# Atomic data from the Iron Project

## VII. Radiative dipole transition probabilities for Fe II*

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**Abstract.** Oscillator strengths, line strengths and Einstein $A$-coefficients are obtained for a large number of dipole allowed ($\Delta S = 0$) fine structure transitions in Fe II. Spectroscopic energies of the observed fine structure levels are employed in the transformation from $LS$ coupled multiplet strengths to the individual fine structure lines. The transition probabilities are thus significantly improved in accuracy over those obtained with calculated energies. As part of the second phase of the Iron Project the present work is part of the effort to improve the accuracy and the utility of the Opacity Project data. The calculations correspond to a 83-state close coupling calculations for Fe II described by Nahar & Pradhan (1994). Comparison of present oscillator strengths and lifetimes is made with experimental values, and with those calculated by Kurucz; the present values show an overall better agreement with the experimental data. Radiative data is obtained for 21,589 dipole allowed fine structure transitions in Fe II.

**Key words:** atomic data – plasmas – ultraviolet: general – infrared: genereal

## 1. Introduction

The atomic radiative data for energy levels, oscillator strengths, and photoionization cross sections for essentially all astrophysically abundant atoms and ions of the Opacity Project (OP) have been calculated in $LS$ coupling (Seaton et al. 1994). The OP calculations are carried out in an *ab initio* manner using the close coupling (CC) approximation and employing the R-matrix method. The aim of the present work, an extension of the OP (Nahar 1993) and a part of the Iron Project (IP, Hummer et al. 1993), is to provide an extensive dataset for the oscillator strengths ($f$-values), the line strengths ($S$) and the spontaneous radiative decay rates ($A$-values) of fine structure levels for the

spectroscopic applications in laboratory and astrophysical plasmas.

While the dominant emphasis of the IP is on collisional processes, it is also envisaged that the accuracy of some of the radiative OP data, particularly for the heavy Iron group elements, would also be improved by the IP effort. Furthermore, the practical utility of the radiative data for a variety of astrophysical and laboratory applications would be enhanced by extending the $LS$ coupling data to include fine structure and using observed spectroscopic energies rather than the calculated ones. With respect to the first criterion, in a recent study we described new OP calculations for Fe II (Nahar & Pradhan 1994, NP) that differ considerably from the earlier work of Sawey & Berrington (1992). The extension of the Fe II calculations to fulfill the second criterion forms the basis of the present report. In principle the fine structure should be considered by a complete treatment of the relativistic effects, in an intermediate coupling scheme, as well as electron-electron correlation effects that manifest themselves as configuration interaction, which for a system as complex as Fe II can be quite extensive. However, at the present time it is beyond the scope of current computational resources to carry through a full Breit-Pauli $R$-matrix calculation for the 83-state close coupling expansion used by NP (1994), that was necessary to adequately represent the electron correlation effects in Fe II. On the other hand, it is expected that the relativistic effects for Fe II should be relatively less important than an accurate representation of the correlation effects (although for higher ion charges this may not be the case).

In an earlier study of a similar nature (Nahar 1993), we considered the dipole allowed ($\Delta S = 0$) transitions in Si I and Si-like ions and found very good agreement with experimental data (usually within the experimental error bars) for the oscillator strengths of a number of fine structure transitions. Fe II is considerably more complex; however, preliminary work reported by NP (1994) showed that the results obtained appear to be of higher accuracy than the data available from Kurucz (1981, and private communication) for most of the transitions studied, when compared with the experimental data compiled and evaluated by the National Institute of Standards and Technology

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* Table for complete data for Fe II transition probabilities are only available from in electronic form: see the editorial in A&A 1992, Vol. 266, No. 2, page E1.

**Table 1.** Calculated and measured lifetimes, $\tau$, of Fe II levels

| State | $J$ | $\tau$(ns) Present | Expt. | Kurucz | State | $J$ | Present | Expt. | Kurucz |
|---|---|---|---|---|---|---|---|---|---|
| $z^6P^0$ | 7/2 | 3.884 | 3.73(.06)[a],3.8(2)[b], 3.5(3)[c],3.73(5)[d] | 3.28 | $z^6F^0$ | 5/2 | 3.063 | 3.3(2)[c],3.33(9)[d] | 2.93 |
| $z^6P^0$ | 5/2 | 3.844 | 3.79(0.12)[a],3.7(2)[b], 3.5(3)[c],3.83(7)[d] | 3.26 | $z^6F^0$ | 3/2 | 3.078 | 3.3(2)[c],3.34(10)[d] | 2.94 |
| $z^6P^0$ | 3/2 | 3.819 | 3.71(.12)[a],3.6(2)[b],3.4(3)[c] | 3.25 | $z^6F^0$ | 1/2 | 3.081 | 3.3(3)[c] | 2.94 |
| $z^6D^0$ | 9/2 | 3.460 | 3.7(.2)[b],3.7(2)[c],3.7(6)[d] | 3.41 | $z^4P^0$ | 5/2 | 3.250 | 3.43(.09)[a] | 2.97 |
| $z^6D^0$ | 7/2 | 3.487 | 3.75(20)[b],3.8(3)[c],3.68(7)[d] | 3.43 | $z^4P^0$ | 3/2 | 3.241 | 3.44(.11)[a] | 2.96 |
| $z^6D^0$ | 5/2 | 3.499 | 3.7(.2)[b],3.8(3)[c],3.63(8)[d] | 3.44 | $z^4D^0$ | 7/2 | 2.476 | 3.02(.07)[a],3.1(2)[b] | 2.43 |
| $z^6D^0$ | 3/2 | 3.498 | 3.7(.2)[b],3.7(2)[c],3.83(10)[d] | 3.45 | $z^4D^0$ | 5/2 | 2.496 | 3.1(.08)[a],3.1(2)[b] | 2.44 |
| $z^6D^0$ | 1/2 | 3.492 | 3.8(.2)[b],3.8(3)[c],3.76(10)[d] | 3.45 | $z^4D^0$ | 3/2 | 2.494 | 3.0(2)[b] | 2.43 |
| $z^6F^0$ | 11/2 | 2.982 | 3.2(.2)[b],3.3(2)[c],3.19(4)[d] | 2.83 | $z^4D^0$ | 1/2 | 2.498 | 2.9(2)[b] | 2.42 |
| $z^6F^0$ | 9/2 | 3.024 | 3.2(.2)[b],3.24(6)[d],3.4(2)[c] | 2.89 | $z^4F^0$ | 9/2 | 3.471 | 3.87(.09)[a],3.7(2)[b] | 3.34 |
| $z^6F^0$ | 7/2 | 3.034 | 3.3(2)[c],3.26(10)[d] | 2.92 | $z^4F^0$ | 7/2 | 3.435 | 3.63(.11)[a],3.6(2)[b] | 3.22 |
| | | | | | $z^4F^0$ | 5/2 | 3.417 | 3.75(.14)[a],3.7(2)[b] | 3.26 |
| | | | | | $z^4F^0$ | 3/2 | 3.422 | 3.7(2)[b] | 3.3 |

[a] Guo et al. (1992), [b] Hannaford et al. (1992), [c] Schade et al. (1988), [d] Biemont et al. (1991).

(NIST; Fuhr et al. 1988). Presently the available data for Fe II derives mainly from two sources: Kurucz (1981) and Fawcett (1988), both of which employ a semi-empirical method due to Cowan (1968). Ekberg & Feldman (1993) also have obtained transition probabilities for 550 transitions based on measured values from various published reports. The present work is a completed account of the work initiated by NP (1994) for a relatively large dataset of Fe II transition probabilities.

The present calculations are carried out through algebraic transformation of the $LS$ multiplet strengths calculated in the close coupling approximation, and observed energies for the fine structure levels which are known to a much higher precision than the calculated energies are used. The dipole allowed transitions ($\Delta S = 0$) are considered for all $LS$ terms for which a partial or complete set of fine structure levels have been observed. The present work employs the level energies of Fe II from Johansson (1978) and 193 (769–576) unpublished levels (Johansson, private communication, 1992). The 265 $LS$ terms observed correspond to 3109 $LS$ multiplets with 21589 fine structure transitions, thus providing a reasonably comprehensive dataset for Fe II for practical applications.

The primary difficulty encountered in the present work is the $LS$ term identification of the large number of computed terms of Fe II, and to establish the correspondence with the measured spectroscopic levels and energies. The theoretical and computational work is described in Sect. 2. A sample of the present extensive data set is provided in Sect. 3, with a discussion of related uncertainties.

## 2. Summary of theoretical work and computations

The $LS$ multiplet strength, $S$, which is independent of the energy difference between the transitional states is obtained from the calculated $LS$ oscillator strength, $f_{if}$, as

$$f_{if} = \frac{E_{fi}}{3g_i} S , \qquad (1)$$

where $E_{fi} = E_f - E_i$ is the transition energy and $g_i = (2S_i + 1)(2L_i + 1)$ is the statistical weight of the initial state. Energies are in Rydberg units throughout unless specified otherwise. In terms of dipole length and velocity operators

$$D_L = \sum_n r_n , \quad D_V = -2 \sum_n \nabla_n , \qquad (2)$$

where the summation is over all atomic electrons, the line strength is given by

$$S_L = |\langle \psi_f \| D_L \| \psi_i \rangle|^2 , \qquad (3a)$$

in the 'length form' and

$$S_V = E_{fi}^{-2} |\langle \psi_f \| D_V \| \psi_i \rangle|^2 , \qquad (3b)$$

in the 'velocity form' respectively.

The fine structure line strengths, $S_{JJ}$, of the $LS$ multiplet strength, $S_{LS}$, is obtained for the allowed transitions ($\Delta J = 0, \pm 1$) through the algebraic transformation,

$$S_{JJ} = C_{Al}(J_i, J_f) S_{LS} / \left[ (2S_i + 1)(2L_i + 1)(2L_f + 1) \right] \qquad (4)$$

where values of coefficients $C_{Al}(J_i, J_f)$ are obtained from Allen (1976). The above expression satisfies the conservation condition

$$S_{LS} = \sum_J S_{JJ} . \qquad (5)$$

The fine structure $f$-values (oscillator strengths) are then obtained using $E_{J_f J_i} = E_{J_f} - E_{J_i}$, where $E_{J_i}$ and $E_{J_i}$ are now the *observed* energies, as

**Table 2.** Calculated and observed (Johansson 1978)[a] energies of Fe II terms. An * next to an energy means the set of observed levels for the term is incomplete. The degeneracy symbol for each state is chosen for convenience as explained in the text

| State | | E(Ryd) Obs. | E(Ryd) Cal. | State | | E(Ryd) Obs. | E(Ryd) Cal. |
|---|---|---|---|---|---|---|---|
| *Octets* | | | | | | | |
| $3d^5\,^6S4s4p^3P^0$ | $z^8P^0$ | 0.70972 | 0.7783 | $3d^54s\,^7S5s$ | $a^8S$ | 0.25023 | 0.2457 |
| $3d^54p^2$ | $a^8P$ | 0.21567 | 0.2742 | $3d^54s\,^7S4d$ | $a^8D$ | 0.19213 | 0.2300 |
| *Sextets* | | | | | | | |
| $3d^54s^2$ | $a^6S$ | 0.97721 | 0.9951 | $3d^5\,^5D6d$ | $c^6G$ | 0.15148* | 0.1550 |
| $3d^5\,^5D4d$ | $b^6S$ | 0.41061 | 0.4128 | $3d^5\,^5D4p$ | $z^6P^0$ | 0.79726 | 0.8111 |
| $3d^5\,^5D5d$ | $c^6S$ | 0.22638 | 0.2388 | $3d^5\,^6S4s4p$ | $y^6P^0$ | 0.62392 | 0.6594 |
| $3d^54s^7S5s$ | $d^6S$ | 0.21835 | 0.2117 | $3d^5\,^6S4s4p$ | $x^6P^0$ | 0.46709 | 0.4785 |
| $3d^5\,^5D4d$ | $a^6P$ | 0.42130 | 0.4219 | $3d^5\,^4P4s4p$ | $w^6P^0$ | 0.37553 | 0.3966 |
| $3d^5\,^5D5d$ | $b^6P$ | 0.23987 | 0.2438 | $3d^5\,^5D5p$ | $v^6P^0$ | 0.35631 | 0.3581 |
| $3d^54p^2$ | $c^6P$ | 0.14166 | 0.1834 | $3d^5\,^4D4s4p$ | $u^6P^0$ | 0.32751 | 0.3443 |
| $3d^6\,^5D4s$ | $a^6D$ | 1.18591 | 1.1782 | $3d^5\,^5D6p$ | $t^6P^0$ | 0.21058 | 0.2126 |
| $3d^5\,^5D5s$ | $b^6D$ | 0.47640 | 0.4687 | $3d^5\,^5D4p$ | $z^6D^0$ | 0.83695 | 0.8466 |
| $3d^5\,^5D4d$ | $c^6D$ | 0.42604 | 0.4273 | $3d^5\,^4P4s4p$ | $y^6D^0$ | 0.38557 | 0.4120 |
| $3d^5\,^5D6s$ | $d^6D$ | 0.25937 | 0.2555 | $3d^5\,^5D5p$ | $x^6D^0$ | 0.37896 | 0.3789 |
| $3d^5\,^5D5d$ | $e^6D$ | 0.23633 | 0.2422 | $3d^5\,^4D4s4p$ | $v^6D^0$ | 0.33345 | 0.3478 |
| $3d^54p^2$ | $f^6D$ | 0.21862 | 0.2713 | $3d^5\,^5D6p$ | $u^6D^0$ | 0.21765 | 0.2197 |
| $3d^5\,^5D7s$ | $g^6D$ | 0.16227 | 0.1638 | $3d^5\,^4F4s4p$ | $t^6D^0$ | 0.20451 | 0.2116 |
| $3d^54s\,^7S4d$ | $h^6D$ | 0.12955 | 0.1446 | $3d^5\,^5D4p$ | $z^6F^0$ | 0.80542 | 0.8177 |
| $3d^5\,^5D4d$ | $a^6F$ | 0.43250 | 0.4312 | $3d^5\,^4G4s4p$ | $y^6F^0$ | 0.39240 | 0.3756 |
| $3d^5\,^5D5d$ | $b^6F$ | 0.24042* | 0.2454 | $3d^5\,^5D5p$ | $x^6F^0$ | 0.36766 | 0.3675 |
| $3d^5\,^5D6d$ | $c^6F$ | 0.15354* | 0.1568 | $3d^5\,^4D4s4p$ | $w^6F^0$ | 0.34940 | 0.3756 |
| $3d^5\,^5D4d$ | $a^6G$ | 0.42021 | 0.4223 | $3d^5\,^4F4s4p$ | $v^6F^0$ | 0.21856 | 0.2275 |
| $3d^5\,^5D5d$ | $b^6G$ | 0.23492 | 0.2417 | $3d^5\,^5D6p$ | $u^6F^0$ | 0.21207 | 0.2146 |
| *Quartets* | | | | | | | |
| $3d^6\,^5D4d$ | $a^4S$ | 0.40848 | 0.4142 | $3d^6\,^5D5p$ | $v^4P^0$ | 0.35518 | 0.3575 |
| $3d^7$ | $a^4P$ | 1.06566 | 0.9846 | $3d^6\,^3P4p$ | $u^4P^0$ | 0.35519 | 0.3348 |
| $3d^6\,^3P4s$ | $b^4P$ | 0.99450 | 0.9313 | $3d^54s^5P4p$ | $t^4P^0$ | 0.32856 | 0.2877 |
| $3d^6\,^3P4s$ | $c^4P$ | 0.73596 | 0.6515 | $3d^54s^5D4p$ | $s^4P^0$ | 0.26375 | 0.2558 |
| $3d^54s^2$ | $d^4P$ | 0.66603 | 0.6331 | $3d^54s^3D4p$ | $r^4P^0$ | 0.21916* | 0.2129 |
| $3d^6\,^5D4d$ | $e^4P$ | 0.38709 | 0.3747 | $3d^6\,^5D6p$ | $q^4P^0$ | 0.20937 | 0.2101 |
| $3d^6\,^3P5s$ | $f^4P$ | 0.29695 | 0.2832 | $3d^6\,^3P5p$ | $p^4P^0$ | 0.19511 | 0.1868 |
| $3d^6\,^3P4d$ | $g^4P$ | 0.23441 | 0.2206 | $3d^6\,^5D4p$ | $z^4D^0$ | 0.78197 | 0.7890 |
| $3d^6\,^5D5d$ | $h^4P$ | 0.21510 | 0.2267 | $3d^6\,^3P4p$ | $y^4D^0$ | 0.62132 | 0.5896 |
| $3d^54p^2$ | $i^4P$ | 0.11286* | 0.1231 | $3d^6\,^3F4p$ | $x^4D^0$ | 0.61370 | 0.5857 |
| $3d^6\,^5D4s$ | $a^4D$ | 1.11388 | 1.1060 | $3d^6\,^3P4p$ | $w^4D^0$ | 0.52817 | 0.4962 |
| $3d^6\,^3D4s$ | $b^4D$ | 0.90338 | 0.8499 | $3d^6\,^3P4p$ | $v^4D^0$ | 0.39918 | 0.3401 |
| $3d^64s^2$ | $c^4D$ | 0.63958 | 0.6191 | $3d^6\,^5D5p$ | $u^4D^0$ | 0.36336 | 0.3631 |
| $3d^6\,^5D5s$ | $d^4D$ | 0.46240 | 0.4555 | $3d^6\,^3F4p$ | $t^4D^0$ | 0.34316 | 0.3100 |
| $3d^6\,^5D4d$ | $e^4D$ | 0.41638 | 0.4225 | $3d^54s^5P4p$ | $s^4D^0$ | 0.31457 | 0.2952 |
| $3d^6\,^5D6s$ | $f^4D$ | 0.25338 | 0.2531 | $3d^54s^5D4p$ | $r^4D^0$ | 0.29153 | 0.2782 |
| $3d^6\,^3P4d$ | $g^4D$ | 0.24970* | 0.2206 | $3d^54s\,^3F4p$ | $q^4D^0$ | 0.20248* | 0.1984 |
| $3d^6\,^5D5d$ | $h^4D$ | 0.23253* | 0.2404 | $3d^54s^3D4p$ | $p^4D^0$ | 0.21354* | 0.2129 |
| $3d^6\,^3F4d$ | $i^4D$ | 0.23106* | 0.1940 | $3d^6\,^5D6p$ | $o^4D^0$ | 0.21308* | 0.2101 |
| $3d^6\,^3D5s$ | $j^4D$ | 0.19884 | 0.1860 | $3d^6\,^3P5p$ | $n^4D^0$ | 0.18767* | 0.1802 |
| $3d^6\,^3G4d$ | $k^4D$ | 0.20003 | 0.1808 | $3d^6\,^3F5p$ | $m^4D^0$ | 0.18237* | 0.1537 |
| $3d^6\,^5D7s$ | $l^4D$ | 0.15833 | 0.1614 | $3d^6\,^5D4p$ | $z^4F^0$ | 0.78223 | 0.7968 |
| $3d^7$ | $a^4F$ | 1.16768 | 1.081 | $3d^6\,^3F4p$ | $y^4F^0$ | 0.62342 | 0.5947 |
| $3d^6\,^3F4s$ | $b^4F$ | 0.98186 | 0.9327 | $3d^6\,^3G4p$ | $x^4F^0$ | 0.58542 | 0.5645 |
| $3d^6\,^3F4s$ | $c^4F$ | 0.73269 | 0.6462 | $3d^6\,^3D4p$ | $w^4F^0$ | 0.52987 | 0.5007 |
| $3d^54s^2$ | $d^4F$ | 0.52031 | 0.4884 | $3d^6\,^5D5p$ | $v^4F^0$ | 0.36261 | 0.3654 |

[a] Observed energies include unpublished level energies of Fe II
(Johansson, private communication, 1992).

**Table 2.** (continued)

| State | | E(Ryd) Obs. | Cal. | State | | E(Ryd) Obs. | Cal. |
|---|---|---|---|---|---|---|---|
| $3d^6\,^5D4d$ | $e^4F$ | 0.40242 | 0.3933 | $3d^54s^5G4p$ | $u^4F^0$ | 0.34810 | 0.3618 |
| $3d^6\,^3F5s$ | $f^4F$ | 0.28108 | 0.2401 | $3d^6\,^3F4p$ | $t^4F^0$ | 0.33817 | 0.2981 |
| $3d^6\,^5D5d$ | $g^4F$ | 0.24320 | 0.2377 | $3d^54s^5D4p$ | $s^4F^0$ | 0.29237 | 0.2822 |
| $3d^6\,^3P4d$ | $h^4F$ | 0.24256 | 0.2188 | $3d^54s^3D4p$ | $r^4F^0$ | 0.23314 | 0.2367 |
| $3d^6\,^3H4d$ | $i^4F$ | 0.23240* | 0.2007 | $3d^6\,^5D6p$ | $q^4F^0$ | 0.21278 | 0.2133 |
| $3d^6\,^3F4d$ | $j^4F$ | 0.21661 | 0.1875 | $3d^54s\,^3F4p$ | $p^4F^0$ | 0.20141 | 0.2022 |
| $3d^6\,^3G4d$ | $k^4F$ | 0.18585 | 0.1695 | $3d^6\,^3F5p$ | $o^4F^0$ | 0.18529 | 0.1664 |
| $3d^6\,^5D6d$ | $l^4F$ | 0.14940* | 0.1396 | $3d^6\,^3G5p$ | $n^4F^0$ | 0.16697 | 0.1575 |
| $3d^6\,^3D4d$ | $m^4F$ | 0.14146* | 0.1158 | $3d^6\,^3H4p$ | $z^4G^0$ | 0.63548 | 0.6168 |
| $3d^6\,^3G4s$ | $a^4G$ | 0.95495 | 0.9168 | $3d^6\,^3F4p$ | $y^4G^0$ | 0.60678 | 0.5844 |
| $3d^54s^2$ | $b^4G$ | 0.69523 | 0.6913 | $3d^6\,^3G4p$ | $x^4G^0$ | 0.59033 | 0.5723 |
| $3d^6\,^5D4d$ | $c^4G$ | 0.41310 | 0.4195 | $b3d^6\,^3F4p$ | $w^4G^0$ | 0.36944 | 0.3475 |
| $3d^6\,^3G5s$ | $d^4G$ | 0.25241 | 0.2403 | $3d^54s^5G4p$ | $v^4G^0$ | 0.33203 | 0.3085 |
| $3d^6\,^3H4d$ | $e^4G$ | 0.24387 | 0.2112 | $3d^54s\,^3F4p$ | $u^4G^0$ | 0.20868* | 0.2115 |
| $3d^6\,^5D5d$ | $f^4G$ | 0.23088 | 0.2389 | $3d^54s^3G4p$ | $t^4G^0$ | 0.20038 | 0.1948 |
| $a3d^6\,^3F4d$ | $g^4G$ | 0.23107 | 0.1946 | $3d^6\,^3H5p$ | $s^4G^0$ | 0.18833 | 0.1588 |
| $3d^6\,^3G4d$ | $h^4G$ | 0.20197 | 0.1830 | $3d^6\,^3F5p$ | $r^4G^0$ | 0.16926 | 0.1498 |
| $3d^6\,^5D6d$ | $i^4G$ | 0.14662 | 0.1538 | $3d^54s^5F4p$ | $q^4G^0$ | 0.16594* | 0.1777 |
| $3d^6\,^3H4s$ | $a^4H$ | 0.99415 | 0.9631 | $3d^6\,^3G5p$ | $p^4G^0$ | 0.14292* | 0.1402 |
| $3d^6\,^3H5s$ | $b^4H$ | 0.29368 | 0.2404 | $3d^6\,^3H4p$ | $z^4H^0$ | 0.63434 | 0.6193 |
| $3d^6\,^3H4d$ | $c^4H$ | 0.24399 | 0.2104 | $3d^6\,^3G4p$ | $y^4H^0$ | 0.58358 | 0.5669 |
| $3d^5\,^3Fa4d$ | $d^4H$ | 0.22898 | 0.1939 | $3d^54s^5G4p$ | $x^4H^0$ | 0.34980 | 0.3693 |
| $3d^6\,^3G4d$ | $e^4H$ | 0.20181 | 0.1830 | $3d^54s^3I4p$ | $w^4H^0$ | 0.23439 | 0.2606 |
| $3d^6\,^3H4d$ | $a^4I$ | 0.24146 | 0.2106 | $3d^54s^3G4p$ | $v^4H^0$ | 0.19810 | 0.2010 |
| $3d^6\,^3G4d$ | $b^4I$ | 0.20019 | 0.1812 | $3d^54s^3G4p$ | $u^4H^0$ | 0.18413* | 0.1380 |
| $3d^6\,^3H4d$ | $a^4K$ | 0.24407 | 0.2120 | $3d^6\,^3H5p$ | $t^4H^0$ | 0.17227 | 0.1821 |
| $3d^6\,^3P4p$ | $z^4So$ | 0.64601 | 0.6075 | $3d^6\,^3G5p$ | $s^4H^0$ | 0.14892* | 0.1455 |
| $3d^6\,^3P4p$ | $y^4So$ | 0.36382 | 0.3144 | $3d^6\,^3H4p$ | $z^4I^0$ | 0.62942 | 0.6194 |
| $3d^54s^5P4p$ | $x^4So$ | 0.29358 | 0.2718 | $3d^54s^3I4p$ | $y^4I^0$ | 0.25027 | 0.2810 |
| $3d^6\,^3P5p$ | $w^4So$ | 0.20214 | 0.1919 | $3d^6\,^3H5p$ | $x^4I^0$ | 0.19004 | 0.1751 |
| $3d^6\,^5D4p$ | $z^4P^0$ | 0.75942 | 0.7706 | $3d^54s^3H4p$ | $w^4I^0$ | 0.16756* | 0.1444 |
| $3d^6\,^3P4p$ | $y^4P^0$ | 0.63549 | 0.5997 | $3d^54s^3I4p$ | $z^4K^0$ | 0.25488* | 0.2852 |
| $3d^54s5S4p$ | $x^4P^0$ | 0.55889 | 0.5729 | | | | |
| $3d^6\,^3D4p$ | $w^4P^0$ | 0.53329 | 0.5009 | | | | |

*Doublets*

| State | | E(Ryd) Obs. | Cal. | State | | E(Ryd) Obs. | Cal. |
|---|---|---|---|---|---|---|---|
| $3d^6a^1S4s$ | $a^2S$ | 0.85046 | 0.7887 | $3d^6b\,^3P4p$ | $v^2P^0$ | 0.32364* | 0.2902 |
| $3d^7$ | $a^2P$ | 1.02079 | 0.9148 | $3d^54s\,^3P4p$ | $u^2P^0$ | 0.30280* | 0.2533 |
| $3d^6a^3P4s$ | $b^2P$ | 0.95123 | 0.8763 | $3d^54s^3D4p$ | $t^2P^0$ | 0.22047 | 0.2001 |
| $3d^6b^3P4s$ | $c^2P$ | 0.69194 | 0.5975 | $3d^6a\,^3P4p$ | $z^2D^0$ | 0.62921 | 0.5944 |
| $3d^6\,^3P5s$ | $d^2P$ | 0.28433 | 0.2750 | $3d^6a^3F4p$ | $y^2D^0$ | 0.57815 | 0.5498 |
| $3d^6\,^3P4d$ | $e^2P$ | 0.23174 | 0.2095 | $3d^6\,^3D4p$ | $x^2D^0$ | 0.51023 | 0.4747 |
| $3d^6a^3F4d$ | $f^2P$ | 0.20457* | 0.1648 | $3d^6a^1D4p$ | $w^2D^0$ | 0.47336 | 0.4134 |
| $3d^7$ | $a^2D$ | 0.99985 | 0.8896 | $3d^6\,^1F4p$ | $v^2D^0$ | 0.42364 | 0.3630 |
| $3d^6\,^3D4s$ | $b^2D$ | 0.85980 | 0.7966 | $3d^6b^3P4p$ | $u^2D^0$ | 0.34674 | 0.2851 |
| $3d^6a^1D4s$ | $c^2D$ | 0.84174 | 0.7565 | $3d^6b^3F4p$ | $t^2D^0$ | 0.32672* | 0.2698 |
| $3d^7$ | $d^2D$ | 0.75326 | 0.6128 | $3d^54s^3P4p$ | $s^2D^0$ | 0.27478* | 0.2521 |
| $3d^6\,^3P4d$ | $e^2D$ | 0.23069* | 0.2108 | $3d^54s^3D4p$ | $r^2D^0$ | 0.25592 | 0.2379 |
| $3d^6a^3F4d$ | $f^2D$ | 0.21085 | 0.1754 | $3d^6\,^3P5p$ | $q^2D^0$ | 0.19703* | 0.1840 |
| $3d^6\,^3D5s$ | $g^2D$ | 0.19066 | 0.1316 | $3d^6a^3F4p$ | $z^2F^0$ | 0.60334 | 0.5794 |
| $3d^6\,^3G4d$ | $h^2D$ | 0.18526 | 0.1646 | $3d^6\,^3G4p$ | $y^2F^0$ | 0.55523 | 0.5278 |
| $3d^6a^3F4s$ | $a\,^2F$ | 0.93960 | 0.8905 | $3d^6a^1G4p$ | $x^2F^0$ | 0.52418 | 0.4907 |
| $3d^7$ | $b\,^2F$ | 0.89883 | 0.7842 | $3d^6\,^3D4p$ | $w^2F^0$ | 0.49955 | 0.4606 |
| $3d^6\,^1F4s$ | $c\,^2F$ | 0.78035 | 0.6907 | $3d^6a^1D4p$ | $v^2F^0$ | 0.47920 | 0.4212 |
| $3d^6b^3F4s$ | $d\,^2F$ | 0.68951 | 0.5997 | $3d^6\,^1F4p$ | $u^2F^0$ | 0.40136 | 0.3411 |

**Table 2.** (continued)

| State | | E(Ryd) Obs. | Cal. | State | | E(Ryd) Obs. | Cal. |
|---|---|---|---|---|---|---|---|
| $3d^5 4s^2$ | $e\,^2F$ | 0.44525 | 0.4881 | $3d^6 b\,^3F4p$ | $t\,^2F^0$ | 0.32340 | 0.3180 |
| $3d^6 a\,^3F5s$ | $f\,^2F$ | 0.27294 | 0.2314 | $3d^5 4s\,^3G4p$ | $s\,^2F^0$ | 0.31193 | 0.2582 |
| $3d^6\,^3H4d$ | $g\,^2F$ | 0.23866 | 0.2066 | $3d^6 b\,^1G4p$ | $r\,^2F^0$ | 0.28847* | 0.2350 |
| $3d^6 a\,^3F4d$ | $h\,^2F$ | 0.22186* | 0.1920 | $3d^5 4s\,^3D4p$ | $q\,^2F^0$ | 0.24883 | 0.2101 |
| $3d^6\,^3G4d$ | $i\,^2F$ | 0.18195 | 0.1519 | $3d^6\,^3F5p$ | $p\,^2F^0$ | 0.17192 | 0.1417 |
| $3d^7$ | $a\,^2G$ | 1.04319 | 0.9380 | $3d^6\,^3H4p$ | $z\,^2G^0$ | 0.62299 | 0.6072 |
| $3d^6\,^3G4s$ | $b\,^2G$ | 0.91126 | 0.8667 | $3d^6 a\,^3F4p$ | $y\,^2G^0$ | 0.59778 | 0.5713 |
| $3d^6 a\,^1G4s$ | $c\,^2G$ | 0.88459 | 0.8307 | $3d^6\,^3G4p$ | $x\,^2G^0$ | 0.54810 | 0.5262 |
| $3d^6 b\,^1G4s$ | $d\,^2G$ | 0.65527 | 0.5513 | $3d^6 a\,^1G4p$ | $w\,^2G^0$ | 0.52343 | 0.4883 |
| $3d^5 4s^2$ | $e\,^2G$ | 0.47524 | 0.4459 | $3d^6\,^1F4p$ | $v\,^2G^0$ | 0.42770 | 0.3710 |
| $3d^6\,^3G5s$ | $f\,^2G$ | 0.24403 | 0.2310 | $3d^6 b\,^3F4p$ | $u\,^2G^0$ | 0.34802 | 0.2886 |
| $3d^6\,^3H4d$ | $g\,^2G$ | 0.23335 | 0.2008 | $3d^5 4s\,^3G4p$ | $t\,^2G^0$ | 0.28166 | 0.2741 |
| $3d^6 a\,^3F4d$ | $h\,^2G$ | 0.21543 | 0.1849 | $3d^6 b\,^1G4p$ | $s\,^2G^0$ | 0.28044 | 0.2090 |
| $3d^6\,^3G4d$ | $i\,^2G$ | 0.18960 | 0.1638 | $3d^5 4s\,^3F4p$ | $r\,^2G^0$ | 0.18128* | 0.1823 |
| $3d^7$ | $a\,^2H$ | 1.00242 | 0.9222 | $3d^6\,^3H5p$ | $q\,^2G^0$ | 0.18530 | 0.1452 |
| $3d^6\,^3H4s$ | $b\,^2H$ | 0.95046 | 0.8958 | $3d^6\,^3F5p$ | $p\,^2G^0$ | 0.17293 | 0.1399 |
| $3d^5 4s^2$ | $c\,^2H$ | 0.48592* | 0.4588 | $3d^6\,^3G5p$ | $o\,^2G^0$ | 0.14285* | 0.1310 |
| $3d^6\,^3H5s$ | $d\,^2H$ | 0.28571 | 0.2324 | $3d^6\,^3H4p$ | $z\,^2H^0$ | 0.59326 | 0.5772 |
| $3d^6 a\,^3F4d$ | $e\,^2H$ | 0.22486 | 0.1917 | $3d^6\,^3G4p$ | $y\,^2H^0$ | 0.57244 | 0.5581 |
| $3d^6\,^3H4d$ | $f\,^2H$ | 0.22313 | 0.1896 | $3d^6 a\,^1G4p$ | $x\,^2H^0$ | 0.53175 | 0.5012 |
| $3d^6\,^3G4d$ | $g\,^2H$ | 0.18885 | 0.1625 | $3d^6\,^1I4p$ | $w\,^2H^0$ | 0.51836 | 0.4880 |
| $3d^6\,^1I4s$ | $a\,^2I$ | 0.88997 | 0.8470 | $3d^5 4s\,^3G4p$ | $v\,^2H^0$ | 0.31358 | 0.3181 |
| $3d^6\,^3H4d$ | $b\,^2I$ | 0.23571 | 0.2061 | $3d^6 b\,^1G4p$ | $u\,^2H^0$ | 0.29589 | 0.2394 |
| $3d^6\,^1I5s$ | $c\,^2I$ | 0.19970 | 0.1374 | $3d^6 4s\,^3I4p$ | $t\,^2H^0$ | 0.21616 | 0.2158 |
| $3d^6\,^3G4d$ | $d\,^2I$ | 0.19454 | 0.1786 | $3d^6\,^3H5p$ | $s\,^2H^0$ | 0.18007 | 0.1370 |
| $3d^6\,^3H4d$ | $a\,^2K$ | 0.24006* | 0.2092 | $3d^6\,^3G5p$ | $r\,^2H^0$ | 0.14510 | 0.1415 |
| $3d^6 a\,^3P4p$ | $z\,^2So$ | 0.58600 | 0.5491 | $3d^6\,^3H4p$ | $z\,^2I^0$ | 0.62049 | 0.5575 |
| $3d^6 b\,^3P4p$ | $y\,^2So$ | 0.37864 | 0.3210 | $3d^6\,^1I4p$ | $y\,^2I^0$ | 0.51565 | 0.4927 |
| $3d^5 4s\,^3P4p$ | $x\,^2So$ | 0.24228 | 0.2123 | $3d^5 4s\,^3I4p$ | $x\,^2I^0$ | 0.19454 | 0.2054 |
| $3d^6 a\,^3P4p$ | $z\,^2P^0$ | 0.59897 | 0.5633 | $3d^6\,^3H5p$ | $w\,^2I^0$ | 0.18664 | 0.1231 |
| $3d^6\,^3D4p$ | $y\,^2P^0$ | 0.52276 | 0.4852 | $3d^6\,^1I4p$ | $z\,^2K^0$ | 0.54065 | 0.5211 |
| $3d^6 a1S4p$ | $x\,^2P^0$ | 0.49460 | 0.4429 | $3d^6 4s\,^3I4p$ | $y\,^2K^0$ | 0.22043 | 0.2409 |
| $3d^6 a\,^1D4p$ | $w\,^2P^0$ | 0.46880 | 0.4130 | | | | |

$$f_{JJ}(J_f, J_i) = S_{JJ} E_{J_f J_i} / [3(2J_i + 1)] . \tag{6}$$

The fine structure oscillator strengths, $f_{JJ}$, can also be obtained directly from the $LS$ oscillator strength, $f_{LS}$, as (Seaton et al. 1994)

$$
\begin{aligned}
f_{JJ}(n_f SL_f J_f, n_i SL_i J_i) \\
= f_{LS}(n_f SL_f, n_i SL_i)(2J_f + 1)(2L_i + 1) \\
\times W^2(L_f L_i J_f J_i; 1S)
\end{aligned}
\tag{7}
$$

where $W(L_f L_i J_f J_i; 1S)$ is a Racah coefficient. The above fine structure $f$-values satisfy the conservation sum

$$
\sum_{J_i J_f} (2J_i + 1) f_{JJ}(n_f SL_f J_f, n_i SL_i J_i)
$$

$$
= (2S + 1)(2L_i + 1) f_{LS}(n_f SL_f, n_i SL_i) . \tag{8}
$$

The improvement in accuracy through the use of observed energies cannot be achieved by splitting of $LS$ oscillator strengths through Eq. (7), which is used only for transitions between two $LS$ states where one or both states have an incomplete set of observed fine structure levels, and for transitions between high angular momenta states (higher than $\boldsymbol{H} \leftrightarrow \boldsymbol{I}$) for which the values of $C_{Al}(J_i, J_f)$ are not available.

The radiative transition probability, $A_{fi}$, from higher state $f$ to lower state $i$ can be obtained, in atomic unit, as

$$A_{fi}(\text{a.u.}) = \frac{1}{2}\alpha^3 \frac{g_i}{g_f} E_{fi}^2 f_{if} , \tag{9}$$

where $\alpha$ is the fine structure constant and $g_f$ is the statistical weight of the final state, and in c.g.s. unit of time as

$$A_{fi}(\text{s}^{-1}) = \frac{A_{fi}(\text{a.u.})}{\tau_0} , \tag{10}$$

where $\tau_0 = 2.419\,10^{-17}$ s is the atomic unit of time. The total radiative probability for the state $f$ is given by

$$A_f = \sum_i A_{fi} , \tag{11}$$

**Table 3.** $f$-, $S$-, and $A$-values for transitions in Fe II. $E_i$ and $E_f$ are the energies in cm$^{-1}$ for the initial and final levels except for the first line where the term energies are Rydberg units. EDIFF is the transition energy in Rydberg

| Transition | $E_i$ (cm$^{-1}$) | $E_f$ (cm$^{-1}$) | EDIFF (Ryd) | $g_i$ | $g_f$ | $f_{if}$ | $S$ | $a_{ji}$ (s$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| z8Po → a8Pe | 0.7097 | 0.2157 | 4.94E-01 | 24 | 24 | 6.697E-01 | 9.760E+01 | 1.313E+09 |
| | 52965.820 | 107219.500 | 4.94E-01 | 10 | 10 | 4.088E-01 | 2.481E+01 | 8.026E+08 |
| | 52965.820 | 106836.000 | 4.91E-01 | 10 | 8 | 2.584E-01 | 1.579E+01 | 6.252E+08 |
| | 52582.510 | 107219.500 | 4.98E-01 | 8 | 10 | 3.276E-01 | 1.579E+01 | 5.219E+08 |
| | 52582.510 | 106836.000 | 4.94E-01 | 8 | 8 | 2.094E-02 | 1.017E+00 | 4.112E+07 |
| | 52582.510 | 106404.920 | 4.90E-01 | 8 | 6 | 3.213E-01 | 1.572E+01 | 8.278E+08 |
| | 52299.390 | 106836.000 | 4.97E-01 | 6 | 8 | 4.341E-01 | 1.572E+01 | 6.459E+08 |
| | 52299.390 | 106404.920 | 4.93E-01 | 6 | 6 | 2.376E-01 | 8.675E+00 | 4.640E+08 |
| a6Se → z6Po | 0.9772 | 0.7973 | 1.80E-01 | 6 | 18 | 4.336E-02 | 4.337E+00 | 3.760E+06 |
| | 23317.633 | 42658.224 | 1.76E-01 | 6 | 8 | 1.887E-02 | 1.928E+00 | 3.531E+06 |
| | 23317.633 | 43238.586 | 1.82E-01 | 6 | 6 | 1.458E-02 | 1.446E+00 | 3.859E+06 |
| | 23317.633 | 43620.957 | 1.85E-01 | 6 | 4 | 9.906E-03 | 9.638E-01 | 4.085E+06 |
| a6Se → y6Po | 0.9772 | 0.6239 | 3.53E-01 | 6 | 18 | 1.610E-02 | 8.204E-01 | 5.381E+06 |
| | 23317.633 | 62171.615 | 3.54E-01 | 6 | 8 | 7.172E-03 | 3.646E-01 | 5.416E+06 |
| | 23317.633 | 62049.025 | 3.53E-01 | 6 | 6 | 5.362E-03 | 2.735E-01 | 5.365E+06 |
| | 23317.633 | 61974.933 | 3.52E-01 | 6 | 4 | 3.568E-03 | 1.823E-01 | 5.334E+06 |
| a6Se → x6Po | 0.9772 | 0.4671 | 5.10E-01 | 6 | 18 | 1.712E+00 | 6.039E+01 | 1.192E+09 |
| | 23317.633 | 79331.500 | 5.10E-01 | 6 | 8 | 7.612E-01 | 2.684E+01 | 1.195E+09 |
| | 23317.633 | 79285.110 | 5.10E-01 | 6 | 6 | 5.704E-01 | 2.013E+01 | 1.192E+09 |
| | 23317.633 | 79246.170 | 5.10E-01 | 6 | 4 | 3.800E-01 | 1.342E+01 | 1.189E+09 |
| a6Pe → y6Do | 0.4213 | 0.3856 | 3.57E-02 | 18 | 30 | 2.768E-06 | 4.182E-03 | 1.704E+01 |
| | 84266.556 | 88614.517 | 3.96E-02 | 8 | 10 | 2.302E-06 | 1.394E-03 | 2.323E+01 |
| | 84266.556 | 88209.453 | 3.59E-02 | 8 | 8 | 5.982E-07 | 3.996E-04 | 6.203E+00 |
| | 84266.556 | 88059.381 | 3.46E-02 | 8 | 6 | 9.571E-08 | 6.644E-05 | 1.225E+00 |
| | 84326.912 | 88209.453 | 3.54E-02 | 6 | 8 | 1.406E-06 | 7.156E-04 | 1.061E+01 |
| | 84326.912 | 88059.381 | 3.40E-02 | 6 | 6 | 9.660E-07 | 5.111E-04 | 8.980E+00 |
| | 84326.912 | 87964.650 | 3.32E-02 | 6 | 4 | 3.081E-07 | 1.673E-04 | 4.079E+00 |
| | 84424.374 | 88059.381 | 3.31E-02 | 4 | 6 | 7.184E-07 | 2.602E-04 | 4.222E+00 |
| | 84424.374 | 87964.650 | 3.23E-02 | 4 | 4 | 1.049E-06 | 3.903E-04 | 8.771E+00 |
| | 84424.374 | 87635.920 | 2.93E-02 | 4 | 2 | 6.800E-07 | 2.788E-04 | 9.359E+00 |
| a6De → z6Po | 1.1859 | 0.7973 | 3.89E-01 | 30 | 18 | 1.263E-01 | 2.926E+01 | 2.555E+08 |
| | 0.000 | 42658.224 | 3.89E-01 | 10 | 8 | 1.264E-01 | 9.752E+00 | 1.917E+08 |
| | 384.790 | 42658.224 | 3.85E-01 | 8 | 8 | 4.487E-02 | 2.796E+00 | 5.348E+07 |
| | 667.683 | 42658.224 | 3.83E-01 | 6 | 8 | 9.882E-03 | 4.648E-01 | 8.716E+06 |
| | 384.790 | 43238.586 | 3.91E-01 | 8 | 6 | 8.145E-02 | 5.006E+00 | 1.330E+08 |
| | 667.683 | 43238.586 | 3.88E-01 | 6 | 6 | 7.706E-02 | 3.576E+00 | 9.315E+07 |
| | 862.613 | 43238.586 | 3.86E-01 | 4 | 6 | 3.766E-02 | 1.170E+00 | 3.007E+07 |
| | 667.683 | 43620.957 | 3.91E-01 | 6 | 4 | 3.958E-02 | 1.820E+00 | 7.307E+07 |
| | 862.613 | 43620.957 | 3.90E-01 | 4 | 4 | 8.866E-02 | 2.731E+00 | 1.081E+08 |
| | 977.053 | 43620.957 | 3.89E-01 | 2 | 4 | 1.263E-01 | 1.950E+00 | 7.661E+07 |

**Table 3.** (continued)

| Transition | $E_i$ (cm$^{-1}$) | $E_f$ (cm$^{-1}$) | EDIFF (Ryd) | $g_i$ | $g_f$ | $f_{if}$ | $S$ | $a_{ji}$ (s$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| a6De → z6Do | 1.1859 | 0.8369 | 3.49E-01 | 30 | 30 | 2.936E-01 | 7.572E+01 | 2.872E+08 |
| | 0.000 | 38458.981 | 3.50E-01 | 10 | 10 | 2.400E-01 | 2.055E+01 | 2.368E+08 |
| | 0.000 | 38660.043 | 3.52E-01 | 10 | 8 | 5.484E-02 | 4.670E+00 | 6.834E+07 |
| | 384.790 | 38458.981 | 3.47E-01 | 8 | 10 | 6.751E-02 | 4.670E+00 | 5.222E+07 |
| | 384.790 | 38660.043 | 3.49E-01 | 8 | 8 | 1.313E-01 | 9.036E+00 | 1.283E+08 |
| | 384.790 | 38858.958 | 3.51E-01 | 8 | 6 | 9.477E-02 | 6.487E+00 | 1.248E+08 |
| | 667.683 | 38660.043 | 3.46E-01 | 6 | 8 | 1.248E-01 | 6.487E+00 | 9.010E+07 |
| | 667.683 | 38858.958 | 3.48E-01 | 6 | 6 | 5.017E-02 | 2.595E+00 | 4.881E+07 |
| | 667.683 | 39013.206 | 3.49E-01 | 6 | 4 | 1.176E-01 | 6.058E+00 | 1.730E+08 |
| | 862.613 | 38858.958 | 3.46E-01 | 4 | 6 | 1.748E-01 | 6.058E+00 | 1.122E+08 |
| | 862.613 | 39013.206 | 3.48E-01 | 4 | 4 | 3.218E-03 | 1.111E-01 | 3.124E+06 |
| | 862.613 | 39109.307 | 3.49E-01 | 4 | 2 | 1.144E-01 | 3.938E+00 | 2.232E+08 |
| | 977.053 | 39013.206 | 3.47E-01 | 2 | 4 | 2.275E-01 | 3.938E+00 | 1.097E+08 |
| | 977.053 | 39109.307 | 3.47E-01 | 2 | 2 | 6.520E-02 | 1.126E+00 | 6.323E+07 |
| a6De → z6Fo | 1.1859 | 0.8054 | 3.80E-01 | 30 | 42 | 3.976E-01 | 9.404E+01 | 3.302E+08 |
| | 0.000 | 41968.046 | 3.82E-01 | 10 | 12 | 3.425E-01 | 2.687E+01 | 3.353E+08 |
| | 0.000 | 42114.818 | 3.84E-01 | 10 | 10 | 5.270E-02 | 4.120E+00 | 6.235E+07 |
| | 0.000 | 42237.033 | 3.85E-01 | 10 | 8 | 4.251E-03 | 3.314E-01 | 6.323E+06 |
| | 384.790 | 42114.818 | 3.80E-01 | 8 | 10 | 2.888E-01 | 1.823E+01 | 2.683E+08 |
| | 384.790 | 42237.033 | 3.81E-01 | 8 | 8 | 9.678E-02 | 6.090E+00 | 1.131E+08 |
| | 384.790 | 42334.822 | 3.82E-01 | 8 | 6 | 1.220E-02 | 7.657E-01 | 1.909E+07 |
| | 667.683 | 42237.033 | 3.79E-01 | 6 | 8 | 2.431E-01 | 1.155E+01 | 2.102E+08 |
| | 667.683 | 42334.822 | 3.80E-01 | 6 | 6 | 1.313E-01 | 6.224E+00 | 1.520E+08 |
| | 667.683 | 42401.302 | 3.80E-01 | 6 | 4 | 2.271E-02 | 1.075E+00 | 3.957E+07 |
| | 862.613 | 42334.822 | 3.78E-01 | 4 | 6 | 2.031E-01 | 6.448E+00 | 1.553E+08 |
| | 862.613 | 42401.302 | 3.79E-01 | 4 | 4 | 1.610E-01 | 5.105E+00 | 1.853E+08 |
| | 862.613 | 42439.822 | 3.79E-01 | 4 | 2 | 3.139E-02 | 9.941E-01 | 7.238E+07 |
| | 977.053 | 42401.302 | 3.77E-01 | 2 | 4 | 1.747E-01 | 2.776E+00 | 9.996E+07 |
| | 977.053 | 42439.822 | 3.78E-01 | 2 | 2 | 2.200E-01 | 3.493E+00 | 2.522E+08 |
| z6Do → a6Pe | 0.8369 | 0.4213 | 4.16E-01 | 30 | 18 | 6.753E-02 | 1.462E+01 | 1.562E+08 |
| | 38458.981 | 84266.556 | 4.17E-01 | 10 | 8 | 6.782E-02 | 4.874E+00 | 1.186E+08 |
| | 38660.043 | 84266.556 | 4.16E-01 | 8 | 8 | 2.419E-02 | 1.397E+00 | 3.356E+07 |
| | 38858.958 | 84266.556 | 4.14E-01 | 6 | 8 | 5.341E-03 | 2.323E-01 | 5.509E+06 |
| | 38660.043 | 84326.912 | 4.16E-01 | 8 | 6 | 4.338E-02 | 2.502E+00 | 8.046E+07 |
| | 38858.958 | 84326.912 | 4.14E-01 | 6 | 6 | 4.114E-02 | 1.787E+00 | 5.672E+07 |
| | 39013.206 | 84326.912 | 4.13E-01 | 4 | 6 | 2.013E-02 | 5.849E-01 | 1.838E+07 |
| | 38858.958 | 84424.374 | 4.15E-01 | 6 | 4 | 2.099E-02 | 9.098E-01 | 4.360E+07 |
| | 39013.206 | 84424.374 | 4.14E-01 | 4 | 4 | 4.706E-02 | 1.365E+00 | 6.473E+07 |
| | 39109.307 | 84424.374 | 4.13E-01 | 2 | 4 | 6.709E-02 | 9.748E-01 | 4.594E+07 |
| z6Do → a6Fe | 0.8369 | 0.4325 | 4.04E-01 | 30 | 42 | 4.966E-01 | 1.105E+02 | 4.660E+08 |
| | 38458.981 | 82853.659 | 4.05E-01 | 10 | 12 | 4.257E-01 | 3.157E+01 | 4.664E+08 |
| | 38458.981 | 82978.677 | 4.06E-01 | 10 | 10 | 6.546E-02 | 4.841E+00 | 8.655E+07 |
| | 38458.981 | 83136.488 | 4.07E-01 | 10 | 8 | 5.284E-03 | 3.894E-01 | 8.795E+06 |
| | 38660.043 | 82978.677 | 4.04E-01 | 8 | 10 | 3.604E-01 | 2.142E+01 | 3.777E+08 |
| | 38660.043 | 83136.488 | 4.05E-01 | 8 | 8 | 1.208E-01 | 7.156E+00 | 1.594E+08 |
| | 38660.043 | 83308.194 | 4.07E-01 | 8 | 6 | 1.525E-02 | 8.998E-01 | 2.704E+07 |
| | 38858.958 | 83136.488 | 4.03E-01 | 6 | 8 | 3.043E-01 | 1.358E+01 | 2.984E+08 |
| | 38858.958 | 83308.194 | 4.05E-01 | 6 | 6 | 1.646E-01 | 7.314E+00 | 2.169E+08 |

**Table 3.** (continued)

| Transition | $E_i$ (cm$^{-1}$) | $E_f$ (cm$^{-1}$) | EDIFF (Ryd) | $g_i$ | $g_f$ | $f_{if}$ | $S$ | $a_{ji}$ (s$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| | 38858.958 | 83459.675 | 4.06E-01 | 6 | 4 | 2.851E-02 | 1.263E+00 | 5.675E+07 |
| | 39013.206 | 83308.194 | 4.04E-01 | 4 | 6 | 2.549E-01 | 7.577E+00 | 2.224E+08 |
| | 39013.206 | 83459.675 | 4.05E-01 | 4 | 4 | 2.025E-01 | 5.998E+00 | 2.668E+08 |
| | 39013.206 | 83558.543 | 4.06E-01 | 4 | 2 | 3.951E-02 | 1.168E+00 | 1.046E+08 |
| | 39109.307 | 83459.675 | 4.04E-01 | 2 | 4 | 2.197E-01 | 3.262E+00 | 1.441E+08 |
| | 39109.307 | 83558.543 | 4.05E-01 | 2 | 2 | 2.771E-01 | 4.104E+00 | 3.651E+08 |
| a4Pe → z4Po | 1.0657 | 0.7594 | 3.06E-01 | 12 | 12 | 8.383E-02 | 9.855E+00 | 6.315E+07 |
| | 13474.411 | 46967.444 | 3.05E-01 | 6 | 6 | 5.849E-02 | 3.449E+00 | 4.376E+07 |
| | 13474.411 | 47389.779 | 3.09E-01 | 6 | 4 | 2.538E-02 | 1.478E+00 | 2.921E+07 |
| | 13673.185 | 46967.444 | 3.03E-01 | 4 | 6 | 3.738E-02 | 1.478E+00 | 1.842E+07 |
| | 13673.185 | 47389.779 | 3.07E-01 | 4 | 4 | 1.121E-02 | 4.380E-01 | 8.504E+06 |
| | 13673.185 | 47626.076 | 3.09E-01 | 4 | 2 | 3.529E-02 | 1.369E+00 | 5.427E+07 |
| | 13904.824 | 47389.779 | 3.05E-01 | 2 | 4 | 6.961E-02 | 1.369E+00 | 2.603E+07 |
| | 13904.824 | 47626.076 | 3.07E-01 | 2 | 2 | 1.402E-02 | 2.738E-01 | 1.063E+07 |
| a4De → z4Po | 1.1139 | 0.7594 | 3.54E-01 | 20 | 12 | 1.421E-01 | 2.406E+01 | 2.391E+08 |
| | 7955.299 | 46967.444 | 3.56E-01 | 8 | 6 | 1.426E-01 | 9.624E+00 | 1.930E+08 |
| | 8391.938 | 46967.444 | 3.52E-01 | 6 | 6 | 4.229E-02 | 2.165E+00 | 4.198E+07 |
| | 8680.454 | 46967.444 | 3.49E-01 | 4 | 6 | 6.996E-03 | 2.406E-01 | 4.560E+06 |
| | 8391.938 | 47389.779 | 3.55E-01 | 6 | 4 | 9.976E-02 | 5.053E+00 | 1.518E+08 |
| | 8680.454 | 47389.779 | 3.53E-01 | 4 | 4 | 7.544E-02 | 2.566E+00 | 7.540E+07 |
| | 8846.768 | 47389.779 | 3.51E-01 | 2 | 4 | 2.347E-02 | 4.010E-01 | 1.163E+07 |
| | 8680.454 | 47626.076 | 3.55E-01 | 4 | 2 | 5.930E-02 | 2.005E+00 | 1.200E+08 |
| | 8846.768 | 47626.076 | 3.53E-01 | 2 | 2 | 1.181E-01 | 2.005E+00 | 1.185E+08 |
| a4Fe → z4Do | 1.1677 | 0.7820 | 3.86E-01 | 28 | 20 | 8.545E-02 | 1.861E+01 | 1.430E+08 |
| | 1872.567 | 44446.878 | 3.88E-01 | 10 | 8 | 8.595E-02 | 6.646E+00 | 1.299E+08 |
| | 2430.097 | 44446.878 | 3.83E-01 | 8 | 8 | 1.209E-02 | 7.576E-01 | 1.423E+07 |
| | 2837.950 | 44446.878 | 3.79E-01 | 6 | 8 | 8.120E-04 | 3.855E-02 | 7.032E+05 |
| | 2430.097 | 44784.761 | 3.86E-01 | 8 | 6 | 7.332E-02 | 4.559E+00 | 1.170E+08 |
| | 2837.950 | 44784.761 | 3.82E-01 | 6 | 6 | 2.061E-02 | 9.703E-01 | 2.418E+07 |
| | 3117.461 | 44784.761 | 3.80E-01 | 4 | 6 | 1.682E-03 | 5.317E-02 | 1.299E+06 |
| | 2837.950 | 45044.168 | 3.85E-01 | 6 | 4 | 6.390E-02 | 2.991E+00 | 1.139E+08 |
| | 3117.461 | 45044.168 | 3.82E-01 | 4 | 4 | 2.370E-02 | 7.443E-01 | 2.779E+07 |
| | 3117.461 | 45206.450 | 3.84E-01 | 4 | 2 | 5.948E-02 | 1.861E+00 | 1.406E+08 |
| a4Fe → z4Fo | 1.1677 | 0.7822 | 3.85E-01 | 28 | 28 | 4.314E-02 | 9.401E+00 | 5.148E+07 |
| | 1872.567 | 44232.512 | 3.86E-01 | 10 | 10 | 3.956E-02 | 3.075E+00 | 4.735E+07 |
| | 1872.567 | 44753.799 | 3.91E-01 | 10 | 8 | 3.624E-03 | 2.782E-01 | 5.556E+06 |
| | 2430.097 | 44232.512 | 3.81E-01 | 8 | 10 | 4.416E-03 | 2.782E-01 | 4.118E+06 |
| | 2430.097 | 44753.799 | 3.86E-01 | 8 | 8 | 3.291E-02 | 2.048E+00 | 3.933E+07 |
| | 2430.097 | 45079.879 | 3.89E-01 | 8 | 6 | 5.826E-03 | 3.598E-01 | 9.425E+06 |
| | 2837.950 | 44753.799 | 3.82E-01 | 6 | 8 | 7.634E-03 | 3.598E-01 | 6.710E+06 |
| | 2837.950 | 45079.879 | 3.85E-01 | 6 | 6 | 2.965E-02 | 1.386E+00 | 3.528E+07 |
| | 2837.950 | 45289.801 | 3.87E-01 | 6 | 4 | 5.773E-03 | 2.686E-01 | 1.041E+07 |
| | 3117.461 | 45079.879 | 3.82E-01 | 4 | 6 | 8.560E-03 | 2.686E-01 | 6.702E+06 |
| | 3117.461 | 45289.801 | 3.84E-01 | 4 | 4 | 3.441E-02 | 1.074E+00 | 4.082E+07 |

**Table 3.** (continued)

| Transition | $E_i$ (cm$^{-1}$) | $E_f$ (cm$^{-1}$) | EDIFF (Ryd) | $g_i$ | $g_f$ | $f_{if}$ | $S$ | $a_{ji}$ (s$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| a4Fe → z4Go | 1.1677 | 0.6355 | 5.32E-01 | 28 | 36 | 8.807E-02 | 1.390E+01 | 1.558E+08 |
| | 1872.567 | 60625.449 | 5.35E-01 | 10 | 12 | 8.269E-02 | 4.634E+00 | 1.587E+08 |
| | 1872.567 | 60807.230 | 5.37E-01 | 10 | 10 | 5.728E-03 | 3.199E-01 | 1.327E+07 |
| | 1872.567 | 60956.781 | 5.38E-01 | 10 | 8 | 1.683E-04 | 9.378E-03 | 4.899E+05 |
| | 2430.097 | 60807.230 | 5.32E-01 | 8 | 10 | 7.838E-02 | 3.536E+00 | 1.425E+08 |
| | 2430.097 | 60956.781 | 5.33E-01 | 8 | 8 | 9.316E-03 | 4.192E-01 | 2.129E+07 |
| | 2430.097 | 61041.748 | 5.34E-01 | 8 | 6 | 2.578E-04 | 1.158E-02 | 7.876E+05 |
| | 2837.950 | 60956.781 | 5.30E-01 | 6 | 8 | 7.823E-02 | 2.659E+00 | 1.322E+08 |
| | 2837.950 | 61041.748 | 5.30E-01 | 6 | 6 | 9.427E-03 | 3.199E-01 | 2.130E+07 |
| | 3117.461 | 61041.748 | 5.28E-01 | 4 | 6 | 8.735E-02 | 1.986E+00 | 1.303E+08 |
| a2Se → z2Po | 0.8505 | 0.5990 | 2.51E-01 | 2 | 6 | 1.317E-02 | 3.141E-01 | 2.229E+06 |
| | 37227.326 | 64834.073 | 2.52E-01 | 2 | 4 | 8.780E-03 | 2.094E-01 | 2.232E+06 |
| | 37227.326 | 64806.487 | 2.51E-01 | 2 | 2 | 4.386E-03 | 1.047E-01 | 2.225E+06 |
| a2Se → y2Po | 0.8505 | 0.5228 | 3.28E-01 | 2 | 6 | 1.123E-01 | 2.056E+00 | 3.229E+07 |
| | 37227.326 | 73189.110 | 3.28E-01 | 2 | 4 | 7.486E-02 | 1.371E+00 | 3.229E+07 |
| | 37227.326 | 73187.280 | 3.28E-01 | 2 | 2 | 3.743E-02 | 6.853E-01 | 3.228E+07 |
| a2Pe → z2So | 1.0208 | 0.5860 | 4.35E-01 | 6 | 2 | 1.706E-01 | 7.063E+00 | 7.772E+08 |
| | 18360.646 | 66248.660 | 4.36E-01 | 4 | 2 | 1.712E-01 | 4.709E+00 | 5.239E+08 |
| | 18886.780 | 66248.660 | 4.32E-01 | 2 | 2 | 1.694E-01 | 2.354E+00 | 2.534E+08 |
| a2Pe → z2Do | 1.0208 | 0.6292 | 3.92E-01 | 6 | 10 | 3.666E-01 | 1.685E+01 | 2.709E+08 |
| | 18360.646 | 61093.413 | 3.89E-01 | 4 | 6 | 3.282E-01 | 1.011E+01 | 2.665E+08 |
| | 18360.646 | 62125.600 | 3.99E-01 | 4 | 4 | 3.734E-02 | 1.124E+00 | 4.771E+07 |
| | 18886.780 | 62125.600 | 3.94E-01 | 2 | 4 | 3.689E-01 | 5.618E+00 | 2.300E+08 |
| a2De → z2Po | 0.9999 | 0.5990 | 4.01E-01 | 10 | 6 | 4.079E-02 | 3.052E+00 | 8.775E+07 |
| | 20516.960 | 64834.073 | 4.04E-01 | 6 | 4 | 4.109E-02 | 1.831E+00 | 8.074E+07 |
| | 21308.040 | 64834.073 | 3.97E-01 | 4 | 4 | 6.726E-03 | 2.035E-01 | 8.500E+06 |
| | 21308.040 | 64806.487 | 3.96E-01 | 4 | 2 | 3.361E-02 | 1.017E+00 | 8.483E+07 |
| a2De → z2Do | 0.9999 | 0.6292 | 3.71E-01 | 10 | 10 | 2.059E-03 | 1.667E-01 | 2.272E+06 |
| | 20516.960 | 61093.413 | 3.70E-01 | 6 | 6 | 1.917E-03 | 9.333E-02 | 2.106E+06 |
| | 20516.960 | 62125.600 | 3.79E-01 | 6 | 4 | 1.404E-04 | 6.667E-03 | 2.433E+05 |
| | 21308.040 | 61093.413 | 3.63E-01 | 4 | 6 | 2.014E-04 | 6.667E-03 | 1.418E+05 |
| | 21308.040 | 62125.600 | 3.72E-01 | 4 | 4 | 1.860E-03 | 6.000E-02 | 2.067E+06 |
| a2De → z2Fo | 0.9999 | 0.6033 | 3.97E-01 | 10 | 14 | 2.723E-02 | 2.060E+00 | 2.456E+07 |
| | 20516.960 | 64286.345 | 3.99E-01 | 6 | 8 | 2.608E-02 | 1.177E+00 | 2.500E+07 |
| | 20516.960 | 64425.408 | 4.00E-01 | 6 | 6 | 1.308E-03 | 5.886E-02 | 1.683E+06 |
| | 21308.040 | 64425.408 | 3.93E-01 | 4 | 6 | 2.698E-02 | 8.240E-01 | 2.230E+07 |

and the lifetime of state f can now be obtained as

$$\tau_f = 1/A_f. \tag{12}$$

Conservation of the total $LS$ multiplet strength, $S_{LS}$, with the sum of fine structure components, Eq. (5), is checked for each $LS$ transition if splitting is carried out through line strength, Eq. (4), and the discrepancy is found to be usually less than 0.01%. Conservation of the total $LS$ multiplet oscillator strength is checked with the sum of fine structure components, Eq. (8), if splitting is carried out through oscillator strength, Eq. (7), to ensure that there is no discrepancy between the two values.

The radiative calculations for Fe II for the OP were carried out (NP, 1994) in the close coupling (CC) approximation employing the $R$-matrix method using a 83 state expansion for the target. The calculations resulted in 743 bound states below the ionization threshold and over 19 000 oscillator strengths in $LS$ multiplet among these states. Present calculations correspond to processing of only 3109 transitions, a small fraction of the total number of bound - bound radiative data computed for Fe II. The major effort in the present work involved in the identification of the calculated states, correlating them with the observed energies, and sorting out the corresponding $f$-values from a large number of transitions obtained from the close coupling calculations. The calculated energies are not necessarily in the same sequence, because of unobserved levels in between, and are not in the same order as the observed set of $LS$ terms. Being a complex system of 25 electrons with considerable correlations effects, Fe II gives rise to many energy levels that are closely spaced. Identification of these states required consistency checks of the effective quantum numbers of the Rydberg series of states belonging to the Fe III core states and percentage contributions of the contributing channels (NP 1994). A code ELEVID is developed specifically for the identification of states. The code also processes the data for calculated energies and oscillator strengths (that is stored encoded in separate files), and to correlate and sort out the transitions of interest.

The fine structure splitting is carried out from the calculated $f$-values obtained in the length form only. As explained in the earlier work (Nahar 1993), in the $R$-matrix calculations the wave functions in the asymptotic region are better represented than in the inner region, and the dipole matrix elements in the length form are weighted more towards the asymptotic region and therefore more accurate than the velocity form. The $LS$ multiplet $f$-values and $A$-values presented in this work correspond to observed $LS$ term energies, obtained through statistical average over the fine structure energies.

Some explanation is necessary for transitions between terms having incomplete sets of observed fine structure levels. The measured energies (Johansson 1992) correspond to a large number of levels, 769 in total belonging to 265 $LS$ terms. Not all the $LS$ terms have complete set of observed fine structure levels. Another code JJTOLS carries out a check for completeness of the set of observed fine structure levels which in general is not specified in the observed energy Table (JJTOLS also computes the oscillator strengths and other quantities). For all transitions

up to angular momenta $H \leftrightarrow I$, the transition energy between one or both unobserved levels is obtained from the values of $f_{JJ}$, Eq. (7), and $S_{JJ}$, Eq. (4), to calculate the transition probability, and for transitions beyond $H \leftrightarrow I$, the transition energy is approximated to $\Delta E_{LS}$ for unobserved levels.

## 3. Results and discussion

As the main aim of the present work is to make available an extensive amount of data for transition probabilities in Fe II, it is necessary to also assess the uncertainties in the theoretical calculations as compared with other reliable measurements and theoretical calculations. Detailed checks and comparison of the $f$-values obtained from the close coupling calculations are carried out in the earlier work (NP 1994) and it is found that, on the whole, present values are in better agreement with the experimental values in the NIST compilation (Fuhr et al. 1988) than those by Kurucz (1981).

The other check for the $f$-values is carried out through a comparison with the lifetimes of the atomic levels, $\tau$, which can be measured usually with higher precision than the transition probabilities. The computed lifetimes were compared earlier (NP 1994) with the available experimental data; however, since the work was not complete, some of the contributing $A$-values from higher levels were not included in the calculated lifetimes. Table 1 presents the revised lifetime values with more contributing levels of Fe II obtained using the additional transition probabilites from the present work, and compares these with the experimental ones (Guo et al. 1992; Hannaford et al. 1992; Schade et al. 1988; Biemont et al. 1991), and with those calculated by Kurucz. Present lifetimes are obtained from allowed transitions only, whereas the Kurucz values consider forbidden transitions as well (though the contribution is small). It can be seen from the Table that the present calculated lifetimes for all the levels agree better with the measured values than the Kurucz data. As the lifetime of a given level involves contributions from several transitions, the good agreement with experiment indicates an improved accuracy in comparison with the earlier works.

It is necessary to designate the multiplet energies in order to tabulate the results. Table 2 presents the observed Fe II $LS$ terms in symmetry order, with even parity terms followed by the odd parity terms and the energies obtained from statistical averaging over the fine structure levels. The degeneracy symbol for each term does not necessarily match the observed one. The notation for degeneracy, in alphabetical order for the even terms and anti-alphabetical order for the odd terms, of the same symmetry is chosen for convenience of identification, and is used throughout for specification of transitions. An asterisk next to the energy of a $LS$ term corresponds to an incomplete set of observed fine structure levels for that term.

Table 3 presents a small sample, taken from the complete table, of the computed $f$-, $S$- and $A$-values for transitions between the lowest few terms of total angular momenta belonging to the four spin symmetries, octet, sextet, quartet and doublet.

The first line of each transition in Table 3 corresponds to $LS$ multiplet $f$-, $S$- and $A$-values, followed by the individual fine structure components. As mentioned earlier, observed energies are used for calculations of the $f$- and $A$-values; in the case of unobserved fine structure levels, calculated energies are used. On the first line, the energies of the $LS$ terms are expressed in Rydberg units whereas the level energies are expressed in $cm^{-1}$ units. The transition energy between the levels is given in Rydberg units. The $g_i$ and $g_f$ are the statistical weight factors of the initial and final levels respectively. There are a few transitions in the complete Table for which no $f$- and $A$-values are obtained. These correspond to transitions between two closely spaced $LS$ terms where the initial term has a lower energy but a few of its fine structure levels lie high above the dipole allowed levels of the higher term. In addition to the transition probabilities, the Table contains all the $LS$ terms considered with explicit configurations and energies. It also contains a FORTRAN program that can read the transition probabilities and calculate the lifetime of a $LS$ term or a fine structure level.

## 4. Conclusion

The oscillator strengths, line strengths, and transition probabilites for transitions among dipole allowed fine structure levels of Fe II are obtained as a part of the Iron Project. These values provide an extensive dataset for astrophysical applications involving the analysis of Fe II spectra. A comparison with available experimental values shows better agreement than currently available data. The present transition probabilities are now being utilized in astrophysical models for spectral intensities of Fe II lines.

The radiative work reported herein required about 500 CPU hours on the Cray Y-MP in Columbus, Ohio. Considering the complexity of the work, it is estimated that the relativistic Breit-Pauli calculations with full intermediate coupling would require several times the CPU time and memory used in the present computations.

The complete Table of 3109 $LS$ multiplets and 21589 fine structure transitions may be obtained electronically via e-mail from nahar@payne.mps.ohio-state.edu.

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