F_{5/2}^o$	117.5928(21)	2	1.11×10^9	0	E	1.00×10^9
6	117.616(3)	850,224(22)	$4d^9 \ ^2D_{5/2} - 4d^8(^1S)4f \ ^2F_{7/2}^o$	117.616(3)	0	6.11×10^8	0	E	1.00×10^9
9	120.197(3)	831,968(21)	$4d^9 \ ^2D_{3/2} - 4d^8(^1S)5p \ ^2P_{3/2}^o$	120.1990(22)	−2	1.13×10^{10}	0.12	D+	1.10×10^{10}
10	120.315(3)	831,152(21)	$4d^9 \ ^2D_{3/2} - 4d^8(^1S)4f \ ^2F_{5/2}^o$	120.3171(22)	−2	4.27×10^9	0	E	4.00×10^9

Table 1. Cont.

$I_{Obs.}^a$ (arb. u.)	$\lambda_{Obs.}^b$ (Å)	σ^b (cm ⁻¹)	Classification	λ_{Ritz}^b (Å)	$\delta\lambda_{O-R}^c$ (mÅ)	gA^d (s ⁻¹)	CF ^d	Acc. ^e	gA_{Prev}^f (s ⁻¹)
6	121.849(3)	820,688(20)	4d ⁹ 2D _{5/2} -4d ⁸ (³ P)4f 2D _{3/2} ^o	121.849(3)	0	1.80 × 10 ⁹	0	E	1.00 × 10 ⁹
20	123.783(3)	807,865(20)	4d ⁹ 2D _{3/2} -4d ⁸ (¹ S)5p 2P _{1/2} ^o	123.783(3)	0	2.63 × 10 ¹⁰	0.11	D+	2.70 × 10 ¹⁰
6	123.908(3)	807,050(20)	4d ⁹ 2D _{5/2} -4d ⁸ (¹ G)4f 2F _{7/2} ^o	123.908(3)	0	6.53 × 10 ⁹	0	E	4.00 × 10 ⁹
38	124.070(3)	805,997(19)	4d ⁹ 2D _{5/2} -4d ⁸ (¹ G)5p b ² G _{7/2} ^o	124.070(3)	0	4.73 × 10 ¹⁰	0.07	D	4.20 × 10 ¹⁰
8	124.370(3)	804,052(19)	4d ⁹ 2D _{5/2} -4d ⁸ (¹ D)5p 2D _{5/2} ^o	124.3693(21)	1	1.11 × 10 ¹⁰	0.01	D	1.10 × 10 ¹⁰
9	124.594(3)	802,607(19)	4d ⁹ 2D _{5/2} -4d ⁸ (¹ D)5p 2F _{7/2} ^o	124.594(3)	0	6.27 × 10 ⁷	0	E	3.00 × 10 ⁹
4	124.689(3)	801,995(19)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)4f 4G _{5/2} ^o	124.689(3)	0	2.52 × 10 ⁹	0	E	3.00 × 10 ⁹
4	124.700(3)	801,925(19)	4d ⁹ 2D _{5/2} -4d ⁸ (¹ G)5p a ² G _{7/2} ^o	124.700(3)	0	1.10 × 10 ¹⁰	0.02	D	1.00 × 10 ¹⁰
20	125.191(3)	798,779(19)	4d ⁹ 2D _{5/2} -4d ⁸ (³ P)5p 2D _{3/2} ^o	125.1919(21)	-1	2.03 × 10 ¹⁰	0.06	D	2.10 × 10 ¹⁰
6	125.591(3)	796,235(19)	4d ⁹ 2D _{5/2} -4d ⁸ (³ P)4f 4G _{7/2} ^o	125.591(3)	0	6.22 × 10 ⁹	0.01	D	8.00 × 10 ⁹
8	125.731(3)	795,349(19)	4d ⁹ 2D _{5/2} -4d ⁸ (³ P)5p 4D _{5/2} ^o	125.7329(21)	-2	1.22 × 10 ¹⁰	0.01	D	1.40 × 10 ¹⁰
7	126.230(3)	792,205(19)	4d ⁹ 2D _{5/2} -4d ⁸ (¹ G)5p 2F _{5/2} ^o	126.2303(21)	0	6.88 × 10 ⁹	0.01	D	5.00 × 10 ⁹
28	126.279(3)	791,897(19)	4d ⁹ 2D _{5/2} -4d ⁸ (³ P)5p a ⁴ G _{3/2} ^o	126.280(3)	-1	5.21 × 10 ¹⁰	0.13	D	3.40 × 10 ¹⁰
5t	126.372(6)	791,310(40)	4d ⁹ 2D _{3/2} -4d ⁸ (¹ D)4f 2P _{1/2} ^o	126.372(6)	0	2.12 × 10 ¹¹	0.14	D+	1.61 × 10 ¹¹
29	126.820(3)	788,519(19)	4d ⁹ 2D _{5/2} -4d ⁸ (³ P)5p 2P _{3/2} ^o	126.8203(21)	0	1.22 × 10 ¹¹	0.26	D+	1.26 × 10 ¹¹
34	126.930(3)	787,836(19)	4d ⁹ 2D _{3/2} -4d ⁸ (³ P)5p 2P _{1/2} ^o	126.930(3)	0	9.20 × 10 ¹⁰	0.07	D	1.48 × 10 ¹¹
16	126.948(3)	787,724(19)	4d ⁹ 2D _{5/2} -4d ⁸ (¹ D)4f 2G _{7/2} ^o	126.948(3)	0	1.17 × 10 ⁹	0	E	1.00 × 10 ⁹
5	127.087(3)	786,863(19)	4d ⁹ 2D _{5/2} -4d ⁸ (³ P)4f 4D _{3/2} ^o	127.089(3)	-2	5.41 × 10 ⁹	0.01	D	5.00 × 10 ⁹
16	127.261(3)	785,787(19)	4d ⁹ 2D _{3/2} -4d ⁸ (¹ D)4f 2P _{3/2} ^o	127.261(3)	0	1.84 × 10 ¹⁰	0.01	D	1.80 × 10 ¹⁰
25	127.393(3)	784,972(18)	4d ⁹ 2D _{5/2} -4d ⁸ (³ P)5p 4D _{7/2} ^o	127.393(3)	0	1.78 × 10 ¹⁰	0.17	D+	1.40 × 10 ¹⁰
55	127.420(3)	784,806(18)	4d ⁹ 2D _{3/2} -4d ⁸ (¹ D)5p 2D _{5/2} ^o	127.4207(22)	-1	2.84 × 10 ¹¹	0.28	D+	2.53 × 10 ¹¹
20	127.637(3)	783,472(18)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)5p 2F _{5/2} ^o	127.637(3)	0	1.79 × 10 ¹⁰	0.05	D	2.00 × 10 ¹⁰
18	127.747(3)	782,797(18)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)5p 2D _{3/2} ^o	127.7472(21)	0	4.69 × 10 ¹⁰	0.25	D+	4.80 × 10 ¹⁰
5	127.784(3)	782,571(18)	4d ⁹ 2D _{3/2} -4d ⁸ (³ P)5p b ⁴ G _{3/2} ^o	127.784(3)	0	1.32 × 10 ⁹	0.01	D	2.00 × 10 ⁹
3	128.285(3)	779,514(18)	4d ⁹ 2D _{3/2} -4d ⁸ (³ P)5p 2D _{3/2} ^o	128.2842(22)	1	1.73 × 10 ⁹	0	E	1.00 × 10 ⁹
4	128.442(3)	778,562(18)	4d ⁹ 2D _{3/2} -4d ⁸ (¹ D)4f 2D _{3/2} ^o	128.442(3)	0	5.64 × 10 ⁹	0	E	8.00 × 10 ⁹
18	128.631(3)	777,418(18)	4d ⁹ 2D _{5/2} -4d ⁸ (³ P)4f 2F _{7/2} ^o	128.631(3)	0	2.23 × 10 ¹⁰	0	E	2.90 × 10 ¹⁰
12	128.658(3)	777,254(18)	4d ⁹ 2D _{3/2} -4d ⁸ (³ P)5p 2S _{1/2} ^o	128.658(3)	0	2.46 × 10 ¹⁰	0.31	D+	2.50 × 10 ¹⁰
34	128.676(3)	777,146(18)	4d ⁹ 2D _{3/2} -4d ⁸ (³ P)4f 4D _{5/2} ^o	128.676(3)	0	2.87 × 10 ¹⁰	0.02	D	3.90 × 10 ¹⁰
58	128.784(3)	776,494(18)	4d ⁹ 2D _{5/2} -4d ⁸ (¹ D)5p 2P _{3/2} ^o	128.7852(21)	-1	3.18 × 10 ¹¹	0.82	D+	2.91 × 10 ¹¹
35	128.854(3)	776,072(18)	4d ⁹ 2D _{3/2} -4d ⁸ (³ P)5p 4D _{5/2} ^o	128.8524(22)	2	2.53 × 10 ¹⁰	0.02	D	1.40 × 10 ¹⁰
4	128.977(3)	775,332(18)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)4f 4F _{5/2} ^o	128.977(3)	0	1.12 × 10 ¹⁰	0.01	E	1.30 × 10 ¹⁰
48	129.045(3)	774,923(18)	4d ⁹ 2D _{5/2} -4d ⁸ (³ P)5p 4P _{5/2} ^o	129.0454(21)	0	1.43 × 10 ¹¹	0.38	E	1.41 × 10 ¹¹
65	129.082(3)	774,701(18)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)5p 2G _{7/2} ^o	129.082(3)	0	3.78 × 10 ¹¹	0.26	D+	3.17 × 10 ¹¹
7	129.260(3)	773,635(18)	4d ⁹ 2D _{5/2} -4d ⁸ (³ P)4f 4F _{7/2} ^o	129.260(3)	0	7.20 × 10 ¹⁰	0.05	E	1.80 × 10 ¹⁰
55	129.375(3)	772,947(18)	4d ⁹ 2D _{3/2} -4d ⁸ (¹ G)5p 2F _{5/2} ^o	129.3748(22)	0	1.29 × 10 ¹¹	0.05	D	1.58 × 10 ¹¹
50 *	129.435(8)	772,590(50)	4d ⁹ 2D _{3/2} -4d ⁸ (³ P)5p a ⁴ G _{3/2} ^o	129.427(3)	8	2.28 × 10 ¹⁰	0.09	E	7.00 × 10 ⁹
50 *	129.435(8)	772,590(50)	4d ⁹ 2D _{5/2} -4d ⁸ (³ P)5p 4D _{3/2} ^o	129.433(3)	2	1.11 × 10 ¹¹	0.45	D+	1.18 × 10 ¹¹
7	129.481(3)	772,314(18)	4d ⁹ 2D _{3/2} -4d ⁸ (³ F)4f 2P _{1/2} ^o	129.481(3)	0	2.32 × 10 ⁶	0	E	3.00 × 10 ⁹
42	129.508(3)	772,153(18)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)5p 4F _{7/2} ^o	129.508(3)	0	2.92 × 10 ¹⁰	0.09	D	3.30 × 10 ¹⁰
13	129.556(3)	771,867(18)	4d ⁹ 2D _{3/2} -4d ⁸ (¹ G)4f 2F _{5/2} ^o	129.556(3)	0	1.05 × 10 ¹¹	0.05	D	8.70 × 10 ¹⁰
57	129.906(3)	769,787(18)	4d ⁹ 2D _{5/2} -4d ⁸ (³ P)5p 2D _{5/2} ^o	129.905(3)	1	2.05 × 10 ¹¹	0.43	D+	1.74 × 10 ¹¹
47	129.995(3)	769,260(18)	4d ⁹ 2D _{3/2} -4d ⁸ (³ P)5p 2P _{3/2} ^o	129.9947(22)	0	2.61 × 10 ¹¹	0.64	D+	2.39 × 10 ¹¹
69 *	130.288(8)	767,530(50)	4d ⁹ 2D _{3/2} -4d ⁸ (³ P)4f 4D _{3/2} ^o	130.277(3)	11	9.90 × 10 ⁹	0.03	D	1.60 × 10 ¹⁰
69 *	130.288(8)	767,530(50)	4d ⁹ 2D _{5/2} -4d ⁸ (¹ G)5p 2F _{7/2} ^o	130.288(8)	0	2.33 × 10 ¹¹	0.48	D+	3.28 × 10 ¹¹
33	130.381(3)	766,983(18)	4d ⁹ 2D _{5/2} -4d ⁸ (¹ D)5p 2F _{5/2} ^o	130.3808(21)	0	4.02 × 10 ¹⁰	0.05	E	1.45 × 10 ¹¹
32t	130.475(6)	766,430(40)	4d ⁹ 2D _{5/2} -4d ⁸ (³ P)4f 4G _{5/2} ^o	130.475(6)	0	1.33 × 10 ¹¹	0.17	E	1.00 × 10 ⁹
40m	130.855(6)	764,200(40)	4d ⁹ 2D _{3/2} -4d ⁸ (³ F)5p 2F _{5/2} ^o	130.853(3)	2	7.51 × 10 ¹⁰	0.17	D+	7.20 × 10 ¹⁰
53	130.969(3)	763,539(17)	4d ⁹ 2D _{3/2} -4d ⁸ (³ F)5p 2D _{3/2} ^o	130.9687(22)	0	3.76 × 10 ¹¹	0.58	D+	3.65 × 10 ¹¹
27	131.042(3)	763,114(17)	4d ⁹ 2D _{3/2} -4d ⁸ (³ F)5p 4D _{1/2} ^o	131.042(3)	0	3.18 × 10 ¹⁰	0.13	D+	3.30 × 10 ¹⁰
60	131.235(3)	761,992(17)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)5p 2D _{5/2} ^o	131.2345(21)	1	3.21 × 10 ¹¹	0.38	D+	3.30 × 10 ¹¹
5	131.400(3)	761,035(17)	4d ⁹ 2D _{5/2} -4d ⁸ (¹ D)4f 2F _{7/2} ^o	131.400(3)	0	9.57 × 10 ⁸	0	E	1.00 × 10 ⁹
5	131.473(3)	760,612(17)	4d ⁹ 2D _{3/2} -4d ⁸ (³ P)4f 4D _{1/2} ^o	131.473(3)	0	3.04 × 10 ⁸	0	E	1.00 × 10 ⁹
21	131.577(3)	760,011(17)	4d ⁹ 2D _{5/2} -4d ⁸ (³ P)5p 4P _{3/2} ^o	131.5760(21)	1	1.88 × 10 ¹⁰	0.05	D	2.40 × 10 ¹⁰
19	131.851(3)	758,432(17)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)4f 4G _{7/2} ^o	131.851(3)	0	1.17 × 10 ¹⁰	0.01	D	1.60 × 10 ¹⁰

Table 1. Cont.

$I_{Obs.}^a$ (arb. u.)	$\lambda_{Obs.}^b$ (Å)	σ^b (cm ^{−1})	Classification	λ_{Ritz}^b (Å)	$\delta\lambda_{O-R}^c$ (mÅ)	gA^d (s ^{−1})	CF ^d	Acc. ^e	gA_{prev}^f (s ^{−1})
4	132.061(3)	757,226(17)	4d ⁹ 2D _{3/2} -4d ⁸ (¹ D)5p 2P _{3/2} ^o	132.0599(22)	1	7.67 × 10 ⁹	0.03	E	2.00 × 10 ⁹
11	132.124(3)	756,865(17)	4d ⁹ 2D _{3/2} -4d ⁸ (¹ D)5p 2P _{1/2} ^o	132.124(3)	0	1.20 × 10 ¹⁰	0.14	D+	1.20 × 10 ¹⁰
60	132.158(3)	756,670(17)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)5p 2F _{7/2} ^o	132.158(3)	0	1.31 × 10 ¹¹	0.23	D+	1.07 × 10 ¹¹
37	132.334(3)	755,664(17)	4d ⁹ 2D _{3/2} -4d ⁸ (³ F)5p 4P _{5/2} ^o	132.3336(22)	0	7.60 × 10 ¹⁰	0.42	E	7.30 × 10 ¹⁰
57	132.536(3)	754,512(17)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)5p 4G _{5/2} ^o	132.5365(21)	−1	1.48 × 10 ¹¹	0.13	D+	1.24 × 10 ¹¹
5	132.708(3)	753,534(17)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)4f 4P _{5/2} ^o	132.7080(21)	0	1.30 × 10 ¹⁰	0.01	D	2.40 × 10 ¹⁰
7	132.741(3)	753,347(17)	4d ⁹ 2D _{3/2} -4d ⁸ (³ F)5p 4D _{3/2} ^o	132.741(3)	0	5.17 × 10 ⁹	0.04	D	6.00 × 10 ⁹
15	133.124(3)	751,179(17)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)5p 4D _{3/2} ^o	133.1235(21)	0	8.39 × 10 ⁹	0.25	D+	9.00 × 10 ⁹
9bl(Al V)	133.234(6)	750,560(30)	4d ⁹ 2D _{3/2} -4d ⁸ (³ F)5p 2D _{5/2} ^o	133.238(3)	−4	8.98 × 10 ⁹	0.03	D	6.00 × 10 ⁹
8	133.521(3)	748,946(17)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)4f 4P _{3/2} ^o	133.521(3)	0	1.71 × 10 ⁹	0	E	1.00 × 10 ⁹
3	133.738(3)	747,731(17)	4d ⁹ 2D _{3/2} -4d ⁸ (¹ D)5p 2F _{5/2} ^o	133.7383(22)	0	5.24 × 10 ⁷	0	E	8.00 × 10 ⁹
11	134.636(3)	742,743(17)	4d ⁹ 2D _{3/2} -4d ⁸ (³ F)5p 2D _{5/2} ^o	134.6366(22)	−1	1.93 × 10 ¹⁰	0.08	D	1.50 × 10 ¹⁰
8	134.662(3)	742,600(17)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)5p 4G _{7/2} ^o	134.662(3)	0	4.43 × 10 ⁹	0.06	D	4.00 × 10 ⁹
37	134.761(3)	742,054(17)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)5p 4F _{5/2} ^o	134.761(3)	0	2.45 × 10 ¹⁰	0.20	D+	2.70 × 10 ¹⁰
14	134.995(3)	740,768(16)	4d ⁹ 2D _{3/2} -4d ⁸ (³ F)5p 4P _{3/2} ^o	134.9961(22)	−1	1.46 × 10 ¹⁰	0.04	D	1.30 × 10 ¹⁰
4	135.092(3)	740,236(16)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)4f 4F _{3/2} ^o	135.0897(21)	2	1.76 × 10 ⁸	0	E	1.00 × 10 ⁹
8	135.230(3)	739,481(16)	4d ⁹ 2D _{3/2} -4d ⁸ (³ F)4f 2P _{3/2} ^o	135.230(3)	0	2.51 × 10 ⁹	0	E	4.00 × 10 ⁹
10	135.535(3)	737,817(16)	4d ⁹ 2D _{5/2} -4d ⁸ (¹ D)5p 2D _{3/2} ^o	135.5346(21)	0	3.44 × 10 ⁹	0.01	D	3.00 × 10 ⁹
15	135.616(3)	737,376(16)	4d ⁹ 2D _{3/2} -4d ⁸ (¹ G)4f 2D _{3/2} ^o	135.616(3)	0	1.88 × 10 ⁹	0	E	2.00 × 10 ⁹
8	135.788(3)	736,442(16)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)4f 4D _{5/2} ^o	135.788(3)	0	3.69 × 10 ⁹	0.01	D	5.00 × 10 ⁹
3	136.008(3)	735,251(16)	4d ⁹ 2D _{3/2} -4d ⁸ (³ F)5p 4G _{5/2} ^o	136.0074(22)	1	6.38 × 10 ⁷	0	E	1.00 × 10 ⁹
4	136.188(3)	734,279(16)	4d ⁹ 2D _{3/2} -4d ⁸ (³ F)4f 4P _{5/2} ^o	136.1880(22)	0	3.20 × 10 ⁸	0	E	1.00 × 10 ⁹
3	136.257(3)	733,907(16)	4d ⁹ 2D _{3/2} -4d ⁸ (³ F)5p 4D _{1/2} ^o	136.257(3)	0	1.14 × 10 ⁹	0	E	2.00 × 10 ⁹
7	136.625(3)	731,930(16)	4d ⁹ 2D _{3/2} -4d ⁸ (³ F)5p 4D _{3/2} ^o	136.6256(22)	−1	1.96 × 10 ⁹	0.02	D	2.00 × 10 ⁹
11	136.882(3)	730,556(16)	4d ⁹ 2D _{3/2} -4d ⁸ (¹ D)4f 2F _{5/2} ^o	136.882(3)	0	1.16 × 10 ⁹	0	E	3.00 × 10 ⁹
5	137.468(3)	727,442(16)	4d ⁹ 2D _{3/2} -4d ⁸ (³ F)4f 4D _{1/2} ^o	137.468(3)	0	3.50 × 10 ⁸	0	E	2.00 × 10 ⁹
7	137.808(3)	725,647(16)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)4f 4F _{7/2} ^o	137.808(3)	0	1.86 × 10 ⁹	0	E	2.00 × 10 ⁹
17	138.423(3)	722,423(16)	4d ⁹ 2D _{5/2} -4d ⁸ (³ F)5p 4D _{7/2} ^o	138.423(3)	0	2.03 × 10 ⁹	0.01	E	5.00 × 10 ⁹
4	138.695(3)	721,007(16)	4d ⁹ 2D _{3/2} -4d ⁸ (³ P)4f 4F _{3/2} ^o	138.6974(22)	−2	9.86 × 10 ⁸	0.01	E	1.00 × 10 ⁹
11	139.166(3)	718,566(15)	4d ⁹ 2D _{3/2} -4d ⁸ (¹ D)5p 2D _{3/2} ^o	139.1664(22)	0	5.72 × 10 ⁹	0.02	D	5.00 × 10 ⁹
7	139.993(3)	714,321(15)	4d ⁹ 2D _{3/2} -4d ⁸ (¹ G)4f 2P _{1/2} ^o	139.993(3)	0	2.73 × 10 ⁸	0	E	3.00 × 10 ⁹
32	145.719(3)	686,252(14)	4d ⁹ 2D _{5/2} -4p ⁵ 4d ¹⁰ 2P _{3/2} ^o	145.7201(21)	−1	4.14 × 10 ¹⁰	0.02	E	2.10 × 10 ¹⁰
5	149.928(3)	666,987(13)	4d ⁹ 2D _{3/2} -4p ⁵ 4d ¹⁰ 2P _{3/2} ^o	149.9268(23)	1	4.99 × 10 ⁹	0.02	D	3.00 × 10 ⁹

^a Observed relative intensities in arbitrary units, which were taken from Churilov et al. [3]. Character of the observed line: bl—blended by a close line; m—masked by a stronger neighboring line; t—tentative line; *—intensity is shared by multiple indicated transitions. ^b Observed and Ritz wavelengths (in Å) are given in a vacuum for all observed wavenumbers (σ) expressed in the cm^{−1} unit. The quantity given in parentheses is the uncertainty in the last digit. ^c Difference between the observed and Ritz wavelengths in mÅ, and 1 mÅ = 10^{−3} Å. ^d Weighted transition probability (gA -value) and absolute cancellation factor (CF) from the present HFR-B model (see Section Theoretical Calculations and Transition Probabilities). ^e Accuracy code of the gA -value given in the Theoretical Calculations and Transition Probabilities Section. ^f gA -value from Churilov et al. [3].

Theoretical Calculations and Transition Probabilities

Two atomic models with different configuration sets, given in Table 2, were used in this study. In both cases, Slater's parameters were scaled to 85% for the F^k , 80% for the G^k , and 70% for the R^k , while E_{av} and $\zeta_{n,\ell}$ were retained at 100% of their HFR values. A least-squares fitting (LSF) procedure was applied to reduce the difference between experimental and calculated energy levels of Cs XI. The resulting standard deviations (SDs), numbers of known levels, and numbers of fitted parameters (curly brackets) are listed in Table 2. Using these optimized parameters, improved gA -values for Cs XI were recalculated. The HFR-B model gA -values and their corresponding absolute cancellation factors (CFs) are presented in Table 1, while the LS percentage compositions of the observed levels are given in Table A1 of Appendix A.

Table 2. Configurations used in HFR models of Cs XI.

Even Parity	Odd Parity
Model: HFR-A	
$4p^6 4d^9$	$4p^6 4d^8 n\ell$ ($n \leq 6$, $\ell = p, f$)
$4p^6 4d^8 5s$	$4p^5 4d^{10}$
$4p^6 4d^7 5s^2$	
.....	
No. of Levels ^a = 2{2}	No. of Levels ^a = 75{13}
SD = 0 cm ⁻¹	SD = 396 cm ⁻¹
Model: HFR-B	
$4p^6 4d^9$	$4p^5 4d^{10}$
$4p^6 4d^8 n\ell$ ($n \leq 9$, $\ell = s, d, g$)	$4p^6 4d^8 n\ell$ ($n \leq 9$, $\ell = p, f$)
$4p^6 4d^7 n\ell^2$ ($n \leq 5$, $\ell = s-f$)	$4p^6 4d^7 5sn\ell$ ($n \leq 9$, $\ell = p, f$)
.....	
No. of Levels ^a = 2{2}	No. of Levels ^a = 75{13}
SD = 0 cm ⁻¹	SD = 417 cm ⁻¹

^a The total number of known levels and the number of free parameters in the LSF; the latter quantity is given in parentheses.

We compared the present LS percentage compositions with previously reported values given in Ref. [3]. A good agreement was found for most levels, except for seven levels of the $4d^8 5p$ and $4d^8 4f$ configurations. Those were the levels with $J = 7/2$ at 761,035, 774,701, and 802,607 cm⁻¹; two levels with $J = 3/2$ at 788,517 and 791,891 cm⁻¹; and two levels with $J = 1/2$ at 807,091 and 810,570 cm⁻¹. In the present work, these levels are fitted according to their second-largest LS percentage component. As noted by Churilov et al. [3], neither LS nor jj coupling adequately describes the levels in this spectrum. Furthermore, Churilov et al. [3] provided level designations that specify the level energy, the J value, and the predominant character of each level.

To evaluate the reliability of the calculated transition probabilities, two atomic models with different configuration sets, namely HFR-A and HFR-B, were employed in this work. The primary aim of using these two models was to compute the transition probabilities and compare the results to estimate the uncertainties associated with the calculations. The obtained values were also compared with those reported by Churilov et al. [3] for the $4d^9 - \{4d^8 5p + 4d^8 4f + 4p^5 4d^{10}\}$ transition arrays in Cs XI. In their study, Churilov et al. [3] applied the HFR method to determine the gA -values for Cs XI. The configuration set adopted in the present HFR-A model is identical to that used in the HFR calculations of Churilov et al. [3]. In contrast, the HFR-B model includes more interacting configurations, providing a more extensive description of configuration interaction (see Table 2). For comparison purposes, gA -values were converted into their corresponding S -values (line-strengths), and a quantitative comparison scheme based on the dS -values was used. The detailed procedure of the scheme is described in Ref. [7], and it has also been implemented in many previous works [8,9,13].

The comparison shows a gross disagreement within 183% for the HFR-A and HFR-B models. Indeed, the uncertainty for 31 lines with $CF \geq 0.10$ falls within 11%; the 45 lines with significant cancellation effects, $0 < CF < 0.10$, have an uncertainty within one order-of-magnitude; and the remaining lines with $CF = 0$ have poor accuracy within two orders-of-magnitude. This dependency has already been described in Ref. [10]; thus, in Cowan's code calculations, the computed gA -values with $CF < 0.10$ are generally treated as unreliable. Both these models were separately compared with S -values of Churilov et al. [3], and a similar pattern of disagreement was noticed. A similar approach, as described in

Refs. [9,13], was followed to perform several sets of calculations (as many as three) with varying parameters. The SD of these datasets was considered as an internal uncertainty estimator for each computed S-value or gA -value (see further details in Refs. [9,13]).

A final comparison was made between the HFR-B model and those values reported by Churilov et al. [3]. The gross disagreements between these two datasets were found to be within 300%. The 31 strong lines with $CF \geq 0.10$ disagreed by 30%, 38 lines with $0 < CF < 0.10$ showed about 40% disagreement, and the remaining strongly affected lines varied by more than 50%. For the final estimate, these uncertainties were combined in quadrature with their internal uncertainties. All the transitions listed in Table 1 were provided with their gA -values, CF-values, and accuracy codes. The final accuracy codes were D+ with an accuracy $\leq 40\%$, D with $\leq 50\%$, and the E types with $> 50\%$. All these uncertainties must be treated as statistical estimates due to the non-availability of accurate experimental radiative parameters or results from competing theories for the Cs XI spectrum.

4. Conclusions

In this work, the atomic data of Cs XI have been evaluated with the help of the extended HFR model. All known levels of Cs XI have been optimized using the LOPT scheme, and thereby the Ritz wavelengths with their uncertainties have been obtained. The inclusion of a more extensive set of configurations leads to the incorporation of improved valence–valence electron-correlation layers in the computation, which enhances the accuracy of the obtained gA -values. The refined dataset strengthens the reliability of Cs XI atomic data, which can be a valuable resource for spectroscopic studies and plasma modeling in laboratory and astrophysical applications.

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Appendix A. Optimization of Energy Levels

All available experimental wavelengths of Cs XI from Ref. [3], corresponding to the $4d^9 - \{4d^8 5p + 4d^8 4f + 4p^5 4d^{10}\}$ transition arrays, were compiled. The energies of the levels involved were derived from the measured transition wavelengths (with uncertainties) using the least-squares optimization code LOPT [14]. The required inputs to LOPT were the observed wavelength, its uncertainty, and the unique lower- and upper-level designations for each transition. A total of 103 lines were included to obtain optimized energies (with uncertainties) for 77 levels. All observed wavelengths were assigned their originally reported uncertainties of $0.003 \text{ \AA}$, and those were doubled for the affected lines. From these optimized levels, precise Ritz wavelengths with their uncertainties were determined for all observed transitions of the Cs XI spectrum.

A direct comparison of our results with those of Churilov et al. [3] shows some marginal changes in energy levels, with an average disagreement of 8%. It should be noted that Churilov et al. did not provide any uncertainties for the level values; however, in the Sansonetti [4] compilation, level uncertainties were presented for Cs XI (nearly 20 cm^{-1} for all levels), and those are found to be roughly estimated from the wavelength uncertainty. We retrieved the level uncertainties for all observed levels using the above-mentioned LOPT schemes, and those are given in the third column of Table A1.

Table A1. Optimized energy levels of Cs XI.

Level	Energy ^a (cm^{-1})	Unc. ^b (cm^{-1})	Leading Compositions ^c					ΔE_{O-C} ^d (cm^{-1})	No. of Lines ^e
			P1	P2	Comp2	P3	Comp3		
$4d^9 \text{ } ^2D_{5/2}$	0	0	99	...	...	...	...	0	28
$4d^9 \text{ } ^2D_{3/2}$	19,255	5	99	...	...	...	...	0	28
$4p^5 4d^{10} \text{ } ^2P_{3/2}^\circ$	686,247	10	70	23	$4d^8(^1G)4f \text{ } ^2P^\circ$	5	$4d^8(^1D)4f \text{ } ^2P^\circ$	−76	2
$4d^8(^3F)5p \text{ } ^4D_{7/2}^\circ$	722,423	16	64	17	$4d^8(^3F)5p \text{ } ^4F^\circ$	9	$4d^8(^3F)5p \text{ } ^2F^\circ$	−17	1
$4d^8(^3F)4f \text{ } ^4F_{7/2}^\circ$	725,647	16	41	32	$4d^8(^3P)4f \text{ } ^4F^\circ$	15	$4d^8(^3F)4f \text{ } ^4D^\circ$	−562	1
$4d^8(^1G)4f \text{ } ^2P_{1/2}^\circ$	733,576	16	46	18	$4d^8(^3F)4f \text{ } ^2P^\circ$	10	$4p^5 4d^{10} \text{ } ^2P^\circ$	7	1
$4d^8(^3F)4f \text{ } ^4D_{5/2}^\circ$	736,442	16	37	23	$4d^8(^3F)4f \text{ } ^4P^\circ$	11	$4d^8(^3P)4f \text{ } ^4F^\circ$	566	1
$4d^8(^1D)5p \text{ } ^2D_{3/2}^\circ$	737,819	12	23	15	$4d^8(^1D)5p \text{ } ^2P^\circ$	15	$4d^8(^3P)5p \text{ } ^4P^\circ$	−155	2
$4d^8(^3P)4f \text{ } ^4F_{3/2}^\circ$	740,249	12	27	19	$4d^8(^3F)4f \text{ } ^4P^\circ$	16	$4d^8(^3F)4f \text{ } ^4F^\circ$	25	2
$4d^8(^3F)5p \text{ } ^4F_{5/2}^\circ$	742,054	17	33	30	$4d^8(^3F)5p \text{ } ^4F^\circ$	22	$4d^8(^3F)5p \text{ } ^4G^\circ$	119	1
$4d^8(^3F)5p \text{ } ^4G_{7/2}^\circ$	742,600	17	64	16	$4d^8(^3F)5p \text{ } ^2G^\circ$	10	$4d^8(^3F)5p \text{ } ^4F^\circ$	628	1
$4d^8(^3F)4f \text{ } ^4D_{1/2}^\circ$	746,697	17	70	8	$4d^8(^1G)4f \text{ } ^2P^\circ$	7	$4d^8(^3F)4f \text{ } ^4P^\circ$	332	1
$4d^8(^3F)4f \text{ } ^4P_{3/2}^\circ$	748,946	17	28	14	$4d^8(^1G)4f \text{ } ^2D^\circ$	13	$4d^8(^3F)4f \text{ } ^4S^\circ$	77	1
$4d^8(^1D)4f \text{ } ^2F_{5/2}^\circ$	749,811	17	30	21	$4d^8(^3F)4f \text{ } ^4P^\circ$	10	$4d^8(^3F)4f \text{ } ^4F^\circ$	−233	1
$4d^8(^3F)5p \text{ } ^4D_{3/2}^\circ$	751,182	12	33	29	$4d^8(^3P)5p \text{ } ^4D^\circ$	16	$4d^8(^3P)5p \text{ } ^4P^\circ$	−634	2
$4d^8(^3P)5p \text{ } ^4D_{1/2}^\circ$	753,162	17	28	17	$4d^8(^3F)5p \text{ } ^4D^\circ$	12	$4d^8(^3P)5p \text{ } ^2P^\circ$	120	1
$4d^8(^3F)4f \text{ } ^4P_{5/2}^\circ$	753,534	12	37	17	$4d^8(^3F)4f \text{ } ^4D^\circ$	8	$4d^8(^1D)4f \text{ } ^2D^\circ$	191	2
$4d^8(^3F)5p \text{ } ^4G_{5/2}^\circ$	754,509	12	29	18	$4d^8(^3F)5p \text{ } ^2D^\circ$	13	$4d^8(^3P)5p \text{ } ^4P^\circ$	−106	2
$4d^8(^1G)4f \text{ } ^2D_{3/2}^\circ$	756,631	17	38	17	$4d^8(^1G)4f \text{ } ^2D^\circ$	9	$4d^8(^3F)4f \text{ } ^4S^\circ$	458	1
$4d^8(^3F)5p \text{ } ^2F_{7/2}^\circ$	756,670	17	55	20	$4d^8(^3F)5p \text{ } ^4D^\circ$	11	$4d^8(^3F)5p \text{ } ^4F^\circ$	638	1
$4d^8(^3F)4f \text{ } ^4G_{7/2}^\circ$	758,432	17	39	21	$4d^8(^3P)4f \text{ } ^4G^\circ$	17	$4d^8(^1D)4f \text{ } ^2F^\circ$	144	1
$4d^8(^3F)4f \text{ } ^2P_{3/2}^\circ$	758,736	17	37	25	$4d^8(^1G)4f \text{ } ^2P^\circ$	11	$4d^8(^1D)4f \text{ } ^2D^\circ$	40	1
$4d^8(^3P)5p \text{ } ^4P_{3/2}^\circ$	760,017	12	25	12	$4d^8(^3F)5p \text{ } ^4D^\circ$	11	$4d^8(^3P)5p \text{ } ^4D^\circ$	−243	2
$4d^8(^1D)4f \text{ } ^2F_{7/2}^\circ$	761,035	17	21	19	$4d^8(^1D)4f \text{ } ^2F^\circ$	8	$4d^8(^3P)4f \text{ } ^4F^\circ$	−9	1
$4d^8(^3F)5p \text{ } ^2D_{5/2}^\circ$	761,995	12	55	12	$4d^8(^3F)5p \text{ } ^4D^\circ$	10	$4d^8(^3P)5p \text{ } ^4P^\circ$	37	2
$4d^8(^3P)4f \text{ } ^4G_{5/2}^\circ$	766,430	40	21	14	$4d^8(^3P)4f \text{ } ^4G^\circ$	12	$4d^8(^1D)5p \text{ } ^2F^\circ$	−844	1
$4d^8(^1D)5p \text{ } ^2F_{5/2}^\circ$	766,984	12	20	15	$4d^8(^1D)5p \text{ } ^2F^\circ$	13	$4d^8(^3P)4f \text{ } ^4G^\circ$	491	2
$4d^8(^1G)5p \text{ } ^2F_{7/2}^\circ$	767,530	50	37	24	$4d^8(^1G)5p \text{ } ^2F^\circ$	19	$4d^8(^3F)5p \text{ } ^2G^\circ$	373	1
$4d^8(^3P)5p \text{ } ^2D_{5/2}^\circ$	769,793	16	27	27	$4d^8(^1D)5p \text{ } ^2D^\circ$	14	$4d^8(^3P)5p \text{ } ^2D^\circ$	75	2
$4d^8(^3F)5p \text{ } ^4F_{7/2}^\circ$	772,153	18	45	21	$4d^8(^1G)5p \text{ } ^2F^\circ$	13	$4d^8(^3F)5p \text{ } ^4G^\circ$	547	1
$4d^8(^3P)5p \text{ } ^4D_{3/2}^\circ$	772,600	17	22	20	$4d^8(^3F)5p \text{ } ^4D^\circ$	19	$4d^8(^3P)5p \text{ } ^4D^\circ$	−458	2
$4d^8(^3P)4f \text{ } ^4F_{7/2}^\circ$	773,635	18	29	21	$4d^8(^3F)4f \text{ } ^4F^\circ$	11	$4d^8(^3F)4f \text{ } ^4H^\circ$	−111	1
$4d^8(^3F)5p \text{ } ^2G_{7/2}^\circ$	774,701	18	22	19	$4d^8(^3F)5p \text{ } ^2G^\circ$	17	$4d^8(^3F)5p \text{ } ^2F^\circ$	430	1
$4d^8(^3P)5p \text{ } ^4P_{5/2}^\circ$	774,921	13	17	16	$4d^8(^1D)5p \text{ } ^2F^\circ$	15	$4d^8(^1D)5p \text{ } ^2D^\circ$	−36	2
$4d^8(^3F)4f \text{ } ^4F_{5/2}^\circ$	775,332	18	34	21	$4d^8(^3P)4f \text{ } ^4F^\circ$	12	$4d^8(^1D)4f \text{ } ^2D^\circ$	−110	1
$4d^8(^1D)5p \text{ } ^2P_{1/2}^\circ$	776,119	18	31	29	$4d^8(^3P)5p \text{ } ^4D^\circ$	21	$4d^8(^3F)5p \text{ } ^4D^\circ$	−201	1
$4d^8(^1D)5p \text{ } ^2P_{3/2}^\circ$	776,487	13	35	33	$4d^8(^3F)5p \text{ } ^4F^\circ$	14	$4d^8(^3P)5p \text{ } ^2P^\circ$	182	2
$4d^8(^3P)4f \text{ } ^2F_{7/2}^\circ$	777,418	18	28	25	$4d^8(^1G)4f \text{ } ^2F^\circ$	25	$4d^8(^3P)4f \text{ } ^2F^\circ$	−379	1

Table A1. Cont.

Level	Energy ^a (cm ^{−1})	Unc. ^b (cm ^{−1})	Leading Compositions ^c					ΔE_{O-C} ^d (cm ^{−1})	No. of Lines ^e
			P1	P2	Comp2	P3	Comp3		
4d ⁸ (³ P)4f ⁴ D _{1/2} ^o	779,867	18	34	22	4d ⁸ (¹ D)4f ² P ^o	20	4d ⁸ (³ F)4f ² S ^o	387	1
4d ⁸ (³ F)5p ⁴ D _{1/2} ^o	782,369	18	41	35	4d ⁸ (³ P)5p ² P ^o	9	4d ⁸ (¹ D)5p ² P ^o	−102	1
4d ⁸ (³ F)5p ² D _{3/2} ^o	782,796	13	53	17	4d ⁸ (¹ D)5p ² D ^o	9	4d ⁸ (³ F)5p ⁴ D ^o	−97	2
4d ⁸ (³ F)5p ² F _{5/2} ^o	783,469	16	34	18	4d ⁸ (³ P)5p ⁴ P ^o	12	4d ⁸ (³ P)5p ² D ^o	99	2
4d ⁸ (³ P)5p ⁴ D _{7/2} ^o	784,972	18	50	27	4d ⁸ (³ F)5p ² G ^o	11	4d ⁸ (³ F)5p ⁴ G ^o	446	1
4d ⁸ (³ P)4f ⁴ D _{3/2} ^o	786,853	17	62	12	4d ⁸ (¹ D)4f ² P ^o	...	...	−572	2
4d ⁸ (¹ D)4f ² G _{7/2} ^o	787,724	19	33	17	4d ⁸ (¹ G)4f ² G ^o	10	4d ⁸ (³ F)4f ⁴ H ^o	11	1
4d ⁸ (³ P)5p ² P _{3/2} ^o	788,517	13	28	25	4d ⁸ (³ P)5p ² P ^o	13	4d ⁸ (³ F)5p ⁴ D ^o	−354	2
4d ⁸ (¹ G)4f ² F _{5/2} ^o	791,122	19	32	15	4d ⁸ (¹ G)4f ² F ^o	8	4d ⁸ (¹ D)5p ² D ^o	−221	1
4d ⁸ (³ F)4f ² P _{1/2} ^o	791,569	19	43	27	4d ⁸ (³ F)4f ² P ^o	21	4p ⁵ 4d ¹⁰ ² P ^o	−84	1
4d ⁸ (³ P)5p ⁴ S _{3/2} ^o	791,891	18	17	16	4d ⁸ (³ P)5p ⁴ S ^o	15	4d ⁸ (³ P)5p ² P ^o	−427	2
4d ⁸ (¹ G)5p ² F _{5/2} ^o	792,203	13	28	19	4d ⁸ (¹ G)4f ² F ^o	15	4d ⁸ (³ P)4f ⁴ D ^o	−841	2
4d ⁸ (³ P)5p ⁴ D _{5/2} ^o	795,337	13	26	20	4d ⁸ (³ P)5p ² D ^o	11	4d ⁸ (³ P)4f ⁴ D ^o	338	2
4d ⁸ (³ P)4f ⁴ G _{7/2} ^o	796,235	19	22	14	4d ⁸ (¹ G)4f ² F ^o	14	4d ⁸ (³ P)4f ⁴ G ^o	−596	1
4d ⁸ (³ P)4f ⁴ D _{5/2} ^o	796,400	19	32	20	4d ⁸ (³ P)5p ⁴ D ^o	11	4d ⁸ (³ P)5p ² D ^o	−6	1
4d ⁸ (³ P)5p ² S _{1/2} ^o	796,509	19	61	11	4d ⁸ (³ P)5p ⁴ P ^o	11	4d ⁸ (³ P)5p ² P ^o	−968	1
4d ⁸ (¹ D)4f ² D _{3/2} ^o	797,816	19	27	14	4d ⁸ (¹ G)4f ² D ^o	13	4d ⁸ (³ F)4f ⁴ F ^o	467	1
4d ⁸ (³ P)5p ² D _{3/2} ^o	798,774	13	37	8	4d ⁸ (¹ D)5p ² P ^o	7	4d ⁸ (¹ D)5p ² D ^o	−392	2
4d ⁸ (³ P)5p ⁴ S _{3/2} ^o	801,825	19	58	10	4d ⁸ (³ P)5p ² P ^o	9	4d ⁸ (¹ D)5p ² P ^o	−597	1
4d ⁸ (¹ G)5p ⁴ G _{7/2} ^o	801,925	19	26	16	4d ⁸ (¹ D)5p ² F ^o	11	4d ⁸ (³ P)4f ⁴ G ^o	297	1
4d ⁸ (³ F)4f ⁴ G _{5/2} ^o	801,995	19	31	25	4d ⁸ (³ P)4f ⁴ G ^o	17	4d ⁸ (¹ G)4f ² F ^o	−26	1
4d ⁸ (¹ D)5p ² F _{7/2} ^o	802,607	19	16	16	4d ⁸ (³ F)4f ⁴ G ^o	14	4d ⁸ (¹ D)5p ² F ^o	−88	1
4d ⁸ (¹ D)5p ² D _{5/2} ^o	804,057	14	24	22	4d ⁸ (¹ G)5p ² F ^o	16	4d ⁸ (³ F)5p ² F ^o	40	2
4d ⁸ (¹ D)4f ² P _{3/2} ^o	805,041	19	29	23	4d ⁸ (³ P)4f ⁴ D ^o	14	4d ⁸ (¹ D)4f ² D ^o	66	1
4d ⁸ (¹ G)5p ⁴ G _{7/2} ^o	805,997	19	42	21	4d ⁸ (¹ D)5p ² F ^o	16	4d ⁸ (¹ G)5p ² F ^o	257	1
4d ⁸ (¹ G)4f ² F _{7/2} ^o	807,050	20	29	19	4d ⁸ (³ F)4f ² F ^o	18	4d ⁸ (³ P)4f ² F ^o	159	1
4d ⁸ (³ P)5p ² P _{1/2} ^o	807,091	19	26	21	4d ⁸ (³ P)5p ² P ^o	13	4d ⁸ (¹ D)5p ² P ^o	−131	1
4d ⁸ (¹ D)4f ² P _{1/2} ^o	810,570	40	22	21	4d ⁸ (¹ D)4f ² P ^o	16	4d ⁸ (³ P)5p ² P ^o	851	1
4d ⁸ (³ P)4f ² D _{3/2} ^o	820,688	20	60	21	4d ⁸ (¹ D)4f ² P ^o	12	4d ⁸ (³ F)4f ² D ^o	−445	1
4d ⁸ (¹ S)5p ² P _{1/2} ^o	827,120	20	71	11	4d ⁸ (¹ D)5p ² P ^o	6	4d ⁸ (³ P)5p ⁴ D ^o	138	1
4d ⁸ (¹ S)4f ² F _{7/2} ^o	850,224	22	74	10	4d ⁸ (¹ D)4f ² F ^o	6	4d ⁸ (³ P)4f ² G ^o	115	1
4d ⁸ (¹ S)4f ² F _{5/2} ^o	850,392	15	67	12	4d ⁸ (¹ D)4f ² F ^o	7	4d ⁸ (³ P)4f ² D ^o	402	2
4d ⁸ (¹ S)5p ² P _{3/2} ^o	851,209	15	84	4	4d ⁸ (³ P)5p ² D ^o	...	...	513	2
4d ⁸ (³ F)4f ² D _{5/2} ^o	935,255	18	57	23	4d ⁸ (¹ G)4f ² D ^o	9	4d ⁸ (¹ D)4f ² D ^o	580	2
4d ⁸ (³ F)4f ² F _{7/2} ^o	941,680	30	38	34	4d ⁸ (³ P)4f ² F ^o	14	4d ⁸ (¹ D)4f ² F ^o	−494	1
4d ⁸ (¹ G)4f ² P _{3/2} ^o	943,093	19	32	24	4d ⁸ (³ F)4f ² P ^o	16	4p ⁵ 4d ¹⁰ ² P ^o	325	2
4d ⁸ (³ F)4f ² D _{3/2} ^o	952,557	19	45	16	4d ⁸ (¹ G)4f ² D ^o	10	4d ⁸ (¹ G)4f ² P ^o	112	2
4d ⁸ (³ F)4f ² F _{5/2} ^o	960,758	24	37	32	4d ⁸ (³ P)4f ² F ^o	15	4d ⁸ (¹ D)4f ² F ^o	−302	2
4p ⁵ 4d ¹⁰ ² P _{1/2} ^o	986,620	30	40	32	4d ⁸ (¹ G)4f ² P ^o	24	4d ⁸ (³ F)4f ² P ^o	−168	1

^a Optimized energies from the LOPT code [14]. ^b Uncertainty from the LOPT code. ^c LS-coupling compositions obtained from parametric least-squares fitting with Cowan's codes. P1 denotes the first percentage of the configuration and term listed in the first column, and the remaining components are given with their corresponding percentages. ^d Difference between observed and calculated energies from the parametric least-squares fitting. ^e Number of observed lines determining the level in the level optimization.

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