PRAMANA
— journal of
physics

Vol. 69, No. 2
August 2007
pp. 209–218

Collision strengths for transitions in Ni XIX

K M AGGARWAL and F P KEENAN
Astrophysics Research Centre, School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, Northern Ireland, UK
E-mail: K.Aggarwal@qub.ac.uk

MS received 7 October 2006; accepted 1 May 2007

Abstract. In this paper we present calculations of electron impact excitation collision strengths for transitions among the 89 fine-structure levels of the $2s^22p^6$, $2s^22p^53\ell$, $2s2p^63\ell$, $2s^22p^54\ell$, and $2s2p^64\ell$ configurations of Ni XIX, for which flexible atomic code (FAC) has been adopted. Comparisons are made with the earlier available results in the literature, and the anomalies observed have been discussed.

Keywords. Collisional excitation; flexible atomic code; Dirac atomic R-matrix code.

PACS No. 34.80.Kw

1. Introduction

Iron group elements (namely Ti, Cr, Fe and Ni) are highly useful for the modelling and diagnostics of a variety of plasmas, such as astrophysical, fusion, and laser-generated plasmas. Many of their emission lines are frequently observed in the spectrum of the solar corona [1,2], and are useful for plasma diagnostics. Additionally, nickel is an important impurity element in fusion reactors, and hence atomic data (namely energy levels, radiative rates, collision strengths, excitation rates, etc.) are required in order to estimate the power loss from the walls of the reactors. Furthermore, Ni XIX, a neon-like ion, is also very useful in lasing plasmas. Similarly many transitions, particularly within the $n = 3$ configurations, have been measured in laboratory plasmas by Feldman *et al* [3], Swartz *et al* [4], Boiko *et al* [5], Buchet *et al* [6], and Biémont *et al* [7]. Since there is a paucity of experimental data for most of the above named parameters, theoretical results are desirable. Therefore, in our earlier work we have already reported atomic data for transitions in Ni XIII–XVI [8] and Ni XVII [9]. Results for energy levels and radiative rates (A-values) for transitions among 89 levels of the ($1s^2$) $2s^22p^6$, $2s^22p^53\ell$, $2s2p^63\ell$, $2s^22p^54\ell$, and $2s2p^64\ell$ configurations of Ni XIX have also been reported in our earlier paper [10], and in this paper we discuss our results for collision strengths (Ω).

Earlier calculations for Ω have been performed by Zhang and Sampson [11] and Mohan *et al* [12]. Zhang and Sampson, who adopted the Coulomb–Born-exchange (CBE) method, reported results for energy levels, radiative rates and collision strengths among 89 levels of the $(1s^2)$ $2s^22p^6$, $2s^22p^53\ell$, $2s2p^63\ell$, $2s^22p^54\ell$, and $2s2p^64\ell$ configurations. However, they did not resolve resonances, and reported values of Ω only at a few energies above thresholds. Since the contribution of resonances is often significant, even at high temperatures at which data are required for Ni XIX, there is an urgent need to include their contribution. Additionally, they calculated A and Ω values for the resonance transitions only, whereas data are required for *all* transitions, as emphasized by Liedahl [13], demonstrated by Del Zanna *et al* [14], and adopted by Keenan *et al* [15]. Therefore, there is a clear need to extend their work.

Mohan *et al* [12] reported results for collision strengths (Ω) and effective collision strengths (Υ), but for LS transitions among the lowest 27 levels, i.e. 15 states of the $(1s^2)$ $2s^22p^6$ and $2s^22p^53\ell$ configurations. They employed the *configuration interaction* (CI) wave functions of Hibbert *et al* [16], and adopted the R-matrix code of Berrington *et al* [17] to calculate values of Ω. Furthermore, they included the contribution of resonances to calculate values of Υ up to a temperature of 10^7 K. Similarly, in a more recent paper Singh and Mohan [18] reported values of Ω for fine-structure transitions among the lowest five levels of the $2s^22p^6$ and $2s^22p^53s$ configurations. However, their values of Ω for fine-structure transitions show erratic variation with energy as already discussed and demonstrated by Aggarwal and Keenan [19]. This encouraged us to have a closer look at their larger data for LS transitions. Unfortunately, we find that their reported values of Ω and Υ show *no relationship* for many transitions, as explained below in §2. Furthermore, a comparison with our present or the earlier calculations of Zhang and Sampson [11] shows that their reported values of Ω are in error for many transitions. Therefore, the *aim* of this paper is to demonstrate the errors in the data of Mohan *et al* and to present the new data, which can be applied with confidence in plasma modelling and diagnostics.

For our calculations, we have adopted the flexible atomic code (FAC) of Gu [20], which is available at the website: http://kipac-tree.stanford.edu/fac. This is a fully relativistic code and is based on the well-known and widely used distorted-wave (DW) method for the calculations of collisional data. Furthermore, it is a self-sufficient code to generate a wide range of atomic parameters, such as energy levels, radiative rates and collision strengths.

2. Effective collision strengths

It is now well-known that the threshold energy region is dominated by numerous closed-channel (Feshbach) resonances, as shown in figures 2 and 3 of Mohan *et al* [12] or figure 2 of Aggarwal and Keenan [19]. For applications in plasma modelling or diagnostics, these resonances are averaged over a Maxwellian distribution of electron velocities to obtain the effective collision strengths Υ, i.e.

$$\Upsilon(T_{\rm e}) = \int_0^\infty \Omega(E) \exp(-E_j/kT_{\rm e}) {\rm d}(E_j/kT_{\rm e}), \qquad (1)$$

where E_j is the incident energy of the electron with respect to the final state of the transition, k is the Boltzmann's constant, and T_e is the electron temperature in K. Once the value of Υ is known for a transition, the corresponding value of the excitation $q(i,j)$ and de-excitation $q(j,i)$ rate coefficients can be easily obtained from the following simple relations:

$$q(i,j) = \frac{8.63 \times 10^{-6}}{\omega_i T_e^{1/2}} \Upsilon \exp(-E_{ij}/kT_e) \text{ cm}^3 \text{ s}^{-1} \tag{2}$$

and

$$q(j,i) = \frac{8.63 \times 10^{-6}}{\omega_j T_e^{1/2}} \Upsilon \text{ cm}^3 \text{ s}^{-1}, \tag{3}$$

where ω_i and ω_j are the statistical weights of the initial (i) and final (j) states, respectively, and E_{ij} is the transition energy. The contribution of resonances may enhance the values of Υ, over those of the background values of collision strengths (Ω_B), especially for the forbidden transitions, up to a factor of ten (or even more) depending on the transition and/or the temperature – see, for example [21]. Therefore, at any given temperature the values of Υ are in general $\geq \Omega_B$ at the corresponding energy (temperature). We first discuss the results of Mohan *et al* [12] to demonstrate that their values of Ω and Υ show no relationship for many transitions, such as: 2 – 6,7,8, 3 – 6,7,8 and 5 – 6,7,8 (see [12] for transition indices).

As an example, for the 2–8 ($2p^5 3s\ ^3P^o$–$2p^5 3p\ ^1P$) transition, their [12] values of Ω are between 5.1 and 6.8 in the entire energy range of $80 \leq E \leq 140$ Ryd, but the corresponding values of Υ vary between 0.04 and 0.006 in the entire temperature range of $5.4 \leq \log T_e\ (\text{K}) \leq 7.0$ (or equivalently $70 \leq E \leq 131$ Ryd), which are lower by up to three orders of magnitude. For these (and many more) transitions, the Ω values behave as for allowed transitions whereas the Υ values show a completely opposite trend of forbidden transitions. Similarly, for the 2–7 ($2p^5 3s\ ^3P^o$–$2p^5 3p\ ^3P$) transition, their values of Ω vary between 0.01 and 0.003 in the entire energy range, but the corresponding values of Υ vary between 3.7 and 8.2 in the entire temperature range, i.e. the Ω values vary as for a forbidden transition whereas the Υ values show the behaviour of an allowed transition. We discuss these further below.

For transitions involving the highest state of their calculations (15), i.e. $2p^5 3d\ ^1P^o$, there should be no resonances, and pseudoresonances if any, because of the inclusion of CI with additional configurations, have been smoothed over as demonstrated by Mohan *et al* [12] in their figure 1. Therefore, their Υ values should directly follow those for Ω. However, we find that many such transitions do not demonstrate this. In figure 1 we compare their reported values of Ω and Υ for only two transitions, namely 6–15 ($2p^5 3p\ ^1D$–$2p^5 3d\ ^1P^o$) and 8–15 ($2p^5 3p\ ^1P$–$2p^5 3d\ ^1P^o$). Both of these are optically allowed transitions, and hence their values of Ω appear to be correct, as these are increasing with increasing energy. However, their values of Υ for both of these (and many other) transitions are well below the corresponding Ω values, and there appears to be no relationship between the two parameters. Therefore, based on this figure and the discussion above, it is fair to conclude that the Υ values of Mohan *et al* are in large error for many transitions,

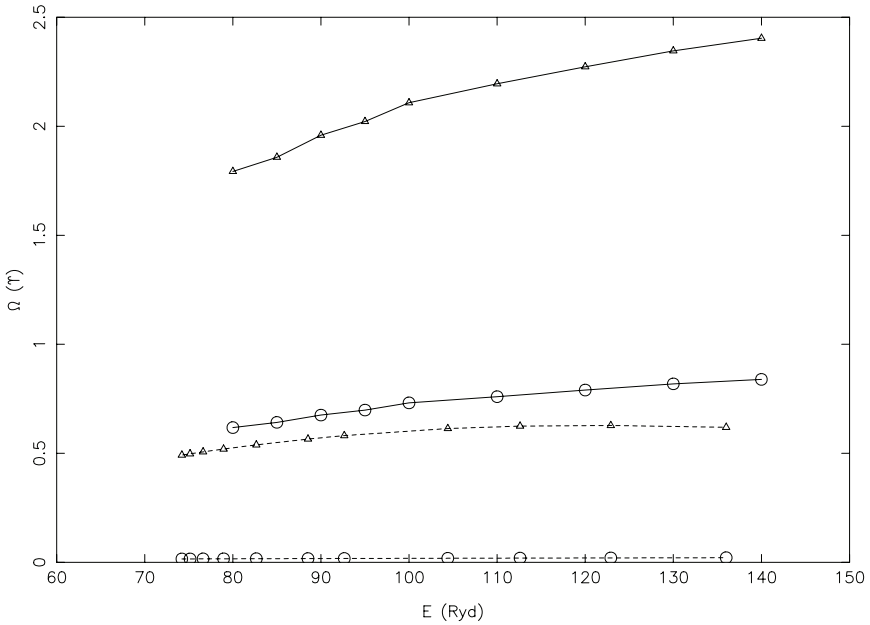

Figure 1. Collision strengths (Ω: continuous curves) and effective collision strengths (Υ: broken curves) of Mohan *et al* [12] for two transitions of Ni XIX. Circles: $2s^2 2p^5 3p\ ^1D$–$2s^2 2p^5 3d\ ^1P^o$ (6–15) and triangles: $2s^2 2p^5\ ^1P$–$2s^2 2p^5 3d\ ^1P^o$ (8–15) transition.

and hence are not reliable. We now focus our attention to assess if their values of Ω are reliable.

3. Collision strengths

As stated earlier in §1, we have performed our calculations for Ω values with the FAC code of Gu [20]. However, as noted in our earlier paper [19], we have also performed other independent calculations by employing the general-purpose relativistic atomic structure package (GRASP) and Dirac atomic R-matrix code (DARC) programs of Dyall *et al* [22] and Norrington and Grant [23] for the generation of wave functions and the computations of collision strengths, respectively. Since our detailed calculations in threshold region are still in progress, we focus on results only at energies *above* thresholds. Additionally, for brevity we will confine our comparisons for the resonance transitions alone, i.e. transitions from the ground level $2s^2 2p^6\ ^1S_0$ to higher excited levels. These limited comparisons will be sufficient to draw the required conclusions. Furthermore, since our calculations are fully relativistic in the jj coupling scheme, henceforth level indices will be for fine-structure transitions (see table 1) among 89 levels of the $2s^2 2p^6$, $2s^2 2p^5 3\ell$, $2s2p^6 3\ell$, $2s^2 2p^5 4\ell$ and $2s2p^6 4\ell$ configurations of Ni XIX.

Table 1. Energy levels of Ni XIX (in Ryd) and collision strengths (Ω) for resonance transitions at three scattered energies (E_j) of 59, 281 and 813 Ryd (a–b $\equiv$ a$\times 10^{-\mathrm{b}}$).

				E_j (Ryd)		
Index	Configuration	Level	Level energy	59	281	813
1	$2s^2 2p^6$	$^1S_0$	0.0000	.....	.....	.....
2	$2s^2 2p^5 3s$	$^3P^o_2$	64.6260	7.576-4	1.765-4	3.256-5
3	.....	$^3P^o_1$	64.7985	3.356-3	8.592-3	1.476-2
4	.....	$^3P^o_0$	65.9271	1.526-4	3.557-5	6.582-6
5	.....	$^1P^o_1$	66.0313	2.617-3	6.526-3	1.126-2
6	$2s^2 2p^5 3p$	$^3S_1$	67.1474	1.936-3	4.612-4	9.261-5
7	.....	$^3D_2$	67.4226	2.811-3	3.402-3	3.632-3
8	.....	$^3D_3$	67.6142	1.931-3	3.856-4	6.476-5
9	.....	$^1P_1$	67.6981	7.076-4	1.336-4	2.154-5
10	.....	$^3P_2$	67.8663	2.491-3	3.395-3	3.701-3
11	.....	$^3P_0$	68.4100	3.374-3	3.545-3	3.662-3
12	.....	$^3D_1$	68.6713	7.636-4	1.480-4	2.412-5
13	.....	$^3P_1$	68.9950	8.307-4	1.670-4	2.892-5
14	.....	$^1D_2$	69.0392	2.855-3	3.775-3	4.077-3
15	.....	$^1S_0$	70.2260	3.777-2	4.135-2	4.297-2
16	$2s^2 2p^5 3d$	$^3P^o_0$	70.9373	7.966-4	1.409-4	2.200-5
17	.....	$^3P^o_1$	71.0272	2.666-3	1.285-3	1.456-3
18	.....	$^3P^o_2$	71.1954	2.904-3	4.969-4	7.647-5
19	.....	$^3F^o_4$	71.1944	2.523-3	3.910-4	5.767-5
20	.....	$^3F^o_3$	71.2481	2.793-3	2.778-3	2.811-3
21	.....	$^1D^o_2$	71.3982	9.151-4	1.165-4	1.536-5
22	.....	$^3D^o_3$	71.4981	2.249-3	2.907-3	3.076-3
23	.....	$^3D^o_1$	71.9383	3.947-2	7.327-2	1.140-1
24	.....	$^3F^o_2$	72.5450	1.148-3	1.665-4	2.366-5
25	.....	$^3D^o_2$	72.6103	1.618-3	2.519-4	3.689-5
26	.....	$^1F^o_3$	72.6662	2.659-3	3.168-3	3.297-3
27	.....	$^1P^o_1$	73.2607	1.120-1	2.087-1	3.243-1
28	$2s2p^6 3s$	$^3S_1$	75.9615	4.222-4	8.993-5	1.808-5
29	.....	$^1S_0$	76.5362	1.481-2	1.691-2	1.793-2
30	$2s2p^6 3p$	$^3P^o_0$	78.6761	1.189-4	2.778-5	4.862-6
31	.....	$^3P^o_1$	78.7185	1.074-3	2.209-3	3.958-3
32	.....	$^3P^o_2$	78.9692	5.796-4	1.375-4	2.442-5
33	.....	$^1P^o_1$	79.1314	4.744-3	1.338-2	2.489-2
34	$2s2p^6 3d$	$^3D_1$	82.3940	7.498-4	1.478-4	2.597-5
35	.....	$^3D_2$	82.4097	1.308-3	3.493-4	1.689-4
36	.....	$^3D_3$	82.4397	1.734-3	3.413-4	5.992-5
37	.....	$^1D_2$	82.8588	1.976-2	3.135-2	3.862-2
38	$2s^2 2p^5 4s$	$^3P^o_2$	87.2234	2.296-4	5.428-5	1.030-5
39	.....	$^1P^o_1$	87.2768	4.676-4	1.141-3	2.018-3
40	$2s^2 2p^5 4p$	$^3S_1$	88.2791	4.696-4	1.119-4	2.251-5

Table 1. *Continued...*

				E_j (Ryd)		
Index	Configuration	Level	Level energy	59	281	813
41	.....	$^3D_2$	88.3411	6.381-4	5.657-4	6.760-4
42	.....	$^3D_3$	88.4233	6.321-4	1.295-4	2.246-5
43	.....	$^1P_1$	88.4517	2.336-4	4.533-5	7.583-6
44	$2s^22p^54p$	$^3P_2$	88.5055	5.189-4	5.003-4	6.212-4
45	$2s^22p^54s$	$^3P^o_0$	88.5288	4.663-5	1.097-5	2.074-6
46	$2s^22p^54s$	$^3P^o_1$	88.5553	3.720-4	7.863-4	1.377-3
47	$2s^22p^54p$	$^3P_0$	88.8453	4.832-3	5.354-3	5.610-3
48	.....	$^3D_1$	89.6236	2.632-4	5.311-5	9.091-6
49	$2s^22p^54d$	$^3P^o_0$	89.6733	2.525-4	4.757-5	8.055-6
50	.....	$^3P^o_1$	89.7099	7.989-4	3.814-4	4.124-4
51	.....	$^3P^o_2$	89.7485	8.016-4	1.413-4	2.300-5
52	$2s^22p^54p$	$^3P_1$	89.7568	2.980-4	6.354-5	1.169-5
53	.....	$^1D_2$	89.7672	6.137-4	5.519-4	6.703-4
54	.....	$^3F^o_4$	89.7705	8.379-4	1.382-4	2.205-5
55	.....	$^3F^o_3$	89.7723	6.778-4	5.182-4	6.458-4
56	$2s^22p^54d$	$^1D^o_2$	89.8237	3.146-4	4.099-5	5.328-6
57	.....	$^3D^o_3$	89.8580	4.839-4	4.264-4	5.675-4
58	$2s^22p^54p$	$^1S_0$	89.9908	7.086-3	7.892-3	8.283-3
59	$2s^22p^54d$	$^3D^o_1$	90.0729	1.867-2	3.307-2	4.985-2
60	$2s^22p^54f$	$^3D_1$	90.4162	9.638-5	1.130-5	1.089-6
61	.....	$^1G_4$	90.4240	2.055-4	2.189-4	2.705-4
62	.....	$^3G_5$	90.4271	1.512-4	1.855-5	2.234-6
63	.....	$^3D_2$	90.4312	5.329-4	7.859-4	1.032-3
64	.....	$^3F_3$	90.4632	1.250-4	1.343-5	1.380-6
65	.....	$^1D_2$	90.4694	1.259-3	2.346-3	3.119-3
66	.....	$^1F_3$	90.4728	6.351-5	5.949-6	7.511-7
67	.....	$^3F_4$	90.4813	1.021-4	7.304-5	8.859-5
68	$2s^22p^54d$	$^3F^o_2$	91.0676	4.168-4	6.546-5	1.003-5
69	.....	$^3D^o_2$	91.0930	6.647-4	1.139-4	1.815-5
70	.....	$^1F^o_3$	91.1176	6.143-4	4.953-4	6.303-4
71	.....	$^1P^o_1$	91.2752	1.743-2	3.096-2	4.684-2
72	$2s^22p^54f$	$^3G_3$	91.7464	7.972-5	9.138-6	1.114-6
73	.....	$^3G_4$	91.7581	1.507-4	1.348-4	1.649-4
74	.....	$^3F_2$	91.7651	1.373-4	1.528-5	1.570-6
75	.....	$^3D_3$	91.7660	8.056-4	1.444-3	1.919-3
76	$2s2p^64s$	$^3S_1$	98.4103	1.664-4	3.542-5	7.162-6
77	.....	$^1S_0$	98.5970	3.000-3	3.484-3	3.706-3
78	$2s2p^64p$	$^3P^o_0$	99.5127	4.541-5	1.026-5	1.733-6
79	.....	$^3P^o_1$	99.5271	4.327-4	8.503-4	1.477-3
80	.....	$^3P^o_2$	99.6305	2.192-4	5.004-5	8.523-6
81	.....	$^1P^o_1$	99.6812	1.529-3	4.025-3	7.263-3
82	$2s2p^64d$	$^3D_1$	100.9235	2.344-4	4.977-5	9.289-6

Table 1. *Continued...*

				E_j (Ryd)		
Index	Configuration	Level	Level energy	59	281	813
83	.....	$^3D_2$	100.9307	4.123-4	1.219-4	6.329-5
84	.....	$^3D_3$	100.9447	5.434-4	1.152-4	2.149-5
85	.....	$^1D_2$	101.0799	3.901-3	6.248-3	7.758-3
86	$2s3p^64f$	$^3F^o_2$	101.5827	8.649-5	1.193-5	1.281-6
87	.....	$^3F^o_3$	101.5845	1.612-4	9.009-5	8.708-5
88	.....	$^3F^o_4$	101.5903	1.551-4	2.139-5	2.295-6
89	.....	$^1F^o_3$	101.6044	7.112-4	1.114-3	1.289-3

In table 1, we define our energy levels and also list the values of Ω at three scattered energies of 59, 281 and 813 Ryd. These results have been obtained from the FAC code, and we would like to remind readers that energy levels from the GRASP code as well as the radiative rates (A-values) for four types of transitions, namely the electric dipole (E1), magnetic dipole (M1), electric quadrupole (E2), and magnetic quadrupole (M2), have already been reported and discussed in our earlier paper [10].

In figure 2 we compare values of Ω from our FAC as well as DARC calculations, with those of Mohan *et al* [12] and Zhang and Sampson [11] for only two *allowed* transitions, namely 1–3 ($2s^22p^6\ ^1S_0$–$2s^22p^53s\ ^1P^o_1$) and 1–27 ($2s^22p^6\ ^1S_0$–$2s^22p^53d\ ^1P^o_1$), at incident energies below 260 Ryd. For both of these (and many other) transitions, there is a complete agreement among our FAC and DARC calculations, and the earlier CBE calculations of Zhang and Sampson, but the corresponding results of Mohan *et al* are in complete contrast, especially for the 1–27 transition. This is in spite of the fact that the oscillator strengths (f-values) are comparable (within 5%) in all sets of calculations, as shown in table 5 of [10]. Furthermore, the Ω values of Mohan *et al* are nearly constant with increasing energy, which is contrary to our calculations or the expected behaviour, as discussed in detail by Burgess and Tully [24] for various types of transitions. In figure 3 we show similar results for two *forbidden* transitions, namely 1–15 ($2s^22p^6\ ^1S_0$–$2s^22p^53p\ ^1S_0$) and 1–26 ($2s^22p^6\ ^1S_0$–$2s^22p^53d\ ^1F^o_3$). For these transitions also there is no discrepancy among our FAC or DARC values of Ω and the earlier ones of Zhang and Sampson, but the corresponding results of Mohan *et al* not only differ in magnitude but also in behaviour, especially for the 1–15 transition. Similar discrepancies and inconsistencies in the Ω values of Mohan *et al* have been observed for many other transitions. Therefore, we can conclude with confidence that the reported results of Mohan *et al* for Ω values are in large error for many transitions, and are not reliable for applications in plasma analysis.

Apart from the above discussed and demonstrated discrepancies in the Ω values of Mohan *et al* [12], their results are unreliable for other reasons also. Firstly, some of their states, such as 7 and 8 ($2p^53p\ ^3P$ and ^1P) and 13 and 14 ($2p^53d\ ^3D^o$ and $^1D^o$) are non-degenerate in energy. This may be responsible for some of the inconsistencies in their reported data for Ω. For example, their 2–7 ($2p^53s\ ^3P^o$–$2p^53p\ ^3P$) transition is allowed, and the 2–8 ($2p^53s\ ^3P^o$–$2p^53p\ ^1P$) transition is

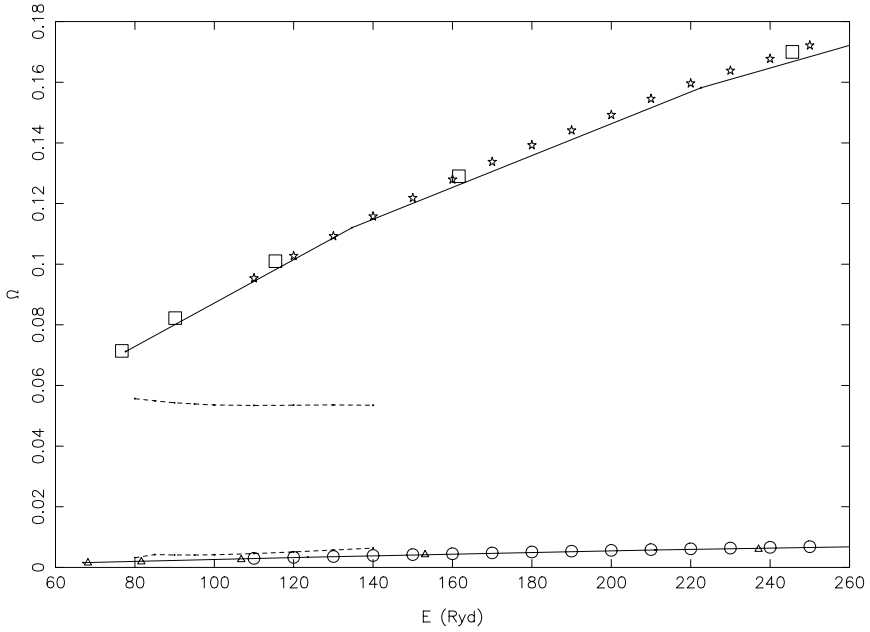

Figure 2. Comparison of collision strengths (Ω) for two allowed transitions of Ni XIX. Continuous curves: present results from FAC, broken curves: Mohan *et al* [12], lower curves: $2s^2 2p^6\ {}^1S_0$–$2s^2 2p^5 3s\ {}^1P^o_1$ (1–3), upper curves: $2s^2 2p^6\ {}^1S_0$–$2s^2 2p^5 3d\ {}^1P^o_1$ (1–27) transition. Circles and stars are from our DARC calculations for the 1–3 and 1–27 transitions, respectively, and triangles and squares are from Zhang and Sampson [11] for the 1–3 and 1–27 transitions, respectively.

forbidden, but contrary to expectations their Ω values for the 2–8 ($5.15 \leq \Omega \leq 6.83$) transition are larger than that for the 2–7 ($0.0028 \leq \Omega \leq 0.011$) transition by over two orders of magnitude. It is likely that their results involving these two (and 13 and 14) states have been mixed up, especially because they have adopted two different programs, namely the standard R-matrix [17] and the no-exchange R-matrix [25] codes for the computations of Ω for partial waves with angular momentum $L \leq 9$ and $L \geq 10$, respectively. As a result of this, the allowed transitions might have become forbidden and vice versa. We are speculating on this because the calculations of Tayal *et al* [26,27] had similar problem for transitions in Al II, as demonstrated and explained by us [28]. However, even if it is true it does not explain the odd behaviour of their Ω values, as shown in figures 2 and 3, or can be noted from the results in table 5 of [10] for the 2–6 ($2p^5 3s\ {}^3P^o$–$2p^5 3p\ {}^1D$) or 4–10 ($2p^5 3p\ {}^3S$–$2p^5 3d\ {}^3D^o$) transitions. Secondly, the scattered energy range of their calculations ($E \sim 100$ Ryd) is not sufficient for the convergence of integral in eq. (1) for the determination of Υ values up to $T_e = 10^7$ K (∼63 Ryd). Finally, higher excited levels of the $2s2p^6 3\ell$, $2s^2 2p^5 4\ell$ and $2s2p^6 4\ell$ configurations need to be included in the collisional calculations, so that the contribution of resonances arising from these could be included in the determination of Υ values.

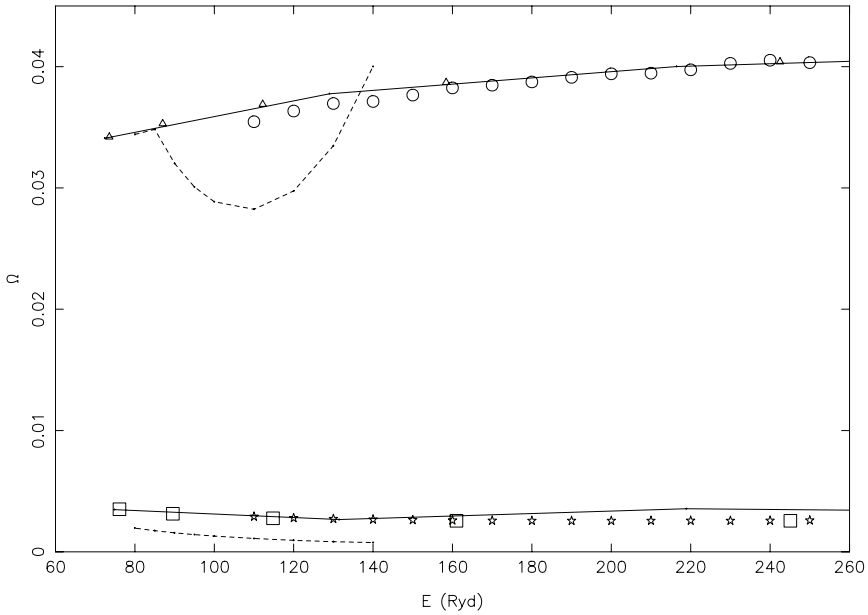

Figure 3. Comparison of collision strengths (Ω) for two forbidden transitions of Ni XIX. Continuous curves: present results from FAC, broken curves: Mohan *et al* [12], upper curves: $2s^2 2p^6\ ^1S_0$–$2s^2 2p^5 3p\ ^1S_0$ (1–15), lower curves: $2s^2 2p^6\ ^1S_0$–$2s^2 2p^5 3d\ ^1F^o_3$ (1–26) transition. Circles and stars are from our DARC calculations for the 1–15 and 1–26 transitions, respectively, and triangles and squares are from Zhang and Sampson [11] for the 1–15 and 1–26 transitions, respectively.

4. Conclusions

In this paper we have reported collision strengths for resonance transitions up to 88 excited levels of Ni XIX. Calculations have been performed with the FAC code of Gu [20], and the results obtained are in complete agreement with our other calculations from the DARC code as well as with the earlier CBE calculations of Zhang and Sampson [11]. However, the previous results of Mohan *et al* [12] agree with neither of the calculations, and are found to have large discrepancies for many transitions. Not only do their values of Ω and/or Υ differ in magnitude for many transitions, they also show unexpected behaviour with energy/temperature. Since there are no systematic discrepancies in their calculations, it is difficult to speculate the source of errors. The only conclusion we can draw with confidence is that their data are reliable neither for Ω nor for Υ.

Our detailed calculations to resolve resonances in the threshold region are still in progress. With the conclusion of those calculations we hope to report our results in a future publication, both for collision strengths and effective collision strengths for all the 3916 transitions among the lowest 89 levels of Ni XIX.

Acknowledgements

This work has been financed by the Engineering and Physical Sciences and Particle Physics and Astronomy Research Councils of the United Kingdom, and FPK is grateful to AWE Aldermaston for the award of a William Penney Fellowship.

References

[1] C Jupen, *Mon. Not. R. Astron. Soc.* **208**, 1P (1984)
[2] U Feldman, W Curdt, E Landi and K Wilhelm, *Astrophys. J.* **544**, 508 (2000)
[3] U Feldman, L Cohan and M Swartz, *Astrophys. J.* **148**, 585 (1967)
[4] M Swartz, S Kastner, E Rothe and W Neupert, *J. Phys.* **B4**, 1747 (1971)
[5] V A Boiko, S A Pikuz, U I Safronova and A Ya Faenov, *J. Phys.* **B10**, 1253 (1977)
[6] J P Buchet, M C Buchet-Poulizac, A Denis, J Desesquelles, M Druetta, S Martin and J F Wyart, *J. Phys.* **B20**, 1709 (1987)
[7] E Biémont *et al*, *J. Phys.* **B33**, 2153 (2000)
[8] K M Aggarwal, F P Keenan and A Z Msezane, *At. Data Nucl. Data Tables* **85**, 453 (2003)
[9] K M Aggarwal, V Tayal, G P Gupta and F P Keenan, *At. Data Nucl. Data Tables* (in press) (2007)
[10] K M Aggarwal and F P Keenan, *Astron. Astrophys.* **460**, 959 (2006)
[11] H L Zhang and D H Sampson, *At. Data Nucl. Data Tables* **43**, 1 (1989)
[12] M Mohan, M Le Dourneuf, A Hibbert and V M Burke, *Pramana – J. Phys.* **41**, 371 (1993)
[13] D A Liedahl, *Atomic data needs for X-ray astronomy* available at http://heasarc.gsfc.nasa.gov/docs/heasarc/atomic/ (2000)
[14] G Del Zanna, K A Berrington and H E Mason, *Astron. Astrophys.* **422**, 731 (2004)
[15] F P Keenan, K M Aggarwal, D S Bloomfield, A Z Msezane and K G Widing, *Astron. Astrophys.* **449**, 1203 (2006)
[16] A Hibbert, M Le Dourneuf and M Mohan, *At. Data Nucl. Data Tables* **53**, 23 (1993)
[17] K A Berrington, P G Burke, M Le Dourneuf, W D Robb, K T Taylor and Vo Ky Lan, *Comput. Phys. Commun.* **14**, 367 (1978)
[18] N Singh and M Mohan, *Pramana – J. Phys.* **64**, **129** (2005)
[19] K M Aggarwal and F P Keenan, *Pramana – J. Phys.* **67**, C553 (2006)
[20] M F Gu, *Astrophys. J.* **582**, 1241 (2003)
[21] K M Aggarwal, *J. Phys.* **B16**, 2405 (1983)
[22] K G Dyall, I P Grant, C T Johnson, F A Parpia and E P Plummer, *Comput. Phys. Commun.* **55**, 424 (1989)
[23] P H Norrington and I P Grant, *Comput. Phys. Commun.* (in preparation) (2007)
[24] A Burgess and J A Tully, *Astron. Astrophys.* **254**, 436 (1992)
[25] V M Burke, P G Burke and N S Scott, *Comput. Phys. Commun.* **69**, 76 (1992)
[26] S S Tayal, P G Burke and A E Kingston, *J. Phys.* **B17**, 3847 (1984)
[27] S S Tayal, P G Burke and A E Kingston, *J. Phys.* **B18**, 4321 (1985)
[28] K M Aggarwal and F P Keenan, *J. Phys.* **B27**, 2343 (1994)