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# Ab-initio Calculations for Forbidden M1/E2 Decay Rates in Ti XIX ion

A. Farrag *

*Physics Department,Faculty of Science,*
*Cairo University, Cairo, Egypt*

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**Abstract:** The rates of the electric quadrupole E2 and magnetic dipole M1 forbidden transitions in the ground configuration and some excited configurations of the Ti XIX ion have been calculated. The multiconfiguration Hartree - Fock (MCHF) method has been used. The relativistic corrections are included in the Breit - Pauli approximation. A detailed comparison of the present theoretical results with previous calculations and the available data in literature is presented.


*Keywords: Ab-initio Calculations, Multiconfiguration Hartree - Fock, Ti XIX Ion, Breit -Pauli Approximation*
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## 1. Introduction

Recently there has been considerable interest in the forbidden electric quadrupole and magnetic dipole transitions in ionic systems. These forbidden lines are spectral lines which arise from transitions that are forbidden by selection rules for the electric dipole E1 transitions. The M1 and E2 transitions have been found to be very useful in the diagnostics of astrophysical and laboratory plasmas [1,2] and are necessary for the interpretation of the observed line intensities and may contribute to the width and shape of the spectral line associated with nearby allowed transitions [3,4]. These transitions often represent optically thin lines i.e isolated lines with low transition probabilities, due to low self-absorption effects in the plasma. Moreover, the M1and E2 lines frequently occur at longer wavelengths, if compared with the electric-dipole allowed transitions, since they may connect the levels within the same electron configuration. Thus, by having lines

* azza_farrag@hotmail .com

in the visible or near uv range, high resolution techniques can be employed in order to obtain detailed information including the shape of the lines.

Traditionally, the interest in these lines has come from the astrophysicists and has been restricted to light elements. More recently, however, such lines have been observed in fusion plasmas. In particular, Tokamak plasmas have been found to be a rich source of forbidden lines in heavy elements, heavier than those observed in the stars; these lines have been used for diagnostic purposes in Tokamak machines.

A current interest in the forbidden transitions of the metallic impurity elements in Tokamak discharges results from their use for certain diagnostic purposes. The intensities of these transitions allow measurements of the concentrations of impurity ions which originate in the high temperature interior of the discharge.

Many calculations of the dipole oscillator strengths have been made for the Be- like ions [5, 6], and dipole transition rates are now known quite accurately for many transitions of he Be-isoelectronic sequence. Some studies of the forbidden transition rates have appeared in literature [7, 8, 13, 15]. Given the importance of forbidden transition for the Be-like –Ti ion, it is important to present accurate data for these transition rates.

Forbidden transitions for highly ionized Be like ions are expected to play an increasingly important role in fusion plasma diagnostics in future, but until recently, very little was known about these transitions. This paper intends to fill this gap.

The theory is presented in section 2. Section 3 displays the results of the present calculations together with a comparison of these results with the available data in literature; finally a conclusion is given in the last section 4.

## 2. Theoretical Method and Computational Procedure

In this study, the atomic state wave functions (ASFs) have been generated by the widely used atomic structure package method, the multiconfiguration Hartree-Fock MCHF method [9].

The theoretical approach employed is sketched below. A more detailed description can be found in [10]. The relativistic effect is included as a correction to the non relativistic Hamiltonian by adding the Breit -Pauli operator.

### 2.1 The Breit - Pauli Wave Functions

In the multiconfiguration approximation, the Breit -Pauli wave functions for a state labeled $\gamma JM_J$, where $\gamma$represents the configuration and the set of quantum numbers required to specify the state, are expanded in terms of configuration state functions (CSFs)

$$\psi(\gamma JM_J) = \sum_{i=1}^{M} c_i \phi(\gamma_i L_i S_i JM_J) \tag{1}$$

The configuration state functions $\phi$ are antisymmetrized linear combinations of the products of the spin-orbitals functions

$$\phi(\gamma LSJM_J) = \sum_{M_L M_S} \langle LM_L SM_S | LSJM_J \rangle \phi(LM_L SM_S) \tag{2}$$

$$\phi_{n\ell m_\ell m_s} = \tfrac{1}{r} P_{n\ell}(r) Y_{\ell m_\ell}(\theta, \varphi) \xi_{m_s}(\sigma) \tag{3}$$

In the present method, the radial functions building the CSFs are taken from a non-relativistic MCHF code and only the expansion coefficients are optimized, this leads to the matrix eigen value problem

$$H\psi = E\psi \tag{4}$$

where H is the Hamiltonian matrix with elements

$$H_{ij} = \langle \gamma_i L_i S_i JM_J | \mathrm{H}_{BP} | \gamma_J L_j S_j JM_J \rangle \tag{5}$$

The problem of finding the eigenvalues and eigenfunctions of the Breit –Pauli Hamiltonian can be reduced to the evaluation of matrix elements between LSJ coupled CSFs and a matrix diagonalization for each J value.

## 2.2 The Breit - Pauli Hamiltonian

The Breit - Pauli Hamiltonian is a first order perturbation correction to the non – relativistic Hamiltonian.
The Breit-Pauli Hamiltonian is given by:

$$\mathrm{H}_{BP} = \mathrm{H}_{NR} + \mathrm{H}_{RS} + \mathrm{H}_{FS} \tag{6}$$

where $\mathrm{H}_{NR}$is the ordinary non-relativistic many electron Hamiltonian .

$$\mathrm{H}_{NR} = \sum_{i=1}^{N} \left( -\frac{1}{2}\nabla_i^2 - \frac{Z}{r_i} \right) + \sum_{i>j}^{N} \frac{i}{r_{ij}} \tag{7}$$

$\mathrm{H}_{RS}$ is the relativistic shift operator which commutes with L and S and can be written as

$$\mathrm{H}_{RS} = \mathrm{H}_{MC} + \mathrm{H}_{D1} + \mathrm{H}_{D2} + \mathrm{H}_{OO} + \mathrm{H}_{SSC} \tag{8}$$

where $\mathrm{H}_{MC}$ is the mass correction term

$$\mathrm{H}_{MC} = -\frac{1}{\alpha^2} \sum_{i=1}^{N} (\nabla_i^2)^\dagger \nabla_i^2 \tag{9}$$

and $\mathrm{H}_{D1}$ and $\mathrm{H}_{D2}$ are the one and two – body Darwin terms

$$\mathrm{H}_{D1} = -\frac{\alpha^2 Z}{8} \sum_{i=1}^{N} \nabla_i^2 (\frac{1}{r_i}) \quad , \tag{10}$$

$$\mathrm{H}_{D2} = \frac{\alpha^2}{4} \sum_{i<j}^{N} \nabla_i^2 (\frac{1}{r_i}) \quad . \tag{11}$$

$\mathrm{H}_{OO}$ is the orbit-orbit term

$$\mathrm{H}_{OO} = -\frac{\alpha^2}{2} \sum_{i<j}^{N} \left[ \frac{P_i.P_j}{r_{ij}} + \frac{r_{ij}(r_{ij}.P_i)P_j}{r_{ij}^3} \right] \tag{12}$$

and finally $\mathrm{H}_{SSC}$ is the spin-spin contact term

$$\mathrm{H}_{SSC} = -\frac{8\pi\alpha^2}{3} \sum_{i<j}^{N} (s_i.s_j)\delta(r_i.r_j) \tag{13}$$

The fine - structure operator $\mathrm{H}_{FS}$ describes the interactions between the spin and orbital angular momenta of the electrons, and does not commute with L and S but only with the total angular momemtum J=L+S.

The fine –structure operator $\mathrm{H}_{FS}$ consists of three terms:

$$\mathrm{H}_{FS} = \mathrm{H}_{SO} + \mathrm{H}_{SOO} + \mathrm{H}_{SS} \tag{14}$$

where $\mathrm{H}_{SO}$ is the spin-orbit term

$$H_{SO} = \frac{\alpha^2 Z}{2} \sum_{i=1}^{N} \frac{1}{r_i^3} \ell_i.s_i \tag{15}$$

$\mathrm{H}_{SOO}$ is the spin-other-orbit term

$$\mathrm{H}_{SOO} = -\frac{\alpha^2}{2} \sum_{i<j}^{N} \frac{r_{ij} \times P_i}{r_{ij}^3} (s_i + 2s_j) \tag{16}$$

and $\mathrm{H}_{SS}$ is spin –spin term

$$H_{SS} = \alpha^2 \sum_{i<j}^{N} \frac{1}{r_{ij}^3} \left[ s_i.s_j - 3\frac{(s_i.r_{ij})(s_j.r_{ij})}{r_{ij}^2} \right] \tag{17}$$

## 2.3 Electric Quadrupole Decay Rates: E2

The transition probabilities are calculated using the following formula

$$A_{E2} = \frac{1.120 \times 10^{18}}{g_i \lambda^5} S_{E2} \quad \mathrm{in}(sec^{-1}) \tag{18}$$

where $\lambda$ is the transition wavelength in Å, $\mathrm{g}_i$ is the statistical weight of the initial state and $\mathrm{S}_{E2}$ is the line strength given by

$$S_{E2} = \left| \langle \Psi_f \left| O_{E2} \right| \Psi_i \rangle \right|^2 \tag{19}$$

$O_{E2}$ is the electric quadrupole operator

$$O_{E2} = \sum_i r_i^2 C_q^{(2)}(i) \tag{20}$$

Because this operator has even parity, the electric quadrupole transitions involve no change in parity . The selection rules on the total angular momentum are

$\Delta$J=0, $\pm$1, $\pm$2 J+J'$\geq$ 2

where J and J' are the total angular momentum for the initial and final states, respectively.

## 2.4 Magnetic Dipole Decay Rates: M1

The transition probabilities are calculated using the following formula

$$A_{M1} = \frac{2.697 \times 10^{13}}{g\lambda^3} S_{M1} \quad (sec^{-1}) \tag{21}$$

where $\lambda$ is the transition wavelength in Å, $g_i$ is the statistical weight of the initial state and $S_{M1}$ is the line strength given by:

$$S_{M1} = |\langle \psi_f | O_{M1} | \psi_i \rangle|^2$$

## 3. Results and Discussion

The MCHF method has been used with the Breit-Pauli relativistic corrections to calculate the transition energies, wavelengths and the electric quadrupole and magnetic dipole transition rates for the Ti XIX ion of the Be-isoelectronic sequence and that among each of the configurations 2s2p, $2p^2$ and the transitions between $2s^2$ and $2p^2$.

It should be mentioned here that there are two alternative forms of the electric dipole matrix element, namely the length form and the velocity form. The two forms are equivalent for exact solutions of the Hamiltonian. It is customary to compute both forms and use the agreement between the two results as one of the quality criteria for the calculation. Moreover that the agreement between the length and velocity form is a necessary condition for accurate wavefunctions. These wavefunctions have been used to calculate the magnetic dipole and the electric quadrupole transitions between the n=2-2 levels.

It should be noticed that the dominant correlation effect is in the n=2 intrashell correlation using the three configuration basis composed of $2s^2$, 2s2p and $2p^2$. To achieve a better agreement between experiment and theory for the transition energies between the n=2-2 levels, additional correlation functions have to be included in the basis set including most of the n=3 configurations. No attempt has been made to include configurations with n=4 and n=5 in the basis functions in the present work.

In these ab-initio calculations, the wavefunctions with configuration interactions (CI) between the levels with the same parity and the same total angular momentum have been obtained. The even configurations considered are ($2s^2$ , $2p^2$ , 2s3s , 2s3d , 2p3p and $3p^2$)

while the odd configurations are (2s2p ,2s3p ,2p3s ,2p3d , 3s3p and 3p3d), outside the$1s^2$ core.

Tables (I), (II) and (III) present the transition energies ΔE, the wavelengths ($\lambda$), the electric quadrupole transitions rates A(E2) and the magnetic dipole transitions rates A(M1) for the transitions among the 2s2p, $2p^2$and the transition from $2s^2$ to $2p^2$ configurations. The present calculated values are referred to (a) while (b) refers to Glass results [11] which presented very sophisticated relativistic intermediate-coupling calculations of the wavefunctions and (c) stands for the calculations of Bhatia et al [12] which also used relativistic intermediate coupling wavefunctions, while (d) stands for the semiempirical wavelengths of Edlén [14], (e) gives the NIST values [16] and (f) are the values for the multiconfiguration Dirac –Fock (MCDF) of Froese-Fischer [15].

The NIST values are followed by a capital letter denoting the uncertainties in the atomic transition probability data which is C for uncertainties within 25%, D for uncertainties within 50% and E for uncertainties greater than 50%.

## 3.1 M1/E2 Transitions Among the 2s2p Levels

The 2s2p configuration of Ti XIX has 4 fine structure levels $^1P_1$ and $^3P_{0,1,2}$. These levels are separated into two groups by the different multiplets. The possible E2 transitions among these 2s2p levels include the 2s2p ($^1P_1$–$^3P_{1,2}$), $2s2p$($^3P_1$–$^3P_2$) and ($^3P_0$–$^3P_2$) lines, while for the possible M1 transitions they include the 2s2p ($^1P_1$–$^3P_{0,1,2}$),$2s2p$($^3P_0$–$^3P_1$) and 2s2p ($^3P_1$–$^3P_2$) lines.

As seen from table I, the calculated transition energies from the singlet state to the triplet states are in good agreement with the calculations (b) of Glass and (f) of Froese- Fischer, both calculations were done performing purely relativistic calculations, the relative percentage is a maximum of 1% with Glass and NIST values and up to 0.2% with Froese –Fischer, the discrepancy with the calculation of Bathia et al. is slightly large, it is up to 3.4% relative percentage difference, while with the semi –empirical values of Edlén, the agreement is good and is less than 1% relative percentage difference.

For the triplet-triplet transitions, the ($^3P_0$–$^3P_1$) line show the biggest discrepancy, the difference is 787.5 $cm^{-1}$ which is 4.8% relative percentage difference as compared to Glass and 670.13 $cm^{-1}$or 4% as compared to Froese–Fischer. For all the other presented data, the relative percentage difference with the other calculations does not exceed 0.2%.

The electric quadrupole E2 and the magnetic dipole M1 transition probabilities show good agreement with the calculations of Froese-Fischer, it is 3.4% maximum of the relative percentage difference and 13.7% maximum of the relative percentage difference with all other calculations.

## 3.2 M1/E2 transitions among the $2p^2$ levels

The $2p^2$ configuration of Ti XIX has 5 fine structure levels $^3P_{0,1,2}$, $^1D_2$, $^1S_0$, which are separated into three groups by the different multiplets. The possible E2 transitions among the $2p^2$ levels include seven transitions, while the M1 transitions include five transitions which are presented in table II.

Our calculated values for the transitions between $2p^2$ levels are close to the semi empirical values of Edlén and the (MCDF) calculations of Froese-Fischer. They have up to 1% relative percentage with Edlén and up to 0.2% with the calculations of Froese-Fischer. The present calculated transition energies among the triplet states show a large difference with that of Glass and Bathia et al. for the ($^3P_1-^3P_2$) transition, the difference is 710 $cm^{-1}$ or 2.5% with Glass and 2268 $cm^{-1}$ or 7.5% with Bathia et al., but it is 116.2 $cm^{-1}$or 0.4% with Edlén and 41.04 $cm^{-1}$or 0.14% with Froese-Fischer. The value of the E2 decay is weak among the triplet states, in these transitions the M1 decay is about four to five orders of magnitude faster than the E2 decay.

In the singlet D and triplet P transitions, our calculated transition energies show the best agreement with the (MCDF) calculations of Froese-Fischer, it is 156.8 $cm^{-1}$or 0.1%, 78.8 $cm^{-1}$ or 0.07% and 119.9 $cm^{-1}$or 0.13 % for the transitions ($^1D_2-^3P_{0,1,2}$ ), respectively.

The transitions to the singlet S show a good agreement with all the calculations as well as with the semi empirical values of Edlén and the NIST values, it is 1% of the relative percentage difference for all transitions except for the ($^3P_{1-}{}^1S_0$) there is a difference of 7852.1 $cm^{-1}$ or 2.5% of the relative percentage difference and for ($^3P_{2-}{}^1S_0$) a difference of 5577.7 $cm^{-1}$ or 2% with the calculations of Bathia et al.. For the transition rates, the A(E2) agree to within 15% and within 9% for the A(M1) of the relative percentage difference with all other calculations.

## 3.3 M1/E2 transitions between the $2s^2 - 2p^2$ levels

In table III the even-even transitions between $2s^2 - 2p^2$ levels arise in two transitions ($^1S_0-^3P_2$) and ($^1S_0-^1D_2$) for the electric quadrupole, they have prominent transition probabilities A(E2), and have one transition ($^1S_0-^3P_1$) for the magnetic dipole. In these transitions the relative percentage difference for the transition energies agrees with all other calculations and with the semi empirical values of Edlén as well as with the NIST values, there is less than 9% as maximum of relative percentage difference.

The quadrupole transition rates present a relative percentage of 50 % and 45 % with the values of Glass and Bathia et al., respectively but show a better agreement with that of Froese-Fischer, it is 16% with the same transition ($^1S_0-^1D_2$) and for the ($^1S_0-^3P_2$) transition the relative percentage difference is 39%, 32% and 40% with that of Glass, Bathia et al and the NIST, respectively, but it is close to the calculation of Froese-Fischer, it is 7.5% of a relative percentage difference.

The magnetic dipole decay rates for ($^1S_0-^3P_1$) transition show a good agreement between all calculations, it has a difference of 4.65% with that of Glass, 8.7% with Bathia et al, 6.8% with the NIST values and 1.75% with Froese-Fischer.

## Conclusion

In summary, the multi-configuration Hartree-Fock (MCHF) method has been used to study the E2 and M1 transitions among some configurations of TiXIX, the inclusion of the configuration interaction and relativistic corrections by using the Breit-Pauli approximation in the calculation of the wave functions yielded satisfactory results as compared with the available theoretical data in literature.

It should be mentioned here that while progress is being made at the theoretical level, there is a lack of experimental data to check this material. Experimental measured transition energies and transition probabilities are highly desirable for the highly ionized atomic system.

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**Table 1** Transition energies ($cm^{-1}$), wavelength (Å) and E2,M1 transition probabilities ($sec^{-1}$) within the 2s2p configuration of Ti XIX

| Transition | | $\Delta E_{ij}$($cm^{-1}$) | $\lambda$ ( Å) | A (E2) | A (M1) |
|---|---|---|---|---|---|
| $^1P_1 - ^3P_0$ | a | 303821 | 329.14 | | 5.03E+03 |
| | b | 303683 | 329.29 | | 4.46E+03 |
| | c | 312470 | 320.03 | | 4.94E+03 |
| | d | 30152 | 331.65 | | |
| | e | 301504.5 | 331.67 | | 4.50E+03 D |
| | f | 303110.9 | 329.91 | | 4.93E+03 |
| $^1P_1 - ^3P_1$ | a | 286691 | 348.8 | 9.69E+00 | 3.21E+03 |
| | b | 286779 | 348.02 | 9.87E+00 | 2.81E+03 |
| | c | 295394 | 338.53 | | 3.10E+03 |
| | d | 285095 | 350.76 | | |
| | e | 285095.2 | 350.76 | 9.90E+00 | 2.80E+03 D |
| | f | 286651.03 | 348.85 | 9.80E+00 | 3.17E+03 |
| $^1P_1 - ^3P_2$ | a | 244459 | 409.06 | 1.89E+00 | 3.32E+03 |
| | b | 244678.9 | 408.7 | 1.49E+00 | 2.92E+03 |
| | c | 253267 | 394.84 | | 3.29E+03 |
| | d | 242453 | 412.45 | | |
| | e | 242453.6 | 412.45 | | 2.90E+03 D |
| | f | 244025.31 | 409.79 | 1.84E+00 | 3.25E+03 |
| $^3P_0 - ^3P_1$ | a | 17130 | 5837.71 | | 8.20E+01 |
| | b | 16342.5 | 6119 | | 7.81E+01 |
| | c | 17073.5 | 5857 | | 8.87E+01 |
| | d | 16433.8 | 6085 | | |
| | f | 16459.87 | 6075.32 | | 7.93E+01 |
| $^3P_0 - ^3P_2$ | a | 59362 | 1684.6 | 3.86E-02 | |
| | b | 58997 | 1695 | 3.65E-02 | |
| | c | 59206.6 | 1689 | 3.77E-02 | |
| | d | 59066.7 | 1693 | | |
| | f | 59085.59 | 1692.44 | 3.77E-02 | |
| $^3P_1 - ^3P_2$ | a | 42232 | 2367.8 | 1.67E-02 | 1.04E+03 |
| | b | 42662.1 | 2344 | 1.60E-02 | 1.04E+03 |
| | c | 42122.9 | 2374 | | 9.99E+02 |
| | d | 42643.9 | 2345 | | |
| | f | 42625.72 | 2345.98 | 1.65E-02 | 1.03E+03 |

**Table 2** Transition energies ($cm^{-1}$), wavelength (Å) and E2,M1 transition probabilities ($sec^{-1}$) within the $2p^2$configuration of Ti XIX

| Transition | | $\Delta E_{ij}$($cm^{-1}$) | λ ( Å) | A (E2) | A (M1) |
|---|---|---|---|---|---|
| $^3P_0-^3P_1$ | a | 29069 | 3440.09 | | 3.44E+02 |
| | b | 28776.98 | 3475 | | 4.19E+02 |
| | c | 28563.27 | 3501 | | 4.08E+02 |
| | d | 29044.44 | 3443 | | |
| | e | 29088.37 | 3437.8 | | 4.19E+02 C |
| | f | 29001.24 | 3448.09 | | 4.25E+02 |
| $^3P_0-^3P_2$ | a | 56695.8 | 1763.8 | 3.54E-02 | |
| | b | 57110.2 | 1751 | 3.32E-02 | |
| | c | 58445.35 | 1711 | 3.79E-02 | |
| | d | 56561 | 1768 | | |
| | f | 56668.59 | 1764.63 | 3.20E-02 | |
| $^3P_1-^3P_2$ | a | 27626.8 | 3619.7 | 1.55E-03 | 2.45E+02 |
| | b | 28336.6 | 3529 | 1.89E-03 | 2.77E+02 |
| | c | 29895.3 | 3345 | | 3.23E+02 |
| | d | 27510.3 | 3635 | | |
| | e | 27527.73 | 3632.7 | | 2.77E+02 C |
| | f | 27667.35 | 3614.33 | 1.64E-03 | 2.50E+02 |
| $^1D_2-^3P_0$ | a | 142806 | 700.25 | 3.30E-03 | |
| | b | 144408.5 | 692.48 | 1.48E-03 | |
| | c | 149423.2 | 669.24 | 2.37E-03 | |
| | d | 141799.7 | 705.22 | | |
| | f | 142657.99 | 700.97 | 7.72E-03 | |
| $^1D_2-^3P_1$ | a | 113737 | 879.22 | 2.44E-01 | 2.14E+03 |
| | b | 115625.7 | 864.86 | 2.43E-01 | 2.14E+03 |
| | c | 120863.4 | 827.38 | | 2.50E+03 |
| | d | 112756.1 | 886.87 | | |
| | e | 112688.8 | 887.4 | | 2.10E+03 D |
| | f | 113656.75 | 879.83 | 2.62E-01 | 2.42E+03 |
| $^1D_2-^3P_2$ | a | 86110.2 | 1161.3 | 3.90E-01 | 2.45E+03 |
| | b | 87260.03 | 1146 | 3.74E-01 | 2.48E+03 |
| | c | 90991.81 | 1099 | | 2.87E+03 |
| | d | 85251.49 | 1173 | | |
| | e | 85171.62 | 1174.1 | | 2.50E+03 D |
| | f | 85989.4 | 1162.92 | 4.09E-01 | 2.77E+03 |
| $^3P_1-^1S_0$ | a | 301837.74 | 331.3 | | 3.90E+04 |
| | b | 304053 | 328.89 | | 4.01E+04 |
| | c | 309.4693 | 322.9 | | 4.27E+04 |
| | d | 299320.5 | 334.09 | | |
| | e | 299275.8 | 334.14 | | 3.80E+04 D |
| | f | 301596.32 | 331.57 | | 4.17E+04 |
| $^3P_2-^1S_0$ | a | 274210.94 | 364.68 | 9.48E+01 | |
| | b | 275710 | 362.7 | 8.71E+01 | |
| | c | 279790.7 | 357.41 | 9.84E+01 | |
| | d | 271805.6 | 367.91 | | |
| | f | 273928.97 | 365.05 | 1.01E+02 | |
| $^1D_2-^1S_0$ | a | 188100.74 | 531.63 | 2.36E+02 | |
| | b | 188423.3 | 530.72 | 2.14E+02 | |
| | c | 188828.9 | 529.58 | 2.19E+02 | |
| | d | 186560.2 | 536.02 | | |
| | f | 187939.57 | 532.08 | 2.05E+02 | |

**Table 3** Transition energies ($cm^{-1}$), wavelength (Å) and E2,M1 transition probabilities ($sec^{-1}$) within the $2s^2$ - $2p^2$ transitions for Ti XIX

| Transition | | $\Delta E_{ij}(cm^{-1})$ | $\lambda$ ( Å) | A (E2) | A (M1) |
|---|---|---|---|---|---|
| $^1S_0 - {^3P_2}$ | a | 832671.8 | 120.09 | 6.74E+02 | |
| | b | 833263.9 | 120.01 | 4.84E+02 | |
| | c | 834794.2 | 119.79 | 5.10E+02 | |
| | d | 832362.2 | 120.14 | | |
| | e | 832431.5 | 120.13 | 4.80E+02 E | |
| | f | 832488.52 | 120.12 | 7.28E+02 | |
| $^1S_0 - {^3P_1}$ | a | 805045 | 124.21 | | 2.05E+03 |
| | b | 804893.8 | 124.24 | | 2.15E+03 |
| | c | 804893.8 | 124.24 | | 2.25E+03 |
| | d | 804829 | 124.25 | | |
| | e | 804893.8 | 124.24 | | 2.20E+03 E |
| | f | 804821.16 | 124.25 | | 2.09E+03 |
| $^1S_0 - {^1D_2}$ | a | 918782 | 108.83 | 8.46E+03 | |
| | b | 920556 | 108.63 | 5.62E+03 | |
| | c | 925754.5 | 108.02 | 5.83E+03 | |
| | d | 917599.6 | 108.98 | | |
| | f | 918477.92 | 108.87 | 7.28E+03 | |