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# Transition probabilities for [Ni I] and [Ni II] lines⋆

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**Abstract.** — New radiative transition probabilities have been calculated for forbidden lines of astrophysical interest in Ni I and Ni II. The accuracy of the transition probability scales is established on the basis of two independent calculations performed with the approximately relativistic Hartree-Fock and SUPERSTRUCTURE codes. Both physical models take into account the most important configuration interaction (CI) and relativistic effects.

**Key words:** atomic data — Ni I – Ni II — transition probabilities

## 1. Introduction

Forbidden lines of neutral and singly ionized nickel have been observed in many astrophysical objects like novae, peculiar stars, planetary nebulae and supernova remnants (see e.g. Swings 1966; Aller & Dunham 1966; Thackeray 1967, 1977; Danziger & Dennefeld 1974; Grandi 1975; Dennefeld & Péquignot 1983; Fesen & Kirshner 1980, 1982; Henry 1984, 1987; Aitken 1988; Nussbaumer & Storey 1988; Osterbrock et al. 1992; Jennings et al. 1993; Hamann 1994; Lucy 1995).

However, a very limited number of transition probability calculations have been published so far for [Ni I] and [Ni II] lines. Up to now, only the results obtained by Garstang (1964) were available for forbidden transitions in Ni I. This author performed intermediate coupling calculations including very limited configuration interaction arising from the three lowest configurations, i.e. $3d^84s^2$, $3d^94s$ and $3d^{10}$. For [Ni II] lines, radiative transition probabilities have been published by Garstang (1958) and Nussbaumer & Storey (1982). In particular, these last authors used the program SUPERSTRUCTURE due to Eissner et al. (1974) and modified by Nussbaumer & Storey (1978) for calculating transition probabilities for forbidden lines connecting the lowest 17 energy levels of Ni II in a three configuration basis (including $3d^9$, $3d^84s$ and $3d^84d$).

The purpose of the present work is to provide new sets of refined transition probabilities for [Ni I] and [Ni II] lines which are observed in astrophysical spectra. The calculations taking into account the most important configuration interaction (CI) and relativistic effects have been performed using two independent theoretical methods, the relativistic Hartree-Fock (HFR) approximation and the formalism implemented in the SUPERSTRUCTURE (SST) code. A brief description of the two physical models used in this study can be found in Sect. 2. Our results are given in Sect. 3 while Sect. 4 consists of a brief conclusion. The calculations reported here are part of a general program of investigation of forbidden transitions of astrophysical interest in iron group elements, which started with studies of [Fe II] (Quinet et al. 1996) and [Fe III] lines (Quinet 1996).

**Table 1.** Fitted parameters (in $cm^{-1}$) used in the HFR calculations for Ni I. The ratios between fitted values and ab initio HFR values are also indicated

| Configuration | Parameter | Fitted value | Ratio |
|---|---|---|---|
| $3d^84s^2$ | $E_{av}$ | 14116. | |
| | $F^2$(3d,3d) | 77120. | 0.8005 |
| | $F^4$(3d,3d) | 51830. | 0.8679 |
| | $\alpha$ | 43. | |
| | $\beta$ | 1059. | |
| | $\zeta_{3d}$ | 654.[a] | 1.0000 |
| $3d^94s$ | $E_{av}$ | 2539. | |
| | $G^2$(3d,4s) | 6585. | 0.8540 |
| | $\zeta_{3d}$ | 594.[a] | 1.0000 |
| $3d^{10}$ | $E_{av}$ | 17732. | |

[a] Fixed to the ab initio value.

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⋆The Tables 7 and 8 are also available in electronic form at the CDS via anonymous ftp 130.79.128.5

**Table 2.** Fitted parameters (in $cm^{-1}$) used in the HFR calculations for Ni II. The ratios between fitted values and ab initio HFR values are also indicated

| Configuration | Parameter | Fitted value | Ratio |
|---|---|---|---|
| $3d^9$ | $E_{av}$ | 3898. | |
| | $\zeta_{3d}$ | 599.[a] | 1.0000 |
| $3d^84s$ | $E_{av}$ | 22619. | |
| | $F^2$(3d,3d) | 80787. | 0.8305 |
| | $F^4$(3d,3d) | 52773. | 0.8746 |
| | $G^2$(3d,4s) | 8455. | 0.8681 |
| | $\alpha$ | 42. | |
| | $\beta$ | 700.[b] | |
| | $\zeta_{3d}$ | 659.[a] | 1.0000 |

[a] Fixed to the ab initio value. [b] Determined from the $3d^8$ configuration in Ni III (see text).

**Table 3.** Calculated HFR energy levels (in $cm^{-1}$) and comparison with experiment for the $3d^84s^2$, $3d^94s$ and $3d^{10}$ configurations of Ni I

| Configuration | Term | $J$ | $E_{calc}$ | $\Delta E$[a] |
|---|---|---|---|---|
| $3d^84s^2$ | $^3$F | 4 | 0. | 0. |
| | | 3 | 1328. | 4. |
| | | 2 | 2216. | 1. |
| $3d^94s$ | $^3$D | 3 | 216. | -11. |
| | | 2 | 877. | 3. |
| | | 1 | 1699. | 14. |
| $3d^94s$ | a$^1$D | 2 | 3408. | 2. |
| $3d^84s^2$ | b$^1$D | 2 | 13508. | 13. |
| $3d^{10}$ | a$^1$S | 0 | 14727. | 2. |
| $3d^84s^2$ | $^3$P | 2 | 15639. | -29. |
| | | 1 | 15728. | 6. |
| | | 0 | 15998. | 19. |
| $3d^84s^2$ | $^1$G | 4 | 22100. | 2. |
| $3d^84s^2$ | b$^1$S | 0 | 50274. | 2. |

[a] $\Delta E = E_{obs} - E_{calc}$ with $E_{obs}$ taken from Litzén et al. (1993).

**Table 4.** Calculated HFR energy levels (in $cm^{-1}$) and comparison with experiment for the $3d^9$ and $3d^84s$ configurations of Ni II

| Configuration | Term | $J$ | $E_{calc}$ | $\Delta E$[a] |
|---|---|---|---|---|
| $3d^9$ | a$^2$D | 5/2 | 0. | 0. |
| | | 3/2 | 1495. | 12. |
| $3d^84s$ | $^4$F | 9/2 | 8392. | 2. |
| | | 7/2 | 9312. | 18. |
| | | 5/2 | 10089. | 27. |
| | | 3/2 | 10634. | 30. |
| | $^2$F | 7/2 | 13571. | -21. |
| | | 5/2 | 15017. | -21. |
| | b$^2$D | 5/2 | 23140. | -32. |
| | | 3/2 | 23756. | 40. |
| | $^4$P | 3/2 | 24792. | -4. |
| | | 1/2 | 24857. | -21. |
| | | 5/2 | 25041. | -5. |
| | $^2$P | 3/2 | 29062. | 9. |
| | | 1/2 | 29538. | 56. |
| | $^2$G | 9/2 | 32505. | -5. |
| | | 7/2 | 32507. | 17. |
| | $^2$S | 1/2 | 61465. | - |

[a] $\Delta E = E_{obs} - E_{calc}$ with $E_{obs}$ taken from Sugar & Corliss (1985).

**Table 5.** Observed energy levels, $E_{obs}$, and fine-structure splittings, $\Delta E_{obs}$, for Ni I. The present fine-structure splittings, $\Delta E_{calc}$, obtained with SST and the semi-empirical corrections to calculated non-relativistic energies, TEC, are also given. All values are in $cm^{-1}$

| Configuration | Term | $J$ | $E_{obs}$[a] | $\Delta E_{obs}$ | $\Delta E_{calc}$ | TEC |
|---|---|---|---|---|---|---|
| $3d^84s^2$ | $^3$F | 4 | 0.0 | | | |
| | | | | 1332. | 1394. | |
| | | 3 | 1332.2 | | | -44. |
| | | | | 885. | 919. | |
| | | 2 | 2216.6 | | | |
| $3d^94s$ | $^3$D | 3 | 204.8 | | | |
| | | | | 675. | 686. | |
| | | 2 | 879.8 | | | 4. |
| | | | | 833. | 890. | |
| | | 1 | 1713.1 | | | |
| $3d^94s$ | a$^1$D | 2 | 3409.9 | | | -90. |
| $3d^84s^2$ | b$^1$D | 2 | 13521.3 | | | -1404. |
| $3d^{10}$ | a$^1$S | 0 | 14728.8 | | | 457. |
| $3d^84s^2$ | $^3$P | 2 | 15609.8 | | | |
| | | | | 124. | 142. | |
| | | 1 | 15734.0 | | | -4002. |
| | | | | 283. | 271. | |
| | | 0 | 16017.3 | | | |
| $3d^84s^2$ | $^1$G | 4 | 22102.3 | | | -5313. |
| $3d^84s^2$ | b$^1$S | 0 | 50276.3 | | | -7779. |

[a] Litzén et al. (1993).

**Table 6.** Observed energy levels, $E_{obs}$, and fine-structure splittings, $\Delta E_{obs}$, for Ni II. The present fine-structure splittings, $\Delta E_{calc}$, obtained with SST and the semi-empirical corrections to calculated non-relativistic energies, TEC, are also given. All values are in $cm^{-1}$

| Configuration | Term | $J$ | $E_{obs}$[a] | $\Delta E_{obs}$ | $\Delta E_{calc}$ | TEC |
|---|---|---|---|---|---|---|
| $3d^9$ | a$^2$D | 5/2 | 0.0 | | | |
| | | | | 1507. | 1431. | 31 . |
| | | 3/2 | 1506.9 | | | |
| $3d^84s$ | $^4$F | 9/2 | 8393.9 | | | |
| | | | | 936. | 968. | |
| | | 7/2 | 9330.0 | | | |
| | | | | 786. | 819. | 688 . |
| | | 5/2 | 10115.7 | | | |
| | | | | 548. | 571. | |
| | | 3/2 | 10663.9 | | | |
| | $^2$F | 7/2 | 13550.4 | | | |
| | | | | 1446. | 1508. | 764 . |
| | | 5/2 | 14995.6 | | | |
| | b$^2$D | 5/2 | 23108.3 | | | |
| | | | | 688. | 677. | -390 . |
| | | 3/2 | 23796.2 | | | |
| | $^4$P | 3/2 | 24788.2 | | | |
| | | | | 48. | 64. | |
| | | 1/2 | 24835.9 | | | -1349 . |
| | | | | 200. | 208. | |
| | | 5/2 | 25036.4 | | | |
| | $^2$P | 3/2 | 29070.9 | | | |
| | | | | 523. | 511. | -1439 . |
| | | 1/2 | 29593.5 | | | |
| | $^2$G | 9/2 | 32499.5 | | | |
| | | | | 24. | 18. | -2984 . |
| | | 7/2 | 32523.5 | | | |

[a] Sugar & Corliss (1985).

**Table 7.** Radiative transition probabilities, $A_{ki}$ in $s^{-1}$, as obtained with HFR and SST for forbidden lines of Ni I. A(B) stands for $A.10^B$

| Multiplet | $J$-$J'$ | $\lambda$(Å)[a] | Type | $A_{ki}$(HFR) | $A_{ki}$(SST) |
|---|---|---|---|---|---|
| $^3$F-$^3$F | 4-3 | 75045.37 | M1 | 6.11(-2) | 6.14(-2) |
| | 3-2 | 113041.98 | M1 | 2.48(-2) | 2.44(-2) |
| $^3$F-a$^1$D | 3-2 | 48115.33 | M1 | 2.03(-3) | 3.39(-3) |
| | 2-2 | 83772.27 | M1 | 2.20(-4) | 3.53(-4) |
| $^3$F-b$^1$D | 4-2 | 7393.68 | E2 | 4.24(-3) | 1.25(-5) |
| | 3-2 | 8201.74 | M1 | 3.86(-1) | 3.96(-1) |
| | 2-2 | 8843.37 | M1 | 1.73(-1) | 1.79(-1) |
| $^3$F-a$^1$S | 2-0 | 7989.94 | E2 | 8.13(-3) | 8.45(-3) |
| $^3$F-$^3$P | 4-2 | 6404.44 | E2 | 2.16(-2) | 3.70(-5) |
| | 3-2 | 7002.01 | M1,E2 | 1.64(-1) | 1.78(-1) |
| | 3-1 | 6941.64 | E2 | 1.75(-2) | 1.79(-5) |
| | 2-2 | 7464.37 | M1 | 3.88(-2) | 4.25(-2) |
| | 2-1 | 7395.81 | M1,E2 | 8.04(-3) | 3.09(-3) |
| | 2-0 | 7243.98 | E2 | 2.25(-2) | 2.63(-4) |
| $^3$F-$^1$G | 4-4 | 4523.14 | M1 | 3.21(-1) | 3.26(-1) |
| | 3-4 | 4813.25 | M1 | 1.60(-1) | 1.62(-1) |
| | 2-4 | 5027.32 | E2 | 2.50(-3) | 6.71(-3) |
| $^3$F-b$^1$S | 2-0 | 2080.08 | E2 | 3.92(-1) | 8.07(-1) |
| $^3$D-$^3$D | 3-2 | 148101.41 | M1 | 6.62(-3) | 6.95(-3) |
| | 2-1 | 119976.27 | M1 | 2.05(-2) | 2.10(-2) |
| $^3$D-$^3$F | 3-2 | 49694.09 | M1 | 3.34(-4) | 6.28(-4) |
| $^3$D-a$^1$D | 3-2 | 31191.28 | M1 | 7.36(-2) | 8.24(-2) |
| | 2-2 | 39513.03 | M1 | 5.84(-3)* | 6.39(-3) |
| | 1-2 | 58916.66 | M1 | 1.09(-2) | 1.18(-2) |
| $^3$D-b$^1$D | 3-2 | 7507.38 | M1,E2 | 2.71(-2) | 3.13(-2) |
| | 2-2 | 7908.26 | M1,E2 | 3.21(-2) | 3.75(-2) |
| | 1-2 | 8466.32 | M1,E2 | 4.99(-3) | 5.94(-3) |
| $^3$D-a$^1$S | 2-0 | 7218.74 | E2 | 1.75(-1) | 2.01(-1) |
| $^3$D-$^3$P | 3-2 | 6489.58 | E2 | 1.33(-1) | 1.38(-1) |
| | 3-1 | 6437.70 | E2 | 1.58(-1) | 1.67(-1) |
| | 2-2 | 6786.98 | E2 | 3.34(-2) | 3.33(-2) |
| | 2-1 | 6730.25 | M1,E2 | 2.15(-2) | 2.24(-2) |
| | 2-0 | 6604.29 | E2 | 3.50(-1) | 3.59(-1) |
| | 1-2 | 7193.94 | M1,E2 | 1.07(-2) | 1.13(-2) |
| | 1-1 | 7130.24 | E2 | 9.33(-2) | 1.02(-1) |
| $^3$D-$^1$G | 3-4 | 4565.44 | E2 | 1.44(-3) | 2.11(-3) |
| | 2-4 | 4710.66 | E2 | 1.18(-1) | 1.22(-1) |
| $^3$D-b$^1$S | 2-0 | 2023.78 | E2 | 1.69(+1) | 9.65(+0) |
| a$^1$D-b$^1$D | 2-2 | 9887.11 | E2 | 2.26(-2) | 2.15(-2) |
| a$^1$D-a$^1$S | 2-0 | 8832.35 | E2 | 7.81(-1) | 6.95(-1) |
| a$^1$D-$^3$P | 2-2 | 8194.53 | M1,E2 | 4.98(-2) | 5.39(-2) |
| | 2-1 | 8111.98 | M1,E2 | 3.22(-3) | 4.02(-3) |
| | 2-0 | 7929.69 | E2 | 3.28(-3) | 1.41(-5) |
| a$^1$D-$^1$G | 2-4 | 5348.28 | E2 | 6.87(-1) | 6.68(-1) |
| a$^1$D-b$^1$S | 2-0 | 2133.05 | E2 | 9.47(+1) | 7.93(+1) |
| b$^1$D-$^3$P | 2-2 | 47868.27 | M1 | 7.74(-2) | 7.55(-2) |
| | 2-1 | 45182.27 | M1 | 6.53(-2) | 6.89(-2) |
| b$^1$D-$^1$G | 2-4 | 11650.49 | E2 | 7.23(-4) | 1.36(-4) |
| b$^1$D-b$^1$S | 2-0 | 2719.91 | E2 | 5.79(+0) | 1.57(-1) |
| a$^1$S-$^3$P | 0-1 | 99459.43 | M1 | 2.43(-4) | 1.42(-4) |
| $^3$P-$^3$P | 1-0 | 352880.27 | M1 | 1.05(-3) | 1.21(-3) |
| $^3$P-b$^1$S | 2-0 | 2883.79 | E2 | 1.62(+0) | 4.05(-2) |
| | 1-0 | 2894.15 | M1 | 4.76(+0) | 5.28(+0) |

[a] Wavelengths in air deduced from the observed energy levels (Litzén et al. 1993).
* Cancellation effects present (see text).

## 2. Calculations

### 2.1. *Relativistic Hartree-Fock (HFR)*

First, the radial wavefunctions were generated using the pseudo relativistic Hartree-Fock (HFR) method originally introduced by Cowan & Griffin (1976) with the computer codes written by Cowan (1981). The relativistic corrections included in the differential equations are derived from a Pauli-type approximation to the Dirac-Hartree-Fock equations and retain both the mass-velocity and Darwin operators. The calculations used the superposition of the configurations $3d^84s^2 + 3d^94s + 3d^{10} + 3d^94d + 3d^84p^2 + 3d^84d^2 + 3d^84s4d + 3d^84s5s + 3d^95s + 3d^95d + 3s3p^63d^94s^2 + 3s3p^63d^{10}4s$ for Ni I and $3d^9 + 3d^84s + 3d^84d + 3d^74s^2 + 3d^74p^2 + 3d^74d^2 + 3d^74s4d + 3d^85s + 3d^85d + 3s3p^63d^{10} + 3s3p^63d^94s$ for Ni II.

In addition to the explicit introduction of CI, the interactions with more distant configurations were simulated in a number of ways. In the first place, the semi-empirical adjustment of the Slater parameters and the inclusion of additional effective parameters such as $\alpha$ and $\beta$, associated with the excitations out of the 3s and 3p subshells into the 3d (see Trees 1951a, b; Racah 1952), allows specifically for the cumulative effects of distant configurations. The fitting procedure was applied to the $3d^84s^2$, $3d^94s$ and $3d^{10}$ configurations of Ni I and to the $3d^9$ and $3d^84s$ configurations of Ni II with the experimental energy levels published by Litzén et al. (1993) and Sugar & Corliss (1985) respectively. For the $3d^84s^2$ (in Ni I) and $3d^84s$ (in Ni II) configurations, there are in both cases five parameters associated with the $3d^8$ parent configuration ($E_{av}$, $F^2$(3d,3d), $F^4$(3d,3d), $\alpha$ and $\beta$). These parameters were determined from the five observed terms $^3$F, $^3$P, $^1$D, $^1$G and $^1$S in Ni I. However, in the case of $3d^84s$ in Ni II, only four parent terms are known ($^1$S is missing). Consequently, for this configuration, the adopted value for the $\beta$ parameter (700 $cm^{-1}$) was determined from the $3d^8$ configuration in Ni III where all five terms are observed (Sugar & Corliss 1985). The ab initio HFR values for the Slater parameters within other configurations than those included in the fitting procedure and for the CI integrals were scaled down by a factor 0.80 as recommended by Cowan (1994) to simulate CI effects while the ab initio values of all the spin-orbit integrals, computed by the Blume-Watson method, were used without scaling. The present fitted parameters together with the ratios between fitted and ab initio HFR values are reported in Tables 1 and 2 for Ni I and Ni II respectively.

Calculated energy levels are compared with experiment in Tables 3 and 4 for the $3d^84s^2$, $3d^94s$ and $3d^{10}$ configurations of Ni I and for the $3d^9$ and $3d^84s$ configurations of Ni II respectively. In both cases, the agreement between observed and computed values is within a few tens of $cm^{-1}$. The $3d^84s$ $^2D_{5/2}$ and $^4P_{5/2}$ levels of Ni II deserve a special attention. As already mentioned by

Garstang (1958) and Nussbaumer & Storey (1982), the coupling between these two levels is so strong that any of the LS designation suggested for them has little significance. Here, we adhere to the traditional designation retained by Nussbaumer & Storey (1982).

### **2**.2. *SUPERSTRUCTURE (SST)*

For this part of the work, calculations were carried out with the computer program of Eissner et al. (1974), as modified by Nussbaumer & Storey (1978). When using the SST code, we were able to add to the HFR expansions the $3s^23p^43d^{10}4s^2$ (Ni I) and $3s^23p^43d^{10}4s$ (Ni II) configurations corresponding to the core excitations $3p^2 \rightarrow 3d^2$ and which are expected to contribute to the energy level values within the configurations of interest as shown recently by Quinet & Hansen (1995).

The radial orbitals were optimized in a statistical model Thomas-Fermi potential (Eissner & Nussbaumer 1969) scaled using $n$- and $l$-dependent parameters, $\lambda_{nl}$, which were determined by minimizing the sum of the non-relativistic term energies in the $3d^84s^2$, $3d^94s$ and $3d^{10}$ configurations in Ni I and the $3d^9$ and $3d^84s$ configurations in Ni II. The resulting scaling parameters are:

$\lambda_{1s} = 1.43283$, $\lambda_{2s} = 1.14077$, $\lambda_{2p} = 1.08446$, $\lambda_{3s} = 1.05178$, $\lambda_{3p} = 1.03183$, $\lambda_{3d} = 1.02145$, $\lambda_{4s} = 0.93846$,

$\lambda_{4p} = 1.04810$, $\lambda_{4d} = 1.31673$, $\lambda_{5s} = 1.30283$, $\lambda_{5d} = 2.24051$ for Ni I,

and

$\lambda_{1s} = 1.43126$, $\lambda_{2s} = 1.13921$, $\lambda_{2p} = 1.08278$, $\lambda_{3s} = 1.05736$, $\lambda_{3p} = 1.03697$, $\lambda_{3d} = 1.01500$, $\lambda_{4s} = 1.14739$,

$\lambda_{4p} = 1.16785$, $\lambda_{4d} = 1.28761$, $\lambda_{5s} = 1.56283$, $\lambda_{5d} = 1.25734$ for Ni II.

In SST, the relativistic wavefunctions are obtained using perturbation theory. Relativistic corrections are introduced by means of the Breit-Pauli approximation. The calculations reported here include the spin-orbit, spin-spin and spin-other orbit interactions which are important for fine-structure splittings. This procedure can be improved by means of semi-empirical corrections (TECs) to the term energies (Zeippen et al. 1977). In practice, the TEC for a given term is simply the difference between the measured and calculated energy of the lowest level in the multiplet. Finally, when computing transition probabilities with SST, experimental energies are substituted for theoretical ones. The TECs used in the present calculations are reported in Table 5 (Ni I) and Table 6 (Ni II) together with the calculated fine-structure splittings. Observed energies taken from Litzén et al. (1993) and Sugar & Corliss (1985) are also given for comparison. It appears that the fine-structure splittings are in very good agreement with experiment for all multiplets.

## 3. Transition probabilities

The transition probabilities, $A_{ki}$, were calculated for magnetic dipole (M1) and electric quadrupole (E2) transitions involving all the states within the $3d^84s^2$, $3d^94s$ and $3d^{10}$ configurations of Ni I and within the $3d^9$ and $3d^84s$ configurations of Ni II. The HFR and SST probabilities obtained in the present work are compared in Tables 7 and 8. If the two types of radiation contribute comparably to the total intensity of a line, then the sum of both components is given. Only transitions for which $A_{ki}$ is greater than $0.0001$ s$^{-1}$ are reported in the tables.

Some of the transitions considered in our work are likely to be affected by cancellation effects in forming the radial integrals. For these transitions (starred in Tables 7 and 8), the cancellation factor (CF) as defined by Cowan (1970) is very small (typically CF $\leq 0.01$) indicating that the corresponding probability must be considered with some care.

For Ni I, the general agreement between HFR and SST transition probabilities is good (within 20%) if we except the weak $^3D_3$–$^3F_2$, $^3F_{2,3}$–$a^1D_2$ and $a^1S_0$–$^3P_1$ M1 transitions and the $^3F_4$–$b^1D_2$, $^3F_4$–$^3P_2$, $^3F_{2,3}$–$^3P_1$, $^3F_2$–$^3P_0$, $^3F_2$–$^1G_4$, $^3F_2$–$b^1S_0$, $^3D_3$–$^1G_4$, $^3D_2$–$b^1S_0$, $a^1D_2$–$^3P_0$, $b^1D_2$–$^1G_4$, $b^1D_2$–$b^1S_0$ and $^3P_2$–$b^1S_0$ E2 transitions for which larger discrepancies are observed. The HFR and SST $A$-values for forbidden transitions of Ni II generally agree to within 10–30% if we except some very weak E2 transitions ($A \leq 10^{-3}$ s$^{-1}$). Exceptions occur also for the $^4F_{9/2}$–$b^2D_{5/2}$, $^4F_{7/2}$–$b^2D_{3/2}$, $^4F_{9/2}$–$^4P_{5/2}$, $^4F_{7/2}$–$^4P_{3/2}$, $^4F_{3/2,5/2}$–$^4P_{1/2}$, $^4F_{3/2,5/2}$–$^2S_{1/2}$ E2 transitions for which the discrepancies can reach 50%. However, for the most intense [Ni I] and [Ni II] lines, the two scales differ in general by at most a few percent.

A very limited number of transition probabilities has been reported previously for [Ni I] and [Ni II] lines. To our knowledge, for Ni I, only the results obtained by Garstang (1964) who performed intermediate coupling calculations including limited configuration interaction arising from the three lowest configurations have been published. In general, for the M1 transitions, these results agree very well with the HFR and SST transition probabilities obtained in the present work. For the E2 contributions, large discrepancies are observed for a number of transitions and they can reach a factor of two in many cases. However, these transitions are more sensitive than the M1 contributions to correlation effects and our results were obtained with more configuration interaction effects taken into account than Garstang's calculations. Therefore, our data are expected to be more accurate. For [Ni II] lines, transition probabilities were published by Garstang (1958) who performed a two-configuration calculation including only the $3d^9$ and $3d^84s$ configurations. More recently, $A$-values for forbidden lines involving the energetically lowest 17 levels of Ni II were calculated by Nussbaumer & Storey (1982) using the SUPERSTRUCTURE code. Only

the $3d^9$, $3d^84s$ and $3d^84d$ configurations were included in these calculations. For the strongest M1 contributions, the agreement between our calculated transition probabilities (using both HFR and SST methods) and the results obtained by Nussbaumer & Storey (1982) is satisfactory (within 30%) if we except the $^4F_{3/2,5/2}-^4P_{3/2}$, $^2F_{5/2}-^4P_{3/2}$, $^4P_{5/2}-^2P_{3/2}$ and $^4P_{3/2}-^2P_{1/2}$ transitions for which the discrepancies can reach a factor of two. For some E2 lines, our $A$-values are substantially different from those reported by these authors . Here also, these differences are mainly due to the inclusion of more configuration interaction effects in our work.

## 4. Conclusion

This paper presents transition probabilities for forbidden lines of astrophysical interest in Ni I and Ni II. The general agreement shown in our work between results obtained with two independent methods indicates that the new $A$ values should be accurate to within a few percent for most of the strongest transitions. For some weak transitions, the differences can be larger and it seems difficult to conclude which approach gives the most reliable results since similar amount of CI and semi-empirical refinements of the energies and mixing coefficients were included in our HFR and SST models. The detailed comparisons reported here throw some light on the level of precision presently attainable for such weak forbidden lines. Accurate experimental data would be welcome to definitely assess the reliability of the calculations discussed in the present work.

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**Table 8.** Radiative transition probabilities, $A_{ki}$ in $s^{-1}$, as obtained with HFR and SST for forbidden lines of Ni II. A(B) stands for $A.10^B$

| Multiplet | $2J-2J'$ | $\lambda$(Å)[a] | Type | $A_{ki}$(HFR) | $A_{ki}$(SST) |
|---|---|---|---|---|---|
| $a^2$D-$a^2$D | 5-3 | 66341.55 | M1 | 5.43(-2) | 5.54(-2) |
| $a^2$D-$^4$F | 5-7 | 10715.13 | M1,E2 | 7.70(-4) | 1.18(-3) |
| | 3-5 | 11612.95 | M1,E2 | 4.33(-4) | 8.64(-4) |
| | 3-3 | 10917.68 | M1,E2 | 2.16(-4) | 5.82(-4) |
| $a^2$D-$^2$F | 5-7 | 7377.83 | E2 | 2.11(-1) | 1.88(-1) |
| | 5-5 | 6666.80 | M1,E2 | 9.39(-2) | 8.26(-2) |
| | 3-7 | 8300.99 | E2 | 1.19(-2) | 1.07(-2) |
| | 3-5 | 7411.61 | E2 | 1.73(-1) | 1.52(-1) |
| $a^2$D-$b^2$D | 5-5 | 4326.24 | E2 | 3.20(-1) | 2.47(-1) |
| | 5-3 | 4201.17 | E2 | 6.15(-1) | 5.42(-1) |
| | 3-5 | 4628.05 | E2 | 1.26(-1) | 1.00(-1) |
| | 3-3 | 4485.21 | E2 | 2.78(-1) | 2.04(-1) |
| $a^2$D-$^4$P | 5-5 | 3993.06 | E2 | 5.58(-1) | 4.52(-1) |
| | 5-3 | 4033.04 | E2 | 1.47(-1) | 1.29(-1) |
| | 5-1 | 4025.29 | E2 | 1.74(-5)* | 1.20(-4) |
| | 3-5 | 4248.80 | E2 | 1.95(-1) | 1.61(-1) |
| | 3-3 | 4294.09 | E2 | 1.26(-1) | 1.04(-1) |
| | 3-1 | 4285.31 | M1,E2 | 3.48(-3) | 4.12(-3) |
| $a^2$D-$^2$P | 5-3 | 3438.88 | E2 | 5.73(+0) | 4.60(+0) |
| | 5-1 | 3378.15 | E2 | 4.34(+0) | 3.53(+0) |
| | 3-3 | 3626.89 | E2 | 2.88(+0) | 2.39(+0) |
| | 3-1 | 3559.41 | E2 | 4.72(+0) | 3.90(+0) |
| $a^2$D-$^2$G | 5-9 | 3076.07 | E2 | 5.15(+0) | 3.92(+0) |
| | 5-7 | 3073.80 | E2 | 3.58(-1) | 2.84(-1) |
| | 3-7 | 3223.15 | E2 | 3.80(+0) | 3.01(+0) |
| $a^2$D-$^2$S | 5-1 | (1626.9) | E2 | 6.65(+1) | 5.89(+1) |
| | 3-1 | (1667.5) | E2 | 4.82(+1) | 4.18(+1) |
| $^4$F-$^4$F | 9-7 | 106792.51 | M1 | 2.60(-2) | 2.71(-2) |
| | 7-5 | 127253.31 | M1 | 2.67(-2) | 2.75(-2) |
| | 5-3 | 182355.48 | M1 | 1.04(-2) | 1.05(-2) |
| $^4$F-$^2$F | 9-7 | 19387.74 | M1 | 8.81(-2) | 9.68(-2) |
| | 7-7 | 23688.25 | M1 | 5.64(-3)* | 6.11(-3) |
| | 7-5 | 17645.78 | M1 | 2.97(-3) | 2.59(-3) |
| | 5-7 | 29106.43 | M1 | 1.48(-2) | 1.61(-2) |
| | 5-5 | 20486.59 | M1 | 7.55(-3)* | 7.95(-3) |
| | 3-5 | 23079.43 | M1 | 3.02(-2) | 3.13(-2) |
| $^4$F-$b^2$D | 9-5 | 6794.20 | E2 | 2.05(-2) | 1.29(-2) |
| | 7-5 | 7255.82 | M1,E2 | 1.71(-1) | 1.83(-1) |
| | 7-3 | 6910.79 | E2 | 6.10(-3) | 4.24(-3) |
| | 5-5 | 7694.56 | M1,E2 | 1.56(-2) | 1.65(-2) |
| | 5-3 | 7307.65 | M1,E2 | 3.80(-1) | 4.23(-1) |
| | 3-5 | 8033.54 | M1,E2 | 1.06(-2) | 1.18(-2) |
| | 3-3 | 7612.72 | M1,E2 | 1.85(-1) | 2.07(-1) |
| $^4$F-$^4$P | 9-5 | 6007.06 | E2 | 2.98(-2) | 1.75(-2) |
| | 7-5 | 6365.10 | M1,E2 | 2.21(-1) | 2.42(-1) |
| | 7-3 | 6467.29 | E2 | 2.49(-2) | 1.45(-2) |
| | 5-5 | 6700.24 | M1,E2 | 1.02(-2) | 1.03(-2) |
| | 5-3 | 6813.57 | M1,E2 | 1.41(-1) | 1.57(-1) |
| | 5-1 | 6791.48 | E2 | 2.09(-2) | 1.26(-2) |
| | 3-5 | 6955.82 | M1,E2 | 8.92(-3) | 9.87(-3) |
| | 3-3 | 7078.04 | M1,E2 | 4.21(-2) | 4.61(-2) |
| | 3-1 | 7054.20 | M1,E2 | 2.64(-2) | 1.63(-2) |
| $^4$F-$^2$P | 7-3 | 5064.22 | E2 | 2.20(-3) | 2.48(-3) |
| | 5-3 | 5274.11 | M1 | 1.40(-2) | 1.85(-2) |
| | 5-1 | 5132.62 | E2 | 1.08(-3) | 9.95(-4) |
| | 3-3 | 5431.19 | M1 | 2.37(-3) | 3.06(-3) |
| | 3-1 | 5281.27 | M1 | 1.54(-3) | 2.05(-3) |
| $^4$F-$^2$G | 9-9 | 4147.24 | M1 | 3.47(-1)* | 3.92(-1) |
| | 9-7 | 4143.11 | M1 | 1.05(-2) | 1.19(-2) |
| | 7-9 | 4314.81 | M1 | 8.05(-2) | 8.93(-2) |
| | 7-7 | 4310.34 | M1 | 1.74(-1) | 1.99(-1) |
| | 5-9 | 4466.25 | E2 | 2.50(-4) | 1.73(-4) |
| | 5-7 | 4461.46 | M1 | 1.08(-1) | 1.23(-1) |
| | 3-7 | 4573.36 | E2 | 6.21(-4) | 5.67(-4) |
| $^4$F-$^2$S | 5-1 | (1946.4) | E2 | 2.54(-2) | 4.22(-2) |
| | 3-1 | (1967.3) | E2 | 5.25(-2) | 8.48(-2) |
| $^2$F-$^2$F | 7-5 | 69176.67 | M1 | 4.73(-2) | 4.71(-2) |
| $^2$F-$b^2$D | 7-5 | 10459.69 | M1 | 7.73(-2) | 8.66(-2) |
| | 7-3 | 9757.43 | E2 | 1.01(-4) | 1.74(-4) |
| | 5-5 | 12322.97 | M1 | 8.48(-2) | 9.58(-2) |
| | 5-3 | 11359.74 | M1 | 5.70(-2) | 6.41(-2) |
| $^2$F-$^4$P | 7-5 | 8703.87 | M1 | 1.01(-1) | 1.16(-1) |
| | 7-3 | 8896.09 | E2 | 2.14(-4) | 2.16(-4) |
| | 5-5 | 9956.63 | M1 | 7.10(-2) | 7.88(-2) |
| | 5-3 | 10208.96 | M1 | 9.95(-3) | 1.10(-2) |
| $^2$F-$^2$P | 7-3 | 6441.29 | E2 | 5.90(-2) | 5.34(-2) |
| | 5-3 | 7102.66 | M1,E2 | 1.47(-2) | 1.72(-2) |
| | 5-1 | 6848.42 | E2 | 5.20(-2) | 4.92(-2) |
| $^2$F-$^2$G | 7-9 | 5275.82 | M1,E2 | 8.96(-2) | 1.05(-1) |
| | 7-7 | 5269.14 | M1 | 1.34(-1) | 1.49(-1) |
| | 5-9 | 5711.41 | E2 | 3.49(-4) | 6.10(-4) |
| | 5-7 | 5703.58 | M1,E2 | 4.55(-2) | 5.21(-2) |
| $^2$F-$^2$S | 5-1 | (2152.3) | E2 | 9.50(-2) | 9.73(-2) |
| $b^2$D-$b^2$D | 5-3 | 145330.35 | M1 | 3.85(-3) | 5.36(-3) |
| $b^2$D-$^4$P | 5-5 | 51850.39 | M1 | 6.58(-2) | 6.82(-2) |
| | 5-3 | 59510.42 | M1 | 1.67(-2) | 1.75(-2) |
| | 3-5 | 80610.18 | M1 | 1.42(-3) | 1.25(-3) |
| | 3-3 | 100776.94 | M1 | 1.62(-2) | 1.46(-2) |
| | 3-1 | 96150.75 | M1 | 1.30(-2) | 1.14(-2) |
| $b^2$D-$^2$P | 5-3 | 16766.49 | M1 | 7.73(-2) | 8.95(-2) |
| | 3-3 | 18953.07 | M1 | 7.88(-2) | 8.82(-2) |
| | 3-1 | 17244.76 | M1 | 7.90(-2) | 9.14(-2) |
| $b^2$D-$^2$G | 5-9 | 10645.29 | E2 | 5.47(-4) | 3.81(-4) |
| | 3-7 | 11455.08 | E2 | 6.04(-4) | 4.13(-4) |
| $b^2$D-$^2$S | 5-1 | (2608.5) | E2 | 3.67(+0) | 3.71(+0) |
| | 3-1 | (2651.1) | M1,E2 | 4.23(+0) | 4.55(+0) |
| $^4$P-$^4$P | 3-5 | 402823.54 | M1 | 1.95(-4) | 1.91(-4) |
| $^4$P-$^2$P | 5-3 | 24779.15 | M1 | 8.83(-3) | 1.09(-2) |
| | 3-3 | 23343.22 | M1 | 2.47(-2) | 2.96(-2) |
| | 3-1 | 20804.85 | M1 | 1.22(-2) | 1.55(-2) |
| | 1-3 | 23606.31 | M1 | 8.90(-4) | 1.01(-3) |
| | 1-1 | 21013.57 | M1 | 5.50(-3) | 6.54(-3) |
| $^4$P-$^2$G | 5-9 | 13395.50 | E2 | 2.28(-4) | 1.61(-4) |
| | 3-7 | 12924.14 | E2 | 9.65(-5) | 7.15(-5) |
| $^4$P-$^2$S | 5-1 | (2744.6) | E2 | 3.57(+0) | 3.86(+0) |
| | 3-1 | (2726.0) | M1,E2 | 3.38(+0) | 4.41(+0) |
| | 1-1 | (2730.8) | M1 | 6.30(-1) | 8.77(-1) |
| $^2$P-$^2$P | 3-1 | 191324.41 | M1 | 1.89(-3) | 2.48(-3) |
| $^2$P-$^2$S | 3-1 | (3085.2) | M1,E2 | 6.87(-1) | 9.59(-1) |
| | 1-1 | (3131.2) | M1 | 9.80(-1) | 1.36(+0) |

[a] Wavelengths in air (above 2000 Å) and in vacuum (below 2000 Å) deduced from the observed energy levels (Sugar & Corliss 1985). Values between parentheses are calculated HFR wavelengths.

* Cancellation effects present (see text).