

***M1* and *E2* transitions in the ground-state configuration of atomic manganese**

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MS received 30 January 2014; revised 11 July 2014; accepted 21 August 2014

DOI: 10.1007/s12043-014-0911-6; ePublication: 13 June 2015

Abstract. Using the multiconfiguration Hartree–Fock approximation within the framework of the Breit–Pauli Hamiltonian (MCHF+BP) and the relativistic Hartree–Fock (HFR) approximation, we have calculated the forbidden transition (*M1* and *E2*) parameters such as transition energies, logarithmic weighted oscillator strengths and transition probabilities between the fine-structure levels in the ground-state configuration of $3d^5 4s^2$ for atomic manganese (Mn I, $Z = 25$). A discussion of these calculations for manganese using MCHF+BP and HFR methods is given here.

Keywords. Forbidden transitions; transition energies; logarithmic weighted oscillator strengths; transition probabilities.

PACS Nos 31.15.ag; 31.15.am; 32.70.Cs

1. Introduction

Radiative properties of atoms having an electromagnetic transition between two states are characterized by the angular momentum and parity of the corresponding photon. They are very useful in the fields of quantum electronics, atomic physics and laser spectroscopy, plasma physics and astrophysics. The reliability of the values is mainly based on the performance of the methods used for calculation. Forbidden transitions within the ground-state configuration are particularly useful because their relatively long wavelengths make them convenient for spectroscopic studies [1]. Although the atomic kinetics depend on, in particular, optical allowed transitions (*E1*), the weak forbidden transitions (in particular, magnetic dipole, *M1* and electric quadrupole, *E2*) have been linked to dominant features in the optical spectra of planetary nebulae and aurora [2–4]. *M1* and *E2* transition rates (or probabilities) are of several orders of magnitude smaller than those for *E1* transitions with a similar energy-level separation.

Atomic manganese (Mn I) belongs to the iron-group elements which have very complex but interesting atomic structures. As lines in the synthetic spectrum of a star are based on the adopted model atom and transitions, the analysis becomes more and more complicated

for elements with increasing number of levels and electrons [5]. Moreover, it is interesting to study the abundance of manganese in stars of different populations. In metal-poor stars, the manganese abundance was found to be correlated with metallicity. Nucleosynthesis path that leads to its information is relatively well understood. However, it is unclear as to which objects are the main donors of manganese to the Galaxy at different times of chemical evolution of the disk and halo of Galaxy [6]. Data on the energy levels and transition parameters for Mn I can be found in the NIST website [7]. Although the level structure of Mn has been investigated extensively for high excited levels, our knowledge about experimental and theoretical works on the forbidden transitions between the fine-structure levels in the ground state are far from complete. The works on forbidden transition parameters for high excited levels of atomic manganese can be found in [8–11].

The aim of this work is to investigate the forbidden transitions ($M1$ and $E2$) between the fine-structure energy levels within the ground-state configuration of atomic manganese (Mn I) using multiconfiguration Hartree–Fock approach within the framework of Breit–Pauli Hamiltonian [12] and HFR method [13]. Mn I has the ground-state configuration of $[\text{Ar}]3d^54s^2$. In calculations, various configuration sets are considered for including correlation effects. We have considered the valence–valence correlation and used the MCHF and HFR atomic codes [14,15] in this work. Other correlation methods (core and core–valence correlations) produce a lot of states, and in this case the convergence problems in the radial functions occur. For valence–valence correlation, we have taken into account the configurations including only one-electron excitation from valence to other high subshells: $3d^54s^2$, $3d^64s$, $3d^7$, $3d^44s^25s$, $3d^54s5s$, $3d^55s^2$ and $3d^65s$ configurations for the calculation A, $3d^54s^2$, $3d^64s$, $3d^55s^2$, $3d^54s5s$ and $3d^65s$ configurations for the calculation B, $3d^54s^2$, $3d^7$, $3d^44s^25s$ and $3d^54s5s$ configurations for the calculation C in MCHF+BP calculations, and $3d^54s^2$, $3d^64s$, $3d^54s4p$, $3d^54s5p$ and $3d^64p$ configurations in HFR calculations, outside the core $[\text{Ar}]$. As the parity of upper and lower levels within the ground-state configuration is the same, the electric dipole ($E1$) transitions are forbidden. The lowest-order metastable levels which radiatively decay correspond to magnetic dipole ($M1$) and electric quadrupole ($E2$) transitions [16]. $M1$ and $E2$ transition rates are several orders of magnitude smaller than those for electric dipole ($E1$) transitions with a similar energy level separation. These transitions, especially in light atoms, have been linked to dominant features in the optical spectra of planetary nebulas and aurora [17].

2. Calculation methods: MCHF and HFR

The detailed information on MCHF and HFR methods can be found in [12] and [13], respectively. We have briefly discussed these methods in this study.

In the MCHF method, the wave function (or atomic state function, ASF) $\Psi(\gamma LS)$ is expressed as the linear combination of configuration state functions (CSFs) $\Phi(\gamma_i LS)$,

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

where γ represents the electronic configuration. The mixing coefficients c_i and the one-electron radial wave functions of Φ are obtained in a self-consistent procedure by

optimizing the energy function based on the non-relativistic Hamiltonian of an atom,

$$H_{\text{NR}} = \sum_{j=1}^N \left(\frac{1}{2} \nabla_j^2 - \frac{Z}{r_j} \right) + \sum_{j < k} \frac{1}{r_{jk}}. \quad (2)$$

This method captures the correlation effects. The exact solution can be approximated with arbitrary accuracy if enough CSFs in (1) are taken into account. However, this case is constrained by computing capacities and limits of the method used for the expansion must be used. In this method, the relativistic effects were included as a first-order correction to the MCHF approximation by evaluating BP Hamiltonian using CI method [18]. BP Hamiltonian consists of a non-relativistic many-electron Hamiltonian (H_{NR}), a relativistic shift Hamiltonian (H_{RS}) which includes a mass correction, one- and two-body Darwin terms, a spin–spin contact term, an orbit–orbit term and fine-structure Hamiltonian (H_{FS}) which includes spin–orbit, spin-other-orbit and spin–spin terms:

$$H_{\text{BP}} = H_{\text{NR}} + H_{\text{RS}} + H_{\text{FS}}. \quad (3)$$

Therefore, the wave functions are obtained as linear combinations of CSFs in LSJ coupling and the matrix eigenvalue problem becomes

$$\mathbf{H}\mathbf{c} = E\mathbf{c}, \quad (4)$$

where \mathbf{H} is the Hamiltonian matrix with elements

$$H_{ij} = \langle \gamma_i L_i S_i J M | H_{\text{BP}} | \gamma_j L_j S_j J M \rangle \quad (5)$$

and $\mathbf{c} = (c_1, \dots, c_M)^t$ is the column vector of the expansion coefficients. The BP Hamiltonian is a first-order perturbation correction to the non-relativistic Hamiltonian.

In the relativistic Hartree–Fock method (HFR) developed by Cowan, the wave function $|\gamma J M\rangle$ of the M sublevel of a level labelled γJ is expressed in terms of LS basis states $|\alpha L S J M\rangle$ by the formula

$$|\gamma J M\rangle = \sum_{\alpha L S} |\alpha L S J M\rangle \langle \alpha L S J | \gamma J \rangle. \quad (6)$$

HFR, although based on the Schrödinger equation, includes relativistic effects like the mass–velocity corrections and Darwin contributions besides the spin–orbit effect. The Hamiltonian for N electron is expanded as

$$H = - \sum_i \nabla_i^2 - \sum_i \frac{2Z_0}{r_i} + \sum_{i>j} \frac{2}{r_{ij}} + \sum_i \zeta_i(r_i) \mathbf{l}_i \cdot \mathbf{s}_i, \quad (7)$$

where ζ_i is the spin–orbit term with α the fine–structure constant. In calculations, the eigenvalues of the Hamiltonian were optimized to the observed energy levels via a least squares fitting procedure using the available experimental energy levels.

Details of theoretical background on radiative transitions can also be found in the literature [12,13]. If the emitted or observed photon has angular momentum k and parity $\pi = (-1)^k$, the transition is an electric multipole transition (E^k), while the transition from absorbed photon with parity $\pi = (-1)^{k+1}$ is a magnetic multipole transition (M^k).

The transition probability for the emission from the upper to the lower level is given by

$$A^{\pi k}(\gamma' J', \gamma J) = 2C_k [\alpha(E_{\gamma' J'} - E_{\gamma J})]^{2k+1} \frac{S^{\pi k}(\gamma' J', \gamma J)}{g_{J'}}, \quad (8)$$

where $S^{\pi k}$ is the line strength,

$$S^{\pi k}(\gamma' J', \gamma J) = |\langle \gamma J \| \mathbf{O}^{\pi(k)} \| \gamma' J' \rangle|^2, \quad (9)$$

$C_k = (2k + 1)(k + 1)/k((2k + 1)!!)^2$ and $\mathbf{O}^{\pi(k)}$ is the transition operator. The transition rates (or probabilities) for forbidden transitions depend on the third (in $M1$ transition) or fifth (in $E2$ transition) power of transition energy.

The oscillator strength is a dimensionless quantity. It expresses the probability of absorption or emission of electromagnetic radiations in transitions between energy levels. For absorption, the oscillator strength is expressed by

$$f^{\pi k}(\gamma J, \gamma' J') = \frac{1}{\alpha} C_k [\alpha(E_{\gamma' J'} - E_{\gamma J})]^{2k-1} \frac{S^{\pi k}(\gamma J, \gamma' J')}{g_J}. \quad (10)$$

A similar expression can be formulated for the emission oscillator strength where $\gamma' J'$ and γJ are interchanged, making the emission oscillator strength negative. The weighted oscillator strength, or gf -value, is completely symmetrical (except sign) between the two levels. The weighted oscillator strength is given by

$$gf^{\pi k}(\gamma' J', \gamma J) = g_{J'} f^{\pi k}(\gamma' J', \gamma J). \quad (11)$$

3. Results and discussion

In this work, transition energies, logarithmic weighted oscillator strengths and transition probabilities for magnetic dipole, $M1$, and electric quadrupole, $E2$, transitions between the fine-structure levels of the ground-state configuration $3d^5 4s^2$ in Mn I have been calculated using the MCHF atomic-structure package [14] and Cowan's HFR code [15]. Both the codes have included correlation and relativistic effects mentioned in §2. $M1$ and $E2$ transitions combine the states with the same parity. We have taken into account $3d^5 4s^2$, $3d^6 4s$, $3d^7$, $3d^4 4s^2 5s$, $3d^5 4s 5s$, $3d^5 5s^2$ and $3d^6 5s$ configurations for the calculation A, $3d^5 4s^2$, $3d^6 4s$, $3d^5 5s^2$, $3d^5 4s 5s$ and $3d^6 5s$ configurations for the calculation B, $3d^5 4s^2$, $3d^7$, $3d^4 4s^2 5s$ and $3d^5 4s 5s$ configurations for the calculation C in MCHF+BP calculations and $3d^5 4s^2$, $3d^6 4s$, $3d^5 4s 4p$, $3d^5 4s 5p$ and $3d^6 4p$ configurations in HFR calculations, outside the core [Ar] in Mn I for considering correlation effects. In HFR calculations, the HFR method was combined with a least-squares optimization routine minimizing the discrepancies between the observed and calculated energy levels. The scaling factors of the Slater parameters (F^k and G^k) and of configuration interaction integrals (R^k) were chosen as 0.80, while the spin-orbit parameters were left at their *ab-initio* values. This low value of the scaling factor is suggested by Cowan [15]. Results obtained from MCHF and HFR codes for transition energies are reported in table 1, and the logarithmic weighted oscillator strengths and transition probabilities (or rates) are listed in table 2.

In HFR calculations, we have obtained 2352 possible $M1$ transitions and 3460 possible $E2$ transitions for the selected configurations. In addition, we have obtained 56488, 37244 and 21552 possible $M1$ transitions and 98492, 65592 and 37482 possible $E2$ transitions for the configurations selected in A, B and C calculations, respectively, in MCHF calculations. This work is a part of the continuing works on atoms with half-filled subshells using MCHF atomic code. Here, we have presented only the fine-structure levels

M1 and E2 transitions in atomic manganese

Table 1. Transition energies, ΔE (cm^{-1}), between the fine-structure levels of $3d^5 4s^2$ in atomic manganese (Mn I). Transition energy values are compared with NIST [7].

Transitions	HFR	MCHF+BP	[7]	Differences (%)	
				HFR	MCHF+BP
$^6S_{5/2} - ^4D_{1/2}$	30760.5	29207.38 ^C	30411.74	1.15	3.96
$^4P_{1/2}$	28652.6	27375.07 ^B	27281.85	5.02	0.34
$^4D_{3/2}$	30924.3	29214.18 ^C	30425.71	1.64	3.98
$^4P_{3/2}$	28435.8	27318.05 ^B	27248.00	4.36	0.26
$^4D_{5/2}$	30947.2	—	30419.61	1.73	—
$^4G_{5/2}$	24604.6	—	25281.04	2.67	—
$^4P_{5/2}$	28257.8	—	27201.54	3.87	—
$^4D_{7/2}$	30542.5	29156.46 ^C	30354.21	0.62	3.95
$^4G_{7/2}$	24669.2	24155.79 ^B	25287.74	2.44	4.48
$^4G_{9/2}$	24707.4	24140.85 ^B	25285.43	2.29	4.53
$^4G_{5/2} - ^4D_{1/2}$	6156.0	5666.98 ^C	5130.70	19.98	10.45
$^4P_{1/2}$	4048.1	3212.28 ^B	2000.81	102.32	60.55
$^4D_{3/2}$	6319.8	5673.78 ^C	5144.67	22.84	10.28
$^4P_{3/2}$	3831.3	3155.26 ^B	1966.96	94.78	60.41
$^4D_{5/2}$	6342.6	—	5138.57	23.43	—
$^4P_{5/2}$	3653.3	—	1920.50	90.23	—
$^4D_{7/2}$	5938.0	5616.0 ^C	5073.17	17.05	10.70
$^4G_{7/2} - ^4D_{3/2}$	6255.2	5679.25 ^C	5137.97	21.74	10.54
$^4P_{3/2}$	3766.7	3162.26 ^B	1960.26	92.15	61.31
$^4D_{5/2}$	6278.0	5671.55 ^C	5131.87	22.33	10.52
$^4P_{5/2}$	3588.7	3107.09 ^B	1913.80	87.52	62.35
$^4D_{7/2}$	5873.4	—	5066.47	15.92	—
$^2I_{11/2}$	10717.7	10687.61 ^B	11860.92	9.63	9.90
$^4G_{11/2} - ^4D_{7/2}$	5856.6	5658.09 ^C	5088.47	15.09	11.19
$^2I_{11/2}$	10700.9	—	11882.92	9.94	—
$^2I_{13/2}$	10859.8	10716.41 ^B	11898.51	8.73	9.94
$^4G_{9/2} - ^4D_{5/2}$	6239.8	5684.16 ^C	5134.18	21.53	10.71
$^4P_{5/2}$	3550.5	3122.02 ^B	1916.11	85.29	62.94
$^4D_{7/2}$	5835.2	5634.13 ^C	5068.78	15.12	11.15
$^2I_{11/2}$	10679.5	10702.54 ^B	11863.23	9.98	9.78
$^2I_{13/2}$	10838.4	10688.99 ^B	11878.82	8.76	10.01
$^4P_{5/2} - ^4D_{1/2}$	2502.7	2631.08 ^C	3210.20	22.04	18.04
$^4P_{1/2}$	394.8	232.23 ^A	80.31	391.59	189.17
$^4D_{3/2}$	2666.5	2637.88 ^C	3224.17	17.29	18.18
$^4D_{5/2}$	2689.3	—	3218.01	16.43	—
$^4D_{7/2}$	2284.7	2580.16 ^C	3152.67	27.53	18.15
$^4P_{3/2} - ^4D_{1/2}$	2324.7	2603.36 ^C	3163.74	26.52	17.71
$^4P_{1/2}$	216.8	131.19 ^A	33.85	540.47	287.56
$^4D_{3/2}$	2488.5	—	3177.71	21.69	—
$^4D_{5/2}$	2511.3	2602.47 ^C	3171.61	20.82	17.94
$^4D_{7/2}$	2106.7	2552.44 ^C	3106.21	32.18	17.83

Table 1. *Continued*

Transitions	HFR	MCHF+BP	[7]	Differences (%)	
				HFR	MCHF+BP
${}^4P_{1/2} - {}^4D_{3/2}$	2271.7	2586.76 ^C	3143.86	27.74	17.72
${}^4D_{5/2}$	2294.5	2579.06 ^C	3137.76	26.87	17.80
${}^4D_{1/2}$	2107.9	2586.76	3129.89	32.65	17.35
${}^4D_{7/2} - {}^4D_{3/2}$	381.8	354.13 ^A	71.5	433.98	395.28
${}^4D_{5/2}$	404.6	320.71 ^A	65.4	518.65	390.38
${}^2I_{11/2}$	4844.3	4433.86 ^C	—	—	—

MCHF+BP calculations:

^A $3d^54s^2$, $3d^64s$, $3d^7$, $3d^44s^25s$, $3d^54s5s$, $3d^55s^2$ and $3d^65s$.

^B $3d^54s^2$, $3d^64s$, $3d^55s^2$, $3d^54s5s$ and $3d^65s$.

^C $3d^54s^2$, $3d^7$, $3d^44s^25s$ and $3d^54s5s$.

HFR calculation:

$3d^54s^2$, $3d^64s$, $3d^54s4p$, $3d^54s5p$ and $3d^64p$.

for the ground state and transition parameters between these levels. A half-filled shell has the largest number of states. The fine-structure levels for the ground-state configuration $3d^54s^2$ are ${}^6S_{5/2}$, ${}^4G_{5/2,7/2,9/2,11/2}$, ${}^4P_{1/2,3/2,5/2}$, ${}^4D_{1/2,3/2,5/2,7/2}$ and ${}^2I_{11/2,13/2}$. There are a few works on the forbidden transitions ($M1$ and $E2$), e.g., [8–11], for highly excited levels of Mn I. Here, we have investigated the forbidden transitions in the ground-state configuration for this atom. For this reason, we have only compared the transition energy results, according to various configuration sets, with the values compiled in NIST [7]. In table 1, we have presented the best of the results obtained according to the configuration sets and the best results are denoted by superscripts A, B and C for MCHF+BP calculations. We have also performed the non-relativistic MCHF calculations. We have obtained non-relativistic transition energies (in cm^{-1}) of 29170.65, 27371.11 and 24139.29 from 4D , 4P and 4G to 6S , respectively. Moreover, the transition energies (in cm^{-1}) are 4344.85, 3231.82 and 10697.38 from 4D , 4P and 2I to 4G and the transition energy for 4P to 4D is 2542.35. These values are almost in agreement with [7]. We can say that the correlation effect is dominant for this atoms. Atomic manganese is a mid- Z atom and the correlation effects are dominant for this atom. The transition energy results obtained from this work are generally in agreement with [7]. We have not obtained $J-J' = 0$ transitions due to the constraint in MCHF code. We have calculated $[(\Delta E_{\text{our}} - \Delta E_{\text{other}})/\Delta E_{\text{other}}] \times 100$, the differences in per cent, for the accuracy of our results for both HFR and MCHF+BP. When we investigate the differences (%) between our results and other results, the differences, in HFR calculations, are in the range of 0.62–5.02 for transitions to 6S . The differences (%) for transition energies obtained from MCHF calculation are in the range of 0.26–4.48 for the transitions to 6S . The other results are poor for some transitions. But, HFR and MCHF transition energies are in agreement with each other.

Table 2 displays the logarithmic weighted oscillator strengths and transition probabilities (in s^{-1}) for $E2$ and $M1$ transitions in the ground state of Mn I. For comparison, there is no reported data of the forbidden transitions between the fine-structure levels in the ground state of Mn I in the literature. Hence, the oscillator strengths and transition

M1 and E2 transitions in atomic manganese

Table 2. Logarithmic weighted oscillator strengths, $\log(gf)$, transition probabilities, A_{ki} (s^{-1}), for the magnetic dipole (*M1*) and electric quadrupole (*E2*) transitions between the fine-structure levels of $3d^5 4s^2$ in atomic manganese (Mn I). The number in brackets represents the power of 10.

Transitions		$\log(gf)$		A_{ki}	
		HFR	MCHF+BP	HFR	MCHF+BP
${}^6S_{5/2} - {}^4D_{1/2}$	<i>E2</i>	-12.16	-12.36 ^C	2.18 (-4)	1.22 (-4) ^C
	<i>E2</i>	-12.97	-13.55 ^A	2.93 (-5)	6.21 (-4) ^A
${}^4P_{1/2}$	<i>E2</i>	-11.38	-11.52 ^C	6.62 (-4)	4.25 (-4) ^C
	<i>M1</i>	-8.95	-9.41	1.79 (-1)	4.25(-2) ^A
${}^4D_{3/2}$	<i>E2</i>	-14.31	-13.89 ^C	6.59 (-7)	1.50 (-6) ^C
	<i>M1</i>	-8.04	-8.91 ^C	1.23	1.43 (-1) ^B
${}^4P_{3/2}$	<i>E2</i>	-11.03	-	9.81 (-4)	-
	<i>M1</i>	-8.52	-	3.20 (-1)	-
${}^4D_{5/2}$	<i>E2</i>	-15.24	-	3.85 (-8)	-
	<i>M1</i>	-11.91	-	8.35 (-5)	-
${}^4G_{5/2}$	<i>E2</i>	-12.48	-	2.97 (-5)	-
	<i>M1</i>	-7.68	-	1.84	-
${}^4P_{5/2}$	<i>E2</i>	-10.96	-10.98 ^C	8.62 (-4)	7.29 (-4) ^C
	<i>M1</i>	-10.66	-12.24 ^C	1.72 (-3)	4.03 (-5) ^C
${}^4D_{7/2}$	<i>E2</i>	-15.01	-14.84 ^A	4.97 (-8)	6.49 (-8) ^A
	<i>M1</i>	-14.17	-16.95 ^B	3.44 (-7)	5.35 (-10) ^B
${}^4G_{7/2}$	<i>E2</i>	-14.71	-14.66 ^A	7.95 (-8)	7.66 (-8) ^A
	<i>E2</i>	-10.99	-10.79 ^A	1.28 (-4)	2.16 (-4) ^B
${}^4G_{5/2} - {}^4D_{1/2}$	<i>E2</i>	-12.36	-12.66 ^A	2.38 (-6)	4.96 (-6) ^A
	<i>E2</i>	-11.04	-10.76 ^B	6.02 (-5)	5.61 (-5) ^B
${}^4D_{3/2}$	<i>M1</i>	-9.77	-11.31 ^C	1.14 (-3)	2.62 (-5) ^C
	<i>E2</i>	-12.15	-12.52 ^A	1.74 (-6)	1.53 (-6) ^A
${}^4P_{3/2}$	<i>M1</i>	-10.07	-11.50 ^A	2.08 (-4)	2.33 (-6) ^A
	<i>E2</i>	-11.36	-	1.97 (-5)	-
${}^4D_{5/2}$	<i>M1</i>	-9.35	-	2.01 (-3)	-
	<i>E2</i>	-12.70	-	2.94 (-7)	-
${}^4P_{5/2}$	<i>M1</i>	-9.09	-	1.21 (-3)	-
	<i>E2</i>	-12.32	-13.06 ^B	1.41 (-6)	1.32 (-7) ^B
${}^4D_{7/2}$	<i>M1</i>	-9.92	-8.40 ^A	3.53 (-4)	1.59 (-6) ^A
	<i>E2</i>	-11.03	-10.31 ^B	6.04 (-5)	2.50 (-5) ^B
${}^4G_{7/2} - {}^4D_{3/2}$	<i>E2</i>	-11.98	-11.26 ^A	2.45 (-6)	4.14 (-6) ^A
	<i>E2</i>	-10.86	-10.68 ^B	6.11 (-5)	4.57 (-5) ^B
${}^4P_{3/2}$	<i>M1</i>	-11.19	-12.57 ^A	2.81 (-5)	2.01 (-7) ^A
	<i>E2</i>	-12.02	-12.36 ^B	1.36 (-6)	1.12 (-6) ^A
${}^4D_{5/2}$	<i>M1</i>	-9.93	-12.13 ^A	1.67 (-4)	3.41 (-7) ^A
	<i>E2</i>	-11.30	-	1.43 (-5)	-
${}^4P_{5/2}$	<i>M1</i>	-8.89	-	3.70 (-3)	-
	<i>E2</i>	-12.55	-13.22 ^B	1.82 (-6)	3.76 (-7) ^B
${}^2I_{11/2}$	<i>E2</i>	-10.57	-10.26 ^A	7.64 (-5)	2.47 (-5) ^A
	<i>E2</i>	-12.15	-	4.51 (-6)	-
${}^4G_{11/2} - {}^4D_{7/2}$	<i>M1</i>	-8.61	-	1.54 (-2)	-
	<i>E2</i>	-10.57	-10.26 ^A	7.64 (-5)	2.47 (-5) ^A
${}^2I_{11/2}$	<i>E2</i>	-12.15	-	4.51 (-6)	-
	<i>M1</i>	-8.61	-	1.54 (-2)	-

Table 2. *Continued*

Transitions		log (gf)		A_{ki}	
		HFR	MCHF+BP	HFR	MCHF+BP
$^2I_{13/2}$	<i>E2</i>	-12.12	-12.10 ^B	4.26 (-6)	4.26 (-6) ^B
	<i>M1</i>	-9.96	-11.52 ^B	6.21 (-4)	1.63 (-5) ^B
$^4G_{9/2}$ - $^4D_{5/2}$	<i>E2</i>	-10.91	-10.50 ^A	5.30 (-5)	2.46 (-5) ^A
	<i>E2</i>	-11.87	-11.77 ^B	1.91 (-6)	1.82 (-6) ^B
	<i>E2</i>	-10.75	-10.77 ^B	5.06 (-5)	2.56 (-5) ^B
$^4D_{7/2}$	<i>M1</i>	-8.98	-10.59 ^B	2.98 (-3)	3.94 (-5) ^B
	<i>E2</i>	-12.15	-12.09 ^A	4.50 (-6)	5.13 (-6) ^A
$^2I_{11/2}$	<i>M1</i>	-9.12	-10.76 ^B	4.75 (-3)	1.10 (-4) ^B
	<i>E2</i>	-12.45	-13.31 ^B	1.99 (-6)	2.63 (-7) ^B
$^4P_{5/2}$ - $^4D_{1/2}$	<i>E2</i>	-12.54	-12.01 ^C	5.96 (-7)	2.26 (-6) ^C
	<i>E2</i>	-14.56	-13.93 ^A	1.45 (-10)	2.11 (-10) ^A
$^4D_{3/2}$	<i>E2</i>	-11.72	-11.17 ^C	2.25 (-6)	7.83 (-6) ^C
	<i>M1</i>	-7.72	-8.58 ^C	2.25 (-2)	2.99 (-3) ^C
$^4D_{5/2}$	<i>E2</i>	-11.58	-	2.11 (-6)	-
	<i>M1</i>	-7.42	-	3.06 (-2)	-
$^4D_{7/2}$	<i>E2</i>	-13.71	-13.21 ^A	8.53 (-9)	3.81 (-10) ^A
	<i>M1</i>	-7.01	-7.64 ^B	4.29 (-2)	2.59 (-3) ^B
$^4P_{3/2}$ - $^4D_{1/2}$	<i>E2</i>	-12.52	-12.43 ^B	5.38 (-7)	1.97 (-7) ^B
	<i>M1</i>	-7.66	-8.21 ^A	3.93 (-2)	5.95 (-3) ^C
$^4P_{1/2}$	<i>E2</i>	-15.85	-15.55 ^A	2.20 (-12)	1.63 (-12) ^A
	<i>M1</i>	-7.52	-7.68 ^A	4.76 (-4)	1.19 (-4) ^A
$^4D_{3/2}$	<i>E2</i>	-13.66	-	2.25 (-8)	-
	<i>M1</i>	-7.30	-	5.20 (-2)	-
$^4D_{5/2}$	<i>E2</i>	-12.13	-12.42 ^C	5.18 (-7)	2.83 (-7) ^C
	<i>M1</i>	-8.07	-8.48 ^A	5.98 (-3)	5.22 (-3) ^A
$^4D_{7/2}$	<i>E2</i>	-13.03	-11.86 ^B	3.49 (-8)	7.89 (-6) ^C
	<i>E2</i>	-13.14	-12.70 ^B	6.22 (-8)	4.93 (-8) ^B
$^4P_{1/2}$ - $^4D_{3/2}$	<i>M1</i>	-8.86	-9.32 ^B	1.20 (-3)	1.18 (-4) ^B
	<i>E2</i>	-13.83	-13.80 ^A	8.65 (-9)	1.81 (-10) ^A
$^4D_{1/2}$	<i>M1</i>	-7.33	-	6.92 (-2)	-
	<i>E2</i>	-15.90	-15.58 ^B	3.02 (-12)	1.08 (-12) ^B
$^4D_{5/2}$	<i>E2</i>	-14.64	-14.77 ^B	4.19 (-11)	8.58 (-11) ^A
	<i>M1</i>	-7.02	-7.25 ^A	1.73 (-3)	0.63 (-3) ^A
$^2I_{11/2}$	<i>E2</i>	-11.91	-14.07 ^A	5.23 (-7)	0.32 (-7) ^A

MCHF+BP calculations:

^A3d⁵4s², 3d⁶4s, 3d⁷, 3d⁴4s²5s, 3d⁵4s5s, 3d⁵5s² and 3d⁶5s.

^B3d⁵4s², 3d⁶4s, 3d⁵5s², 3d⁵4s5s and 3d⁶5s.

^C3d⁵4s², 3d⁷, 3d⁴4s²5s and 3d⁵4s5s.

HFR calculation:

3d⁵4s², 3d⁶4s, 3d⁵4s4p, 3d⁵4s5p and 3d⁶4p.

probabilities obtained from the HFR results and MCHF+BP results have been compared with each other in table 2. HFR and MCHF results for the logarithmic oscillator strengths and transition probabilities are in agreement. But, some results for *M1* transition probabilities are not in agreement.

4. Conclusions

We have calculated transition energies, logarithmic weighted oscillator strengths and transition probabilities for *M1* and *E2* transitions between the fine-structure levels of $3d^54s^2$ in the framework of relativistic and correlation effects using HFR and MCHF codes. These levels in the ground state perform weak spectral lines, and they decay via magnetic dipole (*M1*) and electric quadrupole (*E2*) transitions. The radiative transition parameters such as transition energies, oscillator strengths, wavelengths, transition rates, etc. are fundamental quantities for many scientific applications. Especially, *M1* and *E2* transitions are of great interest for plasma diagnostics and modelling. The oscillator strengths and transition probabilities for *E2* and *M1* transitions obtained from this study for the ground state of atomic manganese are new. Hence, we hope that the results obtained using MCHF+BP and HFR methods will be useful for future work on Mn I spectrum and support further research on this atom.

Acknowledgements

The authors are very grateful to the anonymous reviewer and editor for useful comments and valuable suggestions, which resulted in improving this paper.

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