

Electric Dipole Oscillator Strengths of Boron

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Received 07.07.2008

Abstract

Electric dipole oscillator strengths for both individual and multiplet lines between some excited levels of atomic boron are calculated using the Weakest Bound Electron Potential Model Theory (WBEPMT). The Numerical Coulomb Approximation wave functions for expectation values of radii in all states and experimental ionization energies have been employed to determinate the parameters. The obtained results from this work agree very well with the accepted values taken from NIST, Multi-Configurational Hartree-Fock (MCHF) results and atomic line data.

Key Words: Electric dipole oscillator strength, boron atom, the weakest bound electron potential model theory.

1. Introduction

The boron atom has a closed 2s subshell and one 2p electron in its ground configuration. In the recent years, much interest has been focused on boron in astrophysics. Boron plays an important role in testing models of Big Bang Nucleosynthesis and thermonuclear fusion research, belonging to the most abundant impurities in the plasmas of several presently operating tokamaks. A good knowledge of some spectroscopic properties such as energy values, transition probabilities, oscillator strengths, hyperfine structure and isotope shifts are needed for establishing B abundances in stellar objects [1–3].

Spectroscopic parameters such as oscillator strengths, transition probabilities and radiative lifetimes are fundamental characteristics of excited states of atoms and ions. They are very useful in the fields of quantum electronic, atomic physics and laser spectroscopy, plasma physics and astrophysics. Hence, the reliability of values of these parameters are mainly based on the performance of the calculation methods used. Perhaps, the oscillator strengths and transition probabilities are the most important fundamental parameters in atomic spectroscopy. Their values affect the choice of transition utilized for analysis and the accuracy of many critical measurements such as temperature and atomic concentration [4–6]. Accurate determinations of such parameters in boron element are subject of continuing study to theoretical and experimental workers. Numerous experimental and theoretical studies have been published. For example, Weiss computed oscillator strengths for transitions between low-lying levels in atomic boron using pseudonatural orbital technique. The wave functions were obtained from method of superposition of configurations [7]. Andersen et al. measured lifetimes of excited states in both atomic and ionic boron by using the foil-excitation technique [8]. Sbincic calculated energies and oscillator strengths for some states of atomic boron. He obtained the wave functions from multiconfiguration self-consistent-field calculations [9]. Radiative lifetimes of the eight

lowest even-parity levels in the doublet system of B I were measured using time-resolved laser-induced fluorescence in the UV and VUV on an atomic beam of boron by O'Brian and Lawler [10]. Carlsson et al. calculated transition probabilities and excited-state lifetimes for the term system of boron atom using Multiconfiguration Hartree-Fock method [11]. Jönsson et al. calculated transition probabilities, isotope shifts and hyperfine structures for some allowed transitions in B I. They obtained good agreement between the length and velocity forms of transition probabilities using Multiconfiguration Hartree-Fock method and considered higher-order correlation effects [12]. Breit-Pauli results for energy levels, lifetimes and some transition data were reported for all levels up to $2s2p(P-3)3s P-2(J)$ of the B-like spectrum for 5 less than or equal to Z less than or equal to 14 by Tachiev and Fischer [13]. The energy levels and radiative lifetimes were calculated of Rydberg ns, nd states of B I using multichannel quantum defect theory by Liang and Wang [14]. Safronova calculated energies of the ground np states and the lowest ns and nd states in neutral boron by using the relativistic many-body perturbation theory (RMBPT) method [15].

In this work, the electric dipole oscillator strengths have been calculated using the WBEPM theory for transitions between some excited states of atomic boron. The obtained results have been compared with accepted values taken from NIST [16], MCHF results [13] and atomic line data.

2. Theoretical Procedure

The absorption oscillator strength or f-value for an electric dipole transition between an initial state $|j\rangle$ and a final state $|j'\rangle$ is given as [17]

$$f_{jj'} = \frac{2(E_{j'} - E_j)}{3(2j + 1)} S \quad (1)$$

Here, $(E_{j'} - E_j)$ is the transition energy in atomic units, $(2j+1)$ is the degeneracy of initial level and S is the electric dipole line strength in atomic units. Line strength is determined according to the coupling schemes and the transition types in atomic or ionic systems. The line strength for transitions between two excited levels in LS coupling scheme can be given to be [17]

$$\sqrt{S_{LS}} \equiv \langle [(\dots\alpha_1 L_1, l_2) L (\dots S_1 s_2) S] J \mid r_N^{(1)} \mid [(\dots\alpha'_1 L'_1, l'_2) L' (\dots S'_1 s'_2) S'] J' \rangle \quad (2)$$

$$= (-1)^{S+J'+L_1+l'_2} [J, J', L, L']^{1/2} \left\{ \begin{matrix} LSJ \\ J'1L' \end{matrix} \right\} \left\{ \begin{matrix} L_1 l_2 L \\ 1L' l'_2 \end{matrix} \right\} P_{l_2 l'_2}^{(1)}$$

$$\left\{ \begin{matrix} LSJ \\ J'1L' \end{matrix} \right\} = W(\text{abcd;ef})$$

$$P_{l_2 l'_2}^{(1)} = l_2 \langle n_2, l_2 \mid r^k \mid n'_2, l'_2 \rangle = l_2 \int_0^\infty r^{k+2} R_{n_2 l_2}(r) R_{n'_2 l'_2}(r) dr.$$

If there are n equivalent electrons in a shell, the expression for line strength should be multiplied by the factor of $n(l_1^n \alpha_1 L_1 S_1 \{ l_1^{n-1} \alpha'_1 L'_1 S'_1 \})$ in transitions including equivalent electrons [17]:

$$\begin{aligned} \sqrt{S_{LS}} &\equiv \langle \alpha_1 L_1 S_1, J \mid r^{(1)} \mid \alpha'_1 L'_1 S'_1, l_2 \rangle L' S', J' \rangle \\ &= \delta_{S_1 S'} (-1)^{L'_1 + l_2 + S_1 + J'} (n. [L_1, L', J, J'])^{1/2} x \end{aligned} \quad (3)$$

$$\left\{ \begin{matrix} L_1 S J \\ J' 1 L' \end{matrix} \right\} \left\{ \begin{matrix} l_1 L'_1 L_1 \\ L' 1 l_2 \end{matrix} \right\} (l_1^n \alpha_1 L_1 S_1 \{ l_1^{n-1} \alpha'_1 L'_1 S'_1 \}) P_{l_2 l'_2}^{(1)} .$$

Here, n is the number of equivalent electrons in a shell and the bracketed term is the coefficient of fractional parentage. The tables of numerical values of the fractional parentage coefficients are given in the literature

for various shells [17, 18]. On the other hand, $W(abcd;ef)$ is known as a Racah coefficient, or Wigner's 6-j symbol, and it is used to describe the coupling between two or more angular momentum. Quantity $P_{l_2 l_2'}^{(1)}$ given in equation (3) is known to be radial transition integral. Radial transition integrals can be determined using available different methods in the literature. In this study, we have employed the WBEPM theory in order to calculate radial transition integrals in the determination of oscillator strengths of boron atom. The WBEPM theory has been developed by Zheng [19, 20] and has been applied to calculate various atomic properties in the many electron systems [21–24]. The WBEPM theory base on idea that electrons in a system can be divided into two group of electrons to be the weakest bound electron and non-weakest bound electrons. The weakest bound electron in a given many-electron system is most weakly bound electron to the system when it is compared to the other electrons in the system. By the separation of the electrons in a given system, complex many-electron problem can be simplified as the single electron problem and so can be solve easily. According to the WBEPM theory, electronic radial wave functions are presented as a function of Laguerre polynomial in terms of some parameters which are determined using the experimental energy data and the expectation values of radii [19–25]:

$$R_{nl}(r) = \left(\frac{2Z^*}{n^*}\right)^{l^*+3/2} \left[\frac{2n^*}{(n-l-1)!} \Gamma(n^* + l^* + 1)\right]^{-1/2} \exp\left(-\frac{Z^*r}{n^*}\right) r^{l^*} L_{n-l-1}^{2l^*+1}\left(\frac{2Z^*r}{n^*}\right). \quad (4)$$

The radial transition integral for $k=1$ in case of transition from the level (n_i, l_i) to the level (n_f, l_f) can be obtained as [26–28]

$$\begin{aligned} \langle n_i, l_i | r^k | n_f, l_f \rangle &= \int_0^\infty r^{k+2} R_{n_i l_i}(r) R_{n_f l_f}(r) dr \\ &= (-1)^{n_f+n_i+l_f+l_i} \left(\frac{2Z_f^*}{n_f^*}\right)^{l_f^*} \left(\frac{2Z_i^*}{n_i^*}\right)^{l_i^*} \times \left(\frac{Z_f^*}{n_f^*} - \frac{Z_i^*}{n_i^*}\right)^{-l_f^*-l_i^*-k-3} x \left[\frac{n_f^{*4} \Gamma(n_f^*+l_f^*+1)}{4Z_f^{*3} (n_f-l_f-1)!}\right]^{-1/2} x \\ &\left[\frac{n_i^{*4} \Gamma(n_i^*+l_i^*+1)}{4Z_i^{*3} (n_i-l_i-1)!}\right]^{-1/2} \times \sum_{m_1=0}^{n_f-l_f-1} \sum_{m_2=0}^{n_i-l_i-1} \frac{(-1)^{m_2}}{m_1! m_2!} \left(\frac{Z_f^*}{n_f^*} - \frac{Z_i^*}{n_i^*}\right)^{m_1+m_2} \times \left(\frac{Z_f^*}{n_f^*} + \frac{Z_i^*}{n_i^*}\right)^{-m_1-m_2} x(5) \end{aligned} \quad (5)$$

$$\begin{aligned} &\Gamma(l_f^* + l_i^* + m_1 + m_2 + k + 3) \times \sum_{m_3=0}^S \binom{l_i^* - l_f^* + k + m_2 + 1}{n_f^* - l_f^* - 1 - m_1 - m_3} \times \binom{l_f^* - l_i^* + k + m_1 + 1}{n_i^* - l_i^* - 1 - m_2 - m_3} \times \\ &\binom{l_i^* + l_f^* + k + m_1 + m_2 + m_3 + 2}{m_3}. \end{aligned}$$

Here, quantities Z^* , n^* , l^* are defined to be the effective nuclear charge, effective principal quantum number, and effective azimuthal quantum number, respectively. Moreover, parameters n^* and l^* have been given to be [21–27].

$$n^* = n + d \quad l^* = l + d. \quad (6)$$

Here, d is an adjustable parameter. In order to solve the radial transition integral, Z^* , n^* and l^* parameters must be known. In the determination of these parameters, relevant energy values have been taken from experimental energy data in the literature [15] and expectation values for the radii of levels have been calculated by using the Numerical Coulomb Approximation wave functions [29].

3. Results and Conclusions

In the present paper, electric dipole oscillator strengths have been computed for both individual and multiplet lines between some excited levels of atomic boron using the weakest bound electron potential model theory (WBEPMT). The experimental energy values and expectation values of radii belong to the states are used to obtain parameters Z^* , n^* and l^* . The expectation values of radii for all states have been determined by using Numerical Coulomb approximation (NCA) wave functions [29]. The necessary energy values have been taken from experimental energy data in NIST [15]. The obtained parameters Z^* , d are given in Table 1. Then, making use of these parameters, electric dipole oscillator strengths have been calculated for atomic boron. Our oscillator strength results are listed in Table 2. In this paper, we have studied many transitions belong to both multiplet and individual lines in atomic boron. Experimental and theoretical data are quite limited especially for highly excited and individual transitions. Many of studies have presented low lying states rather than highly excited states and multiplet transitions rather than in-

Table 1. The calculation parameters for oscillator strengths.

| Level | n | l | d | Z^* | $\langle r \rangle$ (a.u.) | Energy (cm^{-1}) |
|----------------------------|-----|-----|------------|-----------|----------------------------|-----------------------------|
| $1s^2 2s^2 3s \ ^2S_{1/2}$ | 3 | 0 | -0.9826218 | 0.9986035 | 6.1218091 | 26888.450 |
| $1s^2 2s^2 3p \ ^2P_{1/2}$ | 3 | 1 | -0.7854374 | 0.9047519 | 7.9868645 | 18316.283 |
| $1s^2 2s^2 3p \ ^2P_{3/2}$ | 3 | 1 | -0.7852724 | 0.9047752 | 7.9877394 | 18314.500 |
| $1s^2 2s^2 3d \ ^2D_{3/2}$ | 3 | 2 | 0.0073581 | 1.0011131 | 10.536153 | 12160.467 |
| $1s^2 2s^2 3d \ ^2D_{5/2}$ | 3 | 2 | 0.0073968 | 1.0011190 | 10.536343 | 12160.296 |
| $1s^2 2s^2 4s \ ^2S_{1/2}$ | 4 | 0 | -0.9688863 | 0.9989076 | 13.811635 | 11917.919 |
| $1s^2 2s^2 4p \ ^2P_{1/2}$ | 4 | 1 | -0.6862802 | 0.9564289 | 17.006006 | 9141.724 |
| $1s^2 2s^2 4p \ ^2P_{3/2}$ | 4 | 1 | -0.6861299 | 0.9564390 | 17.007263 | 9141.086 |
| $1s^2 2s^2 4d \ ^2D_{3/2}$ | 4 | 2 | -0.0349615 | 0.9967445 | 20.736595 | 6934.690 |
| $1s^2 2s^2 4d \ ^2D_{5/2}$ | 4 | 2 | -0.0349159 | 0.9929741 | 20.736937 | 6934.590 |
| $1s^2 2s^2 4f \ ^2F_{5/2}$ | 4 | 3 | -0.0209694 | 0.9975452 | 17.866056 | 6897.073 |
| $1s^2 2s^2 4f \ ^2F_{7/2}$ | 4 | 3 | -0.0209694 | 0.9975452 | 17.866056 | 6897.073 |
| $1s^2 2s^2 5s \ ^2S_{1/2}$ | 5 | 0 | -0.9790742 | 0.9995779 | 24.272253 | 6781.650 |
| $1s^2 2s^2 6s \ ^2S_{1/2}$ | 6 | 0 | -1.0297493 | 1.0004136 | 37.024454 | 4445.870 |
| $1s^2 2s^2 5d \ ^2D_{3/2}$ | 5 | 2 | -0.0434012 | 0.9973078 | 34.051039 | 4442.680 |
| $1s^2 2s^2 5d \ ^2D_{5/2}$ | 5 | 2 | -0.0432719 | 0.9973158 | 34.052373 | 4442.520 |
| $1s^2 2s^2 5f \ ^2F_{5/2}$ | 5 | 3 | -0.0209726 | 0.9983079 | 31.312235 | 4411.580 |
| $1s^2 2s^2 5f \ ^2F_{7/2}$ | 5 | 3 | -0.0209726 | 0.9983079 | 31.312235 | 4411.580 |
| $1s^2 2s^2 5p \ ^2P_{1/2}$ | 5 | 1 | -0.6361346 | 0.9751794 | 29.037577 | 5480.000 |
| $1s^2 2s^2 6d \ ^2D_{3/2}$ | 6 | 2 | -0.0457250 | 0.9979878 | 50.394755 | 3082.810 |
| $1s^2 2s^2 6d \ ^2D_{5/2}$ | 6 | 2 | -0.0457250 | 0.9979878 | 50.394755 | 3082.810 |
| $1s^2 2s^2 6f \ ^2F_{5/2}$ | 6 | 3 | -0.0203907 | 0.9988081 | 47.761675 | 3061.770 |
| $1s^2 2s^2 6f \ ^2F_{7/2}$ | 6 | 3 | -0.0203907 | 0.9988081 | 47.761675 | 3061.770 |
| $1s^2 2s^2 7f \ ^2F_{5/2}$ | 7 | 3 | -0.0198720 | 0.9991238 | 67.211520 | 2248.360 |
| $1s^2 2s^2 7f \ ^2F_{7/2}$ | 7 | 3 | -0.0198720 | 0.9991238 | 67.211520 | 2248.360 |
| $1s^2 2s^2 7s \ ^2S_{1/2}$ | 7 | 0 | -0.7189562 | 0.9982958 | 59.379487 | 2772.100 |
| $1s^2 2s^2 7d \ ^2D_{3/2}$ | 7 | 2 | -0.0467341 | 0.9984698 | 69.744323 | 2262.800 |
| $1s^2 2s^2 7d \ ^2D_{5/2}$ | 7 | 2 | -0.0466545 | 0.9984724 | 69.745609 | 2262.760 |
| $1s^2 2s^2 8d \ ^2D_{3/2}$ | 8 | 2 | -0.0468248 | 0.9988167 | 92.104443 | 1730.790 |
| $1s^2 2s^2 8d \ ^2D_{5/2}$ | 8 | 2 | -0.0468823 | 0.998815 | 92.103344 | 1730.810 |
| $1s^2 2s^2 9d \ ^2D_{3/2}$ | 9 | 2 | -0.0470028 | 0.9990564 | 117.46147 | 1366.460 |
| $1s^2 2s^2 9d \ ^2D_{5/2}$ | 9 | 2 | -0.0470028 | 0.9990564 | 117.46147 | 1366.460 |

Table 2. Electric dipole oscillator strengths for atomic boron

| Lower State (L) | Upper State (U) | TERMS | | Statistical Weight | | This Work | Atomic Line Data | Accepted Values from NIST [Ref.16] | MCHF Result [Ref.13] |
|--------------------|--------------------|-------------|-------------|--------------------|-----------|-----------------|------------------|------------------------------------|----------------------|
| | | L | U | L | U | | | | |
| $2s^2 3s$ | $2s^2 3p$ | 2S | $^2P^\circ$ | 2 | 6 | 1.06e+00 | - | 1.06+00 | 1.11e+00 |
| | | | | 2 | 2 | 3.53e-01 | 3.53e-01 | 3.55e-01[C] | 3.69e-01 |
| | | | | 2 | 4 | 7.06e-01 | 7.07e-01 | 7.10e-01[C] | 7.38e-01 |
| $2s^2 3s$ | $2s^2 4p$ | 2S | $^2P^\circ$ | 2 | 6 | 4.41e-03 | - | - | - |
| | | | | 2 | 2 | 1.48e-03 | 1.07e-03 | - | - |
| | | | | 2 | 4 | 2.92e-03 | 2.14e-03 | - | - |
| $2s^2 3p$ | $2s^2 4s$ | $^2P^\circ$ | 2S | 6 | 2 | 1.79e-01 | - | 1.80e-01 | - |
| | | | | 2 | 2 | 1.79e-01 | 2.05e-01 | 1.90e-01[C] | - |
| | | | | 4 | 2 | 1.80e-01 | 2.05e-01 | 1.89e-01[C] | - |
| $2s^2 3p$ | $2s^2 5s$ | $^2P^\circ$ | 2S | 6 | 2 | 2.10e-02 | - | 1.83e-02 | - |
| | | | | 2 | 2 | 2.10e-02 | 2.08e-02 | 1.83e-02[C] | - |
| | | | | 4 | 2 | 2.10e-02 | 2.08e-02 | 1.83e-02[C] | - |
| $2s^2 3p$ | $2s^2 6s$ | $^2P^\circ$ | 2S | 6 | 2 | 8.51e-03 | - | - | - |
| | | | | 2 | 2 | 8.52e-03 | 6.87e-03 | - | - |
| | | | | 4 | 2 | 8.51e-03 | 6.87e-03 | - | - |
| $2s^2 3p$ | $2s^2 3d$ | $^2P^\circ$ | 2D | 6 | 10 | 8.95e-01 | - | 9.10e-01 | 7.96e-01 |
| | | | | 4 | 4 | 8.95e-01 | 8.24e-01 | 9.10e-01[C] | 7.96e-01 |
| | | | | 4 | 6 | 8.06e-01 | 7.41e-01 | 8.19e-01[C] | 7.16e-01 |
| | | | | 2 | 4 | 8.95e-01 | 8.24e-01 | 9.10e-01[C] | 7.96e-01 |
| $2s^2 3p$ | $2s^2 4d$ | $^2P^\circ$ | 2D | 6 | 10 | 7.47e-04 | - | - | - |
| | | | | 2 | 4 | 7.51e-04 | - | - | - |
| | | | | 4 | 6 | 6.71e-04 | - | - | - |
| | | | | 4 | 4 | 7.44e-05 | - | - | - |
| $2s^2 4p$ | $2s^2 4d$ | $^2P^\circ$ | 2D | 6 | 10 | 1.27e+00 | - | - | - |
| | | | | 2 | 4 | 1.27e+00 | 1.26e+00 | - | - |
| | | | | 4 | 6 | 1.14e+00 | 1.26e+00 | - | - |
| | | | | 4 | 4 | 1.27e+00 | 1.26e+00 | - | - |
| $2s^2 3d$ | $2s^2 4p$ | 2D | $^2P^\circ$ | 10 | 6 | 1.77e-01 | - | - | - |
| | | | | 4 | 2 | 1.48e-01 | 1.52e-01 | - | - |
| | | | | 6 | 4 | 1.77e-01 | 1.82e-01 | - | - |
| | | | | 4 | 4 | 2.96e-02 | 3.04e-02 | - | - |

Estimated accuracy rates (Ref. 16): C < 25%.

Table 2. Continued

| Lower State (L) | Upper State (U) | TERMS | | Statistical Weight | | This Work | Atomic Line Data |
|-------------------------|-------------------------|----------------------------------|----------------------------------|-----------------------|-----------|------------------|------------------------|
| | | <i>L</i> | <i>U</i> | <i>L</i> | <i>U</i> | | |
| 2s²3d | 2s²5p | ²D | ²P^o | 10 | 6 | 8.96e-03 | - |
| | | | | 4 | 2 | 7.46e-03 | - |
| | | | | 6 | 4 | 8.86e-03 | - |
| | | | | 4 | 4 | 1.49e-03 | - |
| 2s²4p | 2s²5s | ²P^o | ²S | 6 | 2 | 3.27e-01 | - |
| | | | | 2 | 2 | 3.27e-01 | 3.35e-01 |
| | | | | 4 | 2 | 3.27e-01 | 3.35e-01 |
| 2s²4p | 2s²6s | ²P^o | ²S | 6 | 2 | 2.87e-02 | - |
| | | | | 2 | 2 | 2.87e-02 | 2.89e-02 |
| | | | | 4 | 2 | 2.87e-02 | 2.89e-02 |
| 2s²4p | 2s²7s | ²P^o | ²S | 6 | 2 | 11.22e-03 | - |
| | | | | 2 | 2 | 11.22e-03 | 8.98e-03 |
| | | | | 4 | 2 | 11.23e-03 | 8.98e-03 |
| 2s²3d | 2s²4f | ²D | ²F^o | 10 | 14 | 1.02e+00 | - |
| | | | | 4 | 6 | 1.02e+00 | 9.85e-01 |
| | | | | 6 | 8 | 9.75e-01 | 9.85e-01 |
| | | | | 6 | 6 | 4.87e-02 | - |
| 2s²3d | 2s²5f | ²D | ²F^o | 10 | 14 | 1.48e-01 | - |
| | | | | 4 | 6 | 1.48e-01 | 1.30e-01 |
| | | | | 6 | 8 | 1.41e-01 | 1.30e-01 |
| | | | | 6 | 6 | 7.08e-03 | - |
| 2s²3d | 2s²6f | ²D | ²F^o | 10 | 14 | 5.43e-02 | - |
| | | | | 4 | 6 | 5.43e-02 | 4.17e-02 |
| | | | | 6 | 8 | 5.17e-02 | 4.17e-02 |
| | | | | 6 | 6 | 2.58e-03 | - |
| 2s²3d | 2s²7f | ²D | ²F^o | 10 | 14 | 2.74e-02 | - |
| | | | | 4 | 6 | 2.73e-02 | 1.90e-02 |
| | | | | 6 | 8 | 2.60e-02 | 1.90e-02 |
| | | | | 6 | 6 | 1.30e-03 | - |
| 2s²4f | 2s²5d | ²F^o | ²D | 14 | 10 | 11.30e-03 | - |
| | | | | 6 | 4 | 10.55e-03 | 9.73e-03 |
| | | | | 8 | 6 | 11.29e-03 | 9.73e-03 |
| | | | | 6 | 6 | 7.53e-04 | - |

Estimated accuracy rates (Ref. 16): C < 25%.

Table 2. Continued

| Lower State (L) | Upper State (U) | TERMS | | Statistical Weight | | This Work | Atomic Line Data |
|-------------------------|-------------------------|----------------------------------|----------------------|-----------------------|-----------|-----------------|------------------------|
| | | <i>L</i> | <i>U</i> | <i>L</i> | <i>U</i> | | |
| 2s²4f | 2s²6d | ²F^o | ²D | 14 | 10 | 1.60e-03 | - |
| | | | | 6 | 4 | 1.89e-03 | 1.82e-03 |
| | | | | 8 | 6 | 2.03e-03 | - |
| | | | | 6 | 6 | 1.35e-04 | - |
| 2s²4f | 2s²7d | ²F^o | ²D | 14 | 10 | 9.30e-04 | - |
| | | | | 6 | 4 | 8.68e-04 | 6.68e-04 |
| | | | | 8 | 6 | 9.30e-04 | - |
| | | | | 6 | 6 | 6.20e-05 | - |
| 2s²5f | 2s²6d | ²F^o | ²D | 14 | 10 | 2.98e-02 | - |
| | | | | 6 | 4 | 2.78e-02 | 2.66e-02 |
| | | | | 8 | 6 | 2.98e-02 | - |
| | | | | 6 | 6 | 1.98e-03 | - |
| 2s²5f | 2s²7d | ²F^o | ²D | 14 | 10 | 5.47e-03 | - |
| | | | | 6 | 4 | 5.11e-03 | 5.13e-03 |
| | | | | 8 | 6 | 5.47e-03 | 5.13e-03 |
| | | | | 6 | 6 | 3.64e-04 | - |
| 2s²5f | 2s²8d | ²F^o | ²D | 14 | 10 | 2.51e-03 | - |
| | | | | 6 | 4 | 2.34e-03 | 1.91e-03 |
| | | | | 8 | 6 | 2.51e-03 | 1.91e-03 |
| | | | | 6 | 6 | 1.67e-04 | - |
| 2s²6f | 2s²7d | ²F^o | ²D | 14 | 10 | 5.31e-02 | - |
| | | | | 6 | 4 | 4.96e-02 | 4.79e-02 |
| | | | | 8 | 6 | 5.31e-02 | - |
| | | | | 6 | 6 | 3.54e-03 | - |
| 2s²6f | 2s²8d | ²F^o | ²D | 14 | 10 | 9.85e-03 | - |
| | | | | 6 | 4 | 9.19e-03 | 9.48e-03 |
| | | | | 8 | 6 | 9.85e-03 | 9.48e-03 |
| | | | | 6 | 6 | 6.56e-04 | - |
| 2s²6f | 2s²9d | ²F^o | ²D | 14 | 10 | 4.54e-03 | - |
| | | | | 6 | 4 | 4.23e-03 | 3.60e-03 |
| | | | | 8 | 6 | 4.54e-03 | 3.60e-03 |
| | | | | 6 | 6 | 3.02e-04 | - |

Estimated accuracy rates (Ref. 16): $C < 25\%$.

Table 2. Continued

| Lower State (L) | Upper State (U) | TERMS | | Statistical Weight | | This Work | Atomic Line Data |
|-------------------------|-------------------------|----------------------|----------------------------------|-----------------------|-----------|-----------------|------------------------|
| | | <i>L</i> | <i>U</i> | <i>L</i> | <i>U</i> | | |
| 2s²4d | 2s²4f | ²D | ²F^o | 10 | 14 | 1.71e-02 | - |
| | | | | 4 | 6 | 1.72e-02 | 1.68e-02 |
| | | | | 6 | 8 | 1.63e-02 | 1.68e-02 |
| | | | | 6 | 6 | 8.17e-04 | - |
| 2s²4d | 2s²5f | ²D | ²F^o | 10 | 14 | 8.61e-01 | - |
| | | | | 4 | 6 | 8.61e-01 | 8.92e-01 |
| | | | | 6 | 8 | 8.20e-01 | - |
| | | | | 6 | 6 | 4.10e-02 | - |
| 2s²4d | 2s²6f | ²D | ²F^o | 10 | 14 | 1.25e-01 | - |
| | | | | 4 | 6 | 1.25e-01 | 1.84e-01 |
| | | | | 6 | 8 | 1.19e-01 | - |
| | | | | 6 | 6 | 5.99e-03 | - |
| 2s²4d | 2s²7f | ²D | ²F^o | 10 | 14 | 8.34e-02 | - |
| | | | | 4 | 6 | 8.34e-02 | 7.08e-02 |
| | | | | 6 | 8 | 7.94e-02 | 7.08e-02 |
| | | | | 6 | 6 | 3.97e-03 | - |
| 2s²5d | 2s²5f | ²D | ²F^o | 10 | 14 | 5.08e-02 | - |
| | | | | 4 | 6 | 5.48e-02 | 5.02e-02 |
| | | | | 6 | 8 | 4.83e-02 | - |
| | | | | 6 | 6 | 2.41e-03 | - |
| 2s²5d | 2s²6f | ²D | ²F^o | 10 | 14 | 8.44e-01 | - |
| | | | | 4 | 6 | 8.44e-01 | 8.26e-01 |
| | | | | 6 | 8 | 8.04e-01 | 8.26e-01 |
| | | | | 6 | 6 | 4.02e-02 | - |
| 2s²6d | 2s²6f | ²D | ²F^o | 10 | 14 | 8.44e-02 | - |
| | | | | 4 | 6 | 8.44e-02 | 8.32e-02 |
| | | | | 6 | 8 | 8.04e-02 | 8.32e-02 |
| | | | | 6 | 6 | 4.02e-03 | - |
| 2s²6d | 2s²7f | ²D | ²F^o | 10 | 14 | 8.89e-01 | - |
| | | | | 4 | 6 | 8.89e-01 | 7.97e-01 |
| | | | | 6 | 8 | 8.13e-01 | 7.97e-01 |
| | | | | 6 | 6 | 4.23e-02 | - |

Estimated accuracy rates (Ref. 16): C < 25%.

dividual transitions in the literature for boron. Moreover, in most of these studies, transition probabilities, lifetimes, and energy values rather than oscillator strengths have been calculated or measured. Therefore, the results obtained from our calculations have been compared only with NIST data, atomic line data and MCHF results. The NIST values are given together with their accuracy rate in relevant columns of tables.

It has been seen from Table 2 that the data calculated via WBEPM theory in this work presents a good agreement with MCHF results, atomic line data and accepted values given with their accurate rates. While the calculation procedure for the systems with a few electrons can be carried out easily, the calculations have become more difficult and complex in the case of increasing number of electrons. Especially for excited states of many-electron systems, more configurations must be considered. Therefore, calculations become more complicated. In the Hartree-Fock calculations, atomic wave functions are expanded with a number of basis-set orbital functions. For more accurate results, larger sets should be taken into account. For highly excited states of many electron atoms, it is difficult to obtain appropriate basis-set orbital functions and configurations.

WBEPM theory is a semi-empirical method. It is a one-electron approximation which assumes that each radiative transition rate can be approximated by hydrogenic expressions in which the orbital parameters are fitted to both energy and radius of the weakest bound electron. In this method, relativistic effects are neglected except for the binding energies. Accuracy and reliability of the results obtained using this theory strongly depend on expectation values of radii and energy values which are used in determination of parameters Z^* , n^* and l^* . Previously, Çelik et al. employed WBEPM theory in atomic lithium [30], nitrogen [31,32], oxygen [33], fluorine [34], sodium [35], potassium [36] and obtained very satisfactory transition probability and oscillator strength results. This method has a simple calculation procedure. Moreover, the determination of parameters Z^* , n^* and l^* is sufficient to calculate spectroscopic parameters.

Acknowledgment

This paper contains atomic line data obtained from the Atomic Line List v2.04, available at <http://www.pa.uky.edu/~peter/atomic>. The authors gratefully acknowledge the Selçuk University Scientific Research Projects (BAP) Coordinating Office for support.

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