Indian J. Phys. **81** (7) 705-715 (2007)

Electric dipole transitions for some excited states in neutral silver

Leyla Özdemir*, Betül Karaçoban and Güldem Ürer

Sakarya University, Department of Physics, 54140, Sakarya, Turkey

E-mail lozdemir@sakarya.edu tr

Received 11 May 2007, accepted 28 June 2007

Abstract : For some excited levels, transition energies, wavelengths, oscillator strengths and transition probabilities calculations in neutral silver (Ag I) have been calculated within the framework multiconfiguration Hartree-Fock approximation with relativistic corrections (Breit-Pauli Hamiltonian). The wavefunctions and some relativistic corrections have been obtained using MCHF + BP atomic package Comparisons with other some calculations and experiments are presented

Keywords : MCHF method, relativistic corrections, wavelengths, oscillator strengths, transition probabilities

PACS Nos. : 31.15 Ne, 31 25.Jf, 31.30 Jv, 31 30 -i, 32 70 Cs

1. Introduction

Such characteristics as energies, oscillator strengths, wavelengths, transition probabilities and rate coefficients of different elementary processes, occurring in laboratory and astrophysical plasmas, are of highly interest in investigations of plasma-kinetic problems, development of new laboratory ion and atom sources, plasma spectroscopy and modelling and other. Recently, data for these characteristics including theoretical computations, laboratory experiments and astronomical measurements for most atoms were compiled. In this work, we presented transition energies, wavelengths, weighted oscillator strengths and transition probabilities for electric dipole transition in neutral silver (Ag I) using multiconfiguration Hartree-Fock approximation and Breit-Pauli Hamiltonian for relativistic corrections development by Fischer *et al* [1].

Relativistic oscillator strengths were calculated with a semiempirical method for transitions in the principal, sharp and diffuse series of Ag I [2]. A model potential for including correlation effects was used to computations of oscillator strengths for the lowest transitions in Ag I [3]. The influence of core polarization effects on oscillator

*Corresponding Author

strengths was discussed [4]. Ionization energies and oscillator strengths for transitions in principal, sharp and diffuse series of neutral silver spectra were obtained using relativistic single-configuration Hartree-Fock method [5]. Local approximations to interelectronic exchange were tested by frozen-core relativistic Hartree-Fock calculations by Migdalek and Baylis [6–8], and Migdalek and Banasińska [9]. Calculations of energies and oscillator strengths for Ag I using single-and multiparameter model potentials were presented [10]. The ability of the relativistic *ab initio* model potential approach with explicit local exchange to produce oscillator strengths in agreement with Dirac-Fock data was tested for some transitions in silver by Migdalek and Garmulewicz [11]. Excitation energies and oscillator strengths for electric dipole transitions between low-lying states in the silver isoelectronic sequence were studied using relativistic Hartree-Fock wavefunctions by Cheng and Kim [12]. Chou and Johnson performed relativistic many-body perturbation theory calculations through third order to study amplitudes of the principal transitions in silverlike ions [13]. Energies of $5l_j$ (l = s,p,d,f,g) and $4f_j$ states were obtained using relativistic many-body perturbation theory and oscillator strengths, transition rates and lifetimes were calculated for the $5l_j - 5l'_{j'}$ and $4f_j - 5l_{j'}$ electric dipole transitions by Safronova *et al* [14].

The corrections and extension of the series of the silver was given by Blair [15]. The absorption spectra of silver were investigated by Paul [16]. Shenstone analyzed the arc spectrum of silver [17]. Optical cross sections corresponding to spectral line of silver were determined by Hinnov and Kohn [18]. Oscillator strengths of the resonance doublets of Ag I were measured by Penkin and Slavenas [19]. Lawrence *et al* measured f values of thirty-eight lines in the spectra of neutral Ag by the atomic-beam technique [20]. Transition rates of atomic transitions of silver were determined by Moise [21]. Lifetime measurement of the first excited states in neutral atoms belonging to first, second, and third group of the periodic system were performed by the beam-foil technique by Andersen *et al* [22]. The mean life of $5p\,^2P_{3/2}$ resonance level in Ag I was measured by Klose [23]. Radiative lifetimes of resonance levels of Ag I using dye laser excitations were measured by Selter and Kunze [24]. Plekhotkina compiled systematically experimental and theoretical study of such radiative constants as the oscillator strengths and probability of spontaneous transitions exist for the silver atom [25]. Verner *et al* presented atomic data for absorption lines from the ground level [26]. In the Ag I sequences some spectral lines were identified by Sugar [27]. The lifetime measurements in the sequences of $^2S_{1/2}$ and $^2D_{3/2}$ states for the alkali-like $4d^{10}$ ns,nd configurations of neutral silver were performed by Zhankui *et al* [28]. Relativistic oscillator strengths for transitions in the principal spectral series of the silver isoelectronic sequence were reported by Martin *et al* [29]. The radiative lifetimes of the $7p\,^2P_{3/2,1/2}$ states of silver were measured by Bengtsson [30]. Carlsson *et al* measured the lifetimes of the silver $5p\,^2P$ states with high accuracy time-resolved laser spectroscopy [31].

In this paper, we considered two interesting subjects in the theoretical study of atomic structure : one deals with the electron correlation and the other deals with the relativistic effects It is used the multiconfiguration Hartree-Fock approximation within the framework Breit-Pauli relativistic corrections for neutral silver (Ag I) And, transition energies, wavelengths, weighted oscillator strengths and transition probabilities have been obtained for electric dipole transitions between *ns* (n = 5, 6, 7), *nd* (n = 5, 6) and *5g* (for even-parity) and *5p, 6p, 4f* and *5f* (for odd-parity) outside the core [Kr]$4d^{10}$ states in neutral silver using the MCHF atomic-structure package [32] In particular it is selected highly excited states which are not in literature besides lower states Because, these data may be essential inputs to a wide range of problems are encountered in many areas of science, such as astrophysics, plasma physics and atmospheric and environmental research

2. Method of calculation

The multiconfiguration Hartree-Fock (MCHF) approximation is a Configuration Interaction (CI) method [1] In this approximation the MCHF Hamiltonian is used for obtaining the best radial functions for the set of non-relativistic energies of the interacting terms The wavefunction is

$$\Psi(\gamma LS) = \sum_{i=1}^{M} c_i \Phi(\gamma_i LS), \quad \sum_{i=1}^{M} c_i^2 = 1 \tag{1}$$

Where $\Phi(\gamma_i LS)$, γ_i and c_i represent configuration state function in LS coupling, configurations and mixing coefficients of configurations, respectively The non-relativistic energy expansion becomes

$$\varepsilon(\gamma LS) = \sum_{i=1}^{M} \sum_{j=1}^{M} c_i c_j \langle \Phi(\gamma_i LS) | H | \Phi(\gamma_j LS) \rangle \tag{2}$$

The Breit-Pauli Hamiltonian includes relativistic effects This Hamiltonian can be written

$$H_{BP} = H_{NR} + H_{RS} + H_{FS}, \tag{3}$$

where H_{NR} is the non-relativistic many-electron Hamiltonian and H_{RS} is the relativistic shift operator including mass correction, one- and two-body Darwin terms, spin-spin contact term and orbit-orbit term,

$$H_{MC} = -\frac{\alpha^2}{8} \sum_{i=1}^{N} (\nabla_i^2)^{\dagger} \nabla_i^2, \tag{4}$$

$$H_{D1} = -\frac{\alpha^2 Z}{8} \sum_{i=1}^{N} (\nabla_i^2) \left(\frac{1}{r_i} \right), \tag{5}$$

$$H_{D2} = \frac{\alpha^2}{4} \sum_{i<j}^{N} (\nabla_i^2) \left(\frac{1}{r_{ij}} \right), \tag{6}$$

$$H_{SSO} = -\frac{8\pi\alpha^2}{3} \sum_{i<j}^{N} (s_i \cdot s_j) \delta(r_i - r_j), \tag{7}$$

$$H_{OO} = -\frac{\alpha^2}{2}\sum_{i<j}^{N}\left[\frac{p_i \cdot p_j}{r_{ij}} + \frac{r_{ij}(r_{ij} \cdot p_i)p_j}{r_{ij}^3}\right]. \tag{8}$$

Fine-structure Hamiltonian H_{FS} consist of the spin-orbit, spin-other-orbit and spin-spin terms.

$$H_{SO} = \frac{\alpha^2 Z}{2}\sum^{N}\left(\frac{1}{r^3}\right) l_i \cdot s_i, \tag{9}$$

$$H_{SOO} = -\frac{\alpha^2}{2}\sum_{i<j}^{N}\left(\frac{r_{ij} \times p_i}{r_{ij}^3}\right)(s_i + 2s_j), \tag{10}$$

$$H_{SS} = \alpha^2\sum_{i<j}^{N}\frac{1}{r_{ij}^3}\left[s_i \cdot s_j - 3\frac{(s_i \cdot r_{ij})(s_j \cdot r_{ij})}{r_{ij}^2}\right] \tag{11}$$

The Breit-Pauli wavefunctions are obtained as linear combinations

$$\Psi(\gamma JM_J) = \sum_{i=1}^{\cdots} c_i \Phi(\gamma_i L_i S_i JM_J). \tag{12}$$

Where $\Phi(\gamma LSMJ_J)$ are LSJ coupled configuration state functions (CSFs), that is

$$\Phi(\gamma LSJM_J) = \sum_{M_L M_S}\langle LM_L SM_S \mid LSJM_J\rangle \Phi(\gamma LM_L SM_S). \tag{13}$$

The orbital L_i and the spin S_i angular momenta are coupled to give the total angular momentum J. The mixing (or expansion) coefficients c_i are obtained by diagonalizing the Breit-Pauli Hamiltonian. The radial functions building the CSFs are taken from a previous non-relativistic MCHF calculation and only the expansion coefficients are optimized.

The matrix eigenvalue problem becomes

$$\mathbf{Hc} = E\mathbf{c}. \tag{14}$$

Where H is the Hamiltonian matrix with elements

$$H_{ij} = \langle \gamma_i L_i S_i JM_J | H_{BP} | \gamma_j L_j S_j JM_J \rangle \tag{15}$$

and $c = (c_1 \ldots\ldots, c_M)^t$ the column vector of the expansion coefficients. The Breit-Pauli Hamiltonian is a first-order perturbation correction to the non-relativistic Hamiltonian.

The transition rate (or probability) for emission transition is

$$A^{\pi k}(\gamma' J', \gamma J) = 2C_k\left[\alpha\left(E_{\gamma' J'} - E_{\gamma J}\right)\right]^{2k+1}\frac{S^{\pi k}(\gamma' J', \gamma J)}{g_{J'}} \tag{16}$$

where, C_k is $C_k = (2k + 1)(k + 1)/k((2k + 1)!!)^2$, and $S^{\pi k}(\gamma' J', \gamma J)$, k and $g_{J'}$ denote line strength, rank of a spherical tensor operator and statistical weight of the upper level, namely $g_{J'} = 2J' + 1$, respectively. The oscillator strength may refer to transition either in absorption or emission. For absorption weighted oscillator strength is,

$$gf^{\pi k}(\gamma J,\gamma' J') = \frac{1}{\alpha} C_k \left[\alpha(E_{\gamma' J'} - E_{\gamma J})\right]^{2k-1} S^{\pi k}(\gamma J,\gamma' J'). \tag{17}$$

Most experiments yield the lifetime of the upper level because of easy measuring. In this case the sum over multipole transitions to all lower lying levels must be taken. The lifetime of upper level is

$$t_{\gamma' J'} = \frac{1}{\sum_{\pi k,\gamma J} A^{\pi k}(\gamma' J',\gamma J)}. \tag{18}$$

The strongest transitions are the electric dipole (E1) transitions. If π and π' denote the parity of two levels, then electric multipole operator is in the form

$$E^{(k)} : \frac{\pi'}{\pi} = (-1)^k. \tag{19}$$

Where k is angular momentum of the emitted or absorbed photon. The electric dipole operator (E1) combines states of different parity.

3. Results and discussion

In this work, transition energies, ΔE (cm^{-1}), wavelengths, λ (Å), weighted oscillator strengths, *gf*, and transition probabilities (or rates), A_{kl} (s^{-1}), have been obtained for electric dipole transitions (E1) between *ns* (n = 5, 6, 7), *nd* (n = 5, 6) and *5g* for even-parity, and *5p*, *6p*, *4f and 5f* for odd-parity outside the core [Kr]$4d^{10}$ states in neutral silver (Ag I, Z = 47) using the MCHF atomic-structure package [32]. We obtained the 42 possible E1 transitions for selected these levels. Results obtained are presented and compared with other works in Table 1. Frequently, the *5s-5p, 5s-6p, 5p-6d, 5p-6s* and *5p-7s* transitions had been studied in literature. We also added transitions for new and some highly excited levels. In table, the number in brackets represents the power of 10. In addition, only odd-parity states are indicated by "0" superscript. Besides, for simplicity, we used n^2S, ^2P, ^2D, ^2F, ^2G instead of nl ^2S, ^2P, ^2D, ^2F, ^2G. Some values of other works in columns for *gf and* A_{kl} are converted from *f* and log(*gf*), and lifetime, respectively, for comparing. These cases are defined in references below the table with superscript lowercase letter.

Except for some transitions an agreement is seen when our results are compared with other works. Especially calculation results for *5s-5p, 5p-5d, 5p-6d, 4f-5g* and *5p-7s* transitions are in very good agreement with other results. In conclusion, we reported new and large-scale data including valence correlation and Breit-Pauli relativistic corrections in neutral silver. Data on atomic radiative characteristics and elementary processes occurring in astrophysical and laboratory plasma are important. In this paper, it is reported energies, transition probabilities, wavelengths and oscillator strengths for electric dipole transition in Ag I. We hope that a large number of results obtained will be useful for some research and, particularly, astrophysical applications.

Table 1. Transition energies, ΔE (cm^{-1}), wavelengths, λ(Å), weighted oscillator strengths, gf, and transition probabilities, A_{ki}(s^{-1}), for electric dipole (E1) transitions between even- and odd- parity states in Ag I

States				ΔE		λ		gf		A_{ki}	
Initial	J_i	Final	J_f	This Work	Other Works	This Work	Other Works	This Work	Other Works	This Work	Other Works
5^2S	1/2	$5\,^2P^o$	3/2	24551 61	30472 71[a], 30472 703[b]	4073 05	3280 679[a], 3280 680[b], 4025[g], 3455[h], 3280 66[i], 3280 680[j] 3281[k], 3280 68[l], 3280 68[m], 3280 68[n], 3281[o], 3280 7[p] 3281 627[r], 3282[t], 3282[u]	1 48816	0 89125[a] 2688[c1], 1 784[c2], 3 288[d1], 1 652[d2], 3 288[e1], 1 776[e2] 1 848[f2], 1 78[f1], 2 664[g], 2 0536[h], 1 56[k] 2 054[l], 1 8[m], 1 836[n], 2 0[o], 1 76[p] 1 808[r] 1 92[t]	1 49586(8)	1 380(8)[a], 1 42(8)[b] 1 36986(8)[g], 1 4347(8)[h] 1 424(8)[n], 1 53(8)[o] 1 37(8)[p], 1 48809(8)[t], 1 49253(8)[w]
5^2S	1/2	5^2P^o	1/2	24051 95	29552 050[a], 29552 061[b]	4157 67	3382 889[a], 3382 887[b], 4126[g], 3562[h], 3382 86[i], 3382 893[j], 3383[k], 3382 89[l], 3382 89[m], 3382 89[n], 3283 836[r], 3384[t], 3384[u]	7 27691(−1)	4 1975(−1)[a] 6 58(−1)[c1], 4 30(−1)[c2], 8 06(−1)[d1], 3 96(−1)[d2], 4 26(−1)[e2], 8 06(−1)[e1], 4 46(−1)[f2], 4 28(−1)[f1], 6 58(−1)[g], 4 994(−1)[h], 0 44[k], 4 94(−1)[l], 4 3(−1)[m], 3 92(−1)[n], 4 20(−1)[r] 4 60(−1)[t]	1 40397(8)	1 223(8)[a], 1 35(8)[b], 1 28205(8)[g], 1 3123(8)[h], 1 143(8)[n], 1 3495(8)[t], 1 333(8)[w]

Table 1. *(Contd)*

States				ΔE		λ		gf		A_{ki}	
Initial	J_i	Final	J_f	This Work	Other Works	This Work	Other Works	This Work	Other Works	This Work	Other Works
5^2P^o	1/2	5^2D	3/2	22896 44	19191 95[a], 19191 908[b]	4367 49	5209 068[a], 5209 078[b], 6741[g], 5209 04[i], 5209 078[l], 5209 07[q], 5211[u]	0 0788306	1 1168[a], 2 408[c1], 2 232[c2], 3 528[d1], 2 248[d2], 2 2[e2], 3 582[e1], 2 256[f1], 2 332[f2], 2 844[g], 2 3092[h], 2 52[s]	0 689145(7)	6 860(7)[a], 7 5(7)[b], 7 75(7)[q]
5^2P^o	3/2	5^2D	5/2	22401 60	18291 51[a], 18291 516[b],	4463 97	5465 498[a], 5465 497[b], 6998[g], 5465 47[i], 5465 503[l], 5465 49[q], 5476[u]	0 138252	2 118[a], 3 18[c2] 3 414[c1], 4 92[d1], 3 192[d2], 4 92[e1], 3 144[e2], 3 252[f1], 3 33[f2], 4 014[g] 3 2946[h]	0 771291(7)	7 879(7)[a], 8 6(7)[b], 7 46(7)[q]
5^2P^o	3/2	5^2D	3/2	22396 78	18271 29[a],	4464 93	5471 547[a], 5471 52[i], 5471 547[l]	0 15425(−1)	0 2365[a], 0 254[c1], 0 2368[c2], 0 364[d1], 0 24[d2], 0 366[e1], 0 2344[e2], 0 244[f1], 0 224[f2] 0 2452[h], 0 244[s]	0 129031(7)	1 317(7)[a]
5^2P^o	1/2	6^2D	3/2	24217 59	24651 08[a],	4129 23	4055 472[a], 4055 27[i], 4055 476[l], 4055 46[q]	0 42944(−1)	2 2803(−1)[a] 5 32(−1)[c1], 4 56(−1)[c2] 6 2(−1)[e1] 4 48(−1)[e2]	0 420002(7)	2 311(7)[a], 3 31(7)[q],

Table 1. *(Contd)*

States				ΔE		λ		gf		A_{ki}	
Initial	J_i	Final	J_f	This Work	Other Works	This Work	Other Works	This Work	Other Works	This Work	Other Works
5^2P^o	3/2	6^2D	5/2	23721 30	23740 89[a]	4251 62	4210 956[a],	0 76404(−1)	4 159(−1)[a],	0 477954(7)	2 606(7)[a],
							4210 94[i],		7 14(−1)[c1],		3 22(7)[q]
							4210 960[j],		6 24(−1)[c2],		
							4210 94[q]		8 22(−1)[e1],		
									6 06(−1)[e2]		
5^2P^o	3/2	6^2D	3/2	23717 94	23730 42[a]	4216 22	4212 814[a],	0 84166(−2)	4 645(−2)[a],	0 789542(6)	4 362(6)[a]
							4212 68[i]		5 32(−2)[c1]		
							4212 817[j]		4 64(−2)[c2],		
							4212 68[q]		6 08(−2)[e1],		
									4 48(−2)[e2]		
5^2S	1/2	6^2P^o	3/2	49022 13	48500 770[a]	2039 90	2061 164[a]	0 30380(−1)	0 8994(−2)[a]	1 21747(9)	3 528(6)[a]
							2061 21[i]		1 156(−1)[e1],		
							2061 830[j]		1 08(−2)[e2],		
							2061 827[r]		1 58[r]		
5^2S	1/2	6^2P^o	1/2	49021 25	48297 380[a]	2039 93	2069 845[a]	0 01521(−2)	0 2197(−2)[a]	1 21944(9)	1 710(6)[a]
							2069 81[i],		7 86(−4)[e2],		
							2070 514		2 2(−2)[e1],		
							2070 511[r]		1 928[r]		
5^2P^o	3/2	6^2S	1/2	27124 58	12083 44[a]	3686 69	8273 515[a],	0 21072(−1)	6 637(−1)[a],	0 517080(7)	3 232(7)[a]
					12083 449[b]		8273 509[b],		3 08(−1)[c1]		
							8273 73[i]		3 32(−1)[c2],		
							8273 519[j]		4 48(−1)[e1],		
									3 32(−1)[e2],		
									3 40(−1)[f1],		
									3 40(−1)[f2],		
									3 0(−1)[s]		

Table 1. *(Contd.)*

States				ΔE		λ		gf		A_{ki}	
Initial	J_i	Final	J_f	This Work	Other Works	This Work	Other Works	This Work	Other Works	This Work	Other Works
5^2P^o	1/2	6^2S	1/2	27624.23	13004.1[a], 13004.091[b]	3620.01	7687.766[a], 7687.772[b], 7688.12[i], 7687.779[j]	0.15266(−1)	3.1405(−1)[a], 2.90(−1)[c1], 3.14(−1)[c2], 3.14(−1)[e2], 4.32(−1)[e1], 3.22(−1)[f2], 3.22(−1)[f1], 2.80(−1)[s]	0.388532(7)	1.771(7)[a]
5^2P^o	1/2	7^2S	1/2	24658.11	22334.93[a]	4055.46	4476.036[a], 4476.06[i], 4476.042[j]	0.88683(−2)	3.162(−2)[a], 3.0(−2)[c1], 3.16(−2)[c2], 3.36(−2)[e1], 3.32(−2)[e2]	1.79833(6)	5.261(6)[a]
5^2P^o	3/2	7^2S	1/2	24158.45	21414.27[a]	4139.34	4668.476[a], 4668.50[i], 4668.478[j], 4668.48[q]	1.80836(−2)	6.123(−2)[a] 2.92(−2)[c1], 3.06(−2)[c2], 3.16(−2)[e2], 3.18(−2)[e1]	3.51993(6)	9.365(6)[a], 2.40(7)[q]
6^2P^o	1/2	6^2S	1/2	2654.94	—	37665.65	—	5.35350(1)	—	1.25851(8)	—
6^2P^o	3/2	6^2S	1/2	2654.06	—	37678.14	—	1.07035(2)	—	2.51454(8)	—
5^2D	3/2	6^2P^o	1/2	2072.86	—	48242.58	—	1.29752(−4)	—	1.85936(2)	—
5^2D	3/2	6^2P^o	3/2	2073.74	—	48222.11	—	2.56367(−5)	—	1.83844(1)	—
4^2F^o	7/2	5^2G	9/2	2917.58	—	34274.95	40450[g], 39900[u]	1.23511(1)	1.308(1)[g], 1.3405(1)[h]	7.01280(6)	—
4^2F^o	7/2	5^2G	7/2	2917.58	—	34274.97	—	3.52887(−1)	3.064(−1)[h]	2.50457(5)	—
4^2F^o	7/2	5^2D	5/2	2980.78	—	33548.21	19570[g]	8.16964(−2)	6.09[g], 5.8068[h]	8.06963(4)	—

Table 1. *(Contd)*

States				ΔE		λ		gf		A_{ki}	
Initial	J_i	Final	J_f	This Work	Other Works	This Work	Other Works	This Work	Other Works	This Work	Other Works
4^2F^o	5/2	5^2G	7/2	2917 59	—	34274 90	40450[g], 39900[u]	9 52793	10 768[g], 11 04[h]	6 76234(6)	—
4^2F^o	5/2	6^2D	3/2	4297 13	—	23271 33	—	1 22411(−2)	—	3 76927(4)	—
4^2F^o	7/2	6^2D	5/2	4300 49	—	23253 16	—	1 77787(−2)	—	3 65531(4)	—
5^2F^o	5/2	6^2D	3/2	1827 79	—	54710 78	—	8 77627(−2)	—	4 88928(4)	—
4^2F^o	5/2	5^2D	3 2	2975 98	—	33602 42	19320[g]	5 72257(−2)	4 292[g], 4 0472[h]	8 45143(4)	—
5^2F^o	5/2	5^2D	3,2	506 64	—	197379 92	—	3 35300	—	1 43519(5)	—
5^2D	5/2	6^2P^o	3/2	2068 92	—	48334 34	—	2 27589(−4)	—	1 62450(2)	—
4^2F^o	5/2	5^2D	5/2	2980 79	—	33548 14	—	4 08453(−3)	2 904(−1)[h]	4 03454(3)	—
4^2F^o	5/2	6^2D	5/2	4300 50	—	23253 13	—	8 88949(−4)	—	1 82769(3)	—
5^2F^o	7/2	5^2G	9/2	448 25	—	223091 68	4(7)[g]	3 06595	0 02[g]	4 10903(4)	—
5^2F^o	7/2	5^2G	7/2	448 24	—	223092 77	—	8 75982(−2)	—	1 46749(3)	—
5^2F^o	5/2	5^2G	7/2	448 25	—	223090 59	4(7)[g]	2 36518	0 024[g]	3 96235(4)	—
5^2F^o	7/2	5^2D	5/2	511 45	—	195523 29	—	4 83795	—	1 40687(5)	—
5^2F^o	5/2	5^2D	5/2	511 45	—	195521 61	—	2 41900(−1)	—	7 03453(3)	—
5^2F^o	7/2	6^2D	5/2	1831 15	—	54610 39	—	1 16779(−1)	—	4 35316(4)	—
5^2F^o	5/2	6^2D	5/2	1831 16	—	54610 26	—	5 83897(−3)	—	2 17659(3)	—
6^2D	3/2	6^2P^o	3/2	752 58	—	132875 99	—	3 22279(−5)	—	3 04382	—
6^2D	3/2	6^2P^o	1/2	751 70	—	133031 56	—	1 61736(−4)	—	3 04795(1)	—
6^2D	5/2	6^2P^o	3/2	749 22	—	133472 70	—	2 89698(−4)	—	2 71170(1)	—
7^2S	1/2	6^2P^o	3/2	312 07	—	320443 74	—	1 26974(−1)	—	2 06202(3)	—
7^2S	1/2	6^2P^o	1/2	311 19	—	321350 01	—	6 33127(−2)	—	2 04477(3)	—

[a]Atomic Spectral Line database from R L Kurucz's CD-ROM 23 [35, log(*gf*)], [b]NIST Atomic Spectra Database [36], [c1 c2]Migdalek [2,f],[d1 d2]Migdalek and Baylis [3,f], [e1,e2]Migdalek and Baylis [5,f], [f1 f2]Migdalek and Garmulewicz [11,f], [g]Cheng and Kim [12 f,τ(ns)], [h]Safronova *et al* [14,f,τ(ns)], [i]Blair [15], [j]Shenstone [17], [k]Hinnov and Kohn [18,f], [l]Penkin and Slavenas [19,f], [m]Lawrence *et al* [20,f], [n]Moise [21,f] [o]Klose [23 f,τ,(ns)], [p]Selter and Kunze [24,f], [q]Plekhotkina [25,τ(ns)], [r]Verner *et al* [26,f], [s]Zhankui *et al* [28, f], [t]Carlsson *et al* [31,f,τ(ns)], [u]Moore [33] [w]Cunningham and Link [34,τ(ns)]

References

[1] C F Fischer, T Brage and P Jönsson *Computational Atomic Structure-an MCHF approach* (Bristol and Philadelphia : Institute of Physics Publishing) (1997)

[2] J Migdalek *J. Quant. Spectrosc. Radiat. Transfer* **20** 81 (1978)

[3] J Migdalek and WE Baylis *J. Phys. B: Atom Molec. Phys.* **11** L497 (1978)

[4] J Migdalek and WE Baylis *J. Quant. Spectrosc. Radiat. Transfer* **22** 113 (1979)

[5] J Migdalek and WE Baylis *Can. J. Phys.* **57** 1708 (1979)

[6] J Migdalek and WE Baylis *Phys. Rev.* **A22** *22* (1980)

[7] J Migdalek and WE Baylis *Phys. Rev.* **A24** 649 (1981)

[8] J Migdalek and WE Baylis *Phys. Rev.* A24 2228 (1981)

[9] J Migdalek and E Banasińska *J. Quant. Spectrosc. Radiat. Transfer* **39** 409 (1988)

[10] J Migdalek and E Banasińska *J. Quant. Spectrosc. Radiat. Transfer* **48** 341 (1992)

[11] J Migdalek and M Garmulewicz *J. Phys. B: Atom Mol. Opt. Phys.* **33** 1735 (2000)

[12] K-T Cheng and Y-Ki Kim *J. Opt. Soc. Am.* **69** 125 (1979)

[13] H-S Chou and W R Johnson *Phys. Rev.* **A56** 2424 (1997)

[14] U I Safronova, I M Savukov, M S Safronova and W R Johnson *Phys. Rev.* **A68** 062505 (2003)

[15] H A Blair *Phys. Rev.* **36** 1531 (1930)

[16] F W Paul *Phys. Rev.* **52** 923 (1937)

[17] A G Shenstone *Phys. Rev.* **57** 846 (1940)

[18] E Hinnov and H Kohn *J. Opt. Soc. Am.* **47** 156 (1957)

[19] N P Penkin and I-Yu Slavenas *Opt. Spectrosc.* **15** 3 (*1963)*

[20] G M Lawrence, J K Link and R B King *Astrophys. J.* **141** 293 (1965)

[21] N L Moise *Astrophys. J.* **144** 774 (1966)

[22] T Andersen, K A Jessen and G Sørensen *Nuclear Instruments and Methods* **90** 35 (1970)

[23] J Z Klose *Astrophys. J.* **198** 229 (1975)

[24] K P Selter and H-J Kunze *Astrophys. J.* **221** 713 (1978)

[25] G L Plekhotkina *Opt. Spectrosc.* **51** 106 (1981)

[26] D A Verner, P D Barthel and D Tytler *Astronomy & Astrophysics Supplement Series* **108** 287 (1994)

[27] J Sugar *J. Opt. Soc. Am.* **67** 1518 (1977)

[28] J Zhankui, P Jönsson, J Larsson and S Svanberg *Zeitschrifi für Physik D Atoms, Molecules and Clusters* **17** 1 (1990)

[29] I Martin, M A Almaraz and C Lavin *Zeitschrift für Physik D Atoms, Molecules and Clusters* **35** 239 (1995)

[30] G J Bengtsson, P Jönsson, J Larsson and S Svanberg *Zeitschrifi für Physik D Atoms, Molecules and Clusters* **22** 437 (1991)

[31] J Carlsson, P Jönsson and L Șturesson *Zeitschrifi für Physik D Atoms, Molecules and Clusters* **16** 87 (1990)

[32] C F Fischer *Computer Physics Communications* **64** 369 (1991)

[33] C E Moore *Atomic Energy Levels* (Circular of the National Bureau of Standards) **Vol III** 497 (1958)

[34] P T Cunningham and J K Link *J. Opt. Soc. Am.* **57** 1000 (1967)

[35] http://www.pmp.uni-hannover.de/cgi-bin/ssi/test/kurucz/sekur.html

[36] http://physics.nist.gov/PhysRefData/ASD/index.html