Electron impact excitation of Be-like ions: a comparison of DARC and ICFT results

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ABSTRACT

Emission lines of Be-like ions are frequently observed in astrophysical plasmas, and many are useful for density and temperature diagnostics. However, accurate atomic data for energy levels, radiative rates (A-values) and effective electron excitation collision strengths (Υ) are required for reliable plasma modelling. In general it is reasonably straightforward to calculate energy levels and A-values to a high level of accuracy. By contrast, considerable effort is required to calculate Υ, and hence it is not always possible to assess the accuracy of available data. Recently, two independent calculations (adopting the R-matrix method) but with different approaches (DARC and ICFT) have appeared for a range of Be-like ions. Therefore, in this work we compare the two sets of Υ, highlight the large discrepancies for a significant number of transitions and suggest possible reasons for these.

Key words: atomic data – atomic processes

1 INTRODUCTION

Emission lines of Be-like ions are widely detected in a variety of astrophysical plasmas, including the solar transition region and corona, with the prominent ions including C III, O V, Ca XVII and Fe XXIII – see for example, the CHIANTI database at http://www.chiantidatabase.org/ and the Atomic Line List (v2.04) of Peter van Hoof at http://www.pa.uky.edu/~peter/atomic/. Many of the observed lines are sensitive to variations in density or temperature, and hence are useful as diagnostics – see for example, Landi et al. (2001). However, for the reliable modelling of plasmas, accurate atomic data are required, particularly for energy levels, radiative rates (A-values), and excitation rates or equivalently the effective collision strengths (Υ), which are obtained from the electron impact collision strengths (Ω). Unfortunately, existing atomic data for Be-like ions prior to 2014 were very limited, particularly for Υ. However, very recently Fernández-Menchero, Del Zanna & Badnell (2014) have reported data for a range of Be-like ions up to Z = 36. For their calculations they have adopted the AutoStructure (AS) code of Badnell (1997) for the generation of wave functions, i.e. to determine energy levels and A-values. In the subsequent calculations of Ω and Υ they have adopted the R-matrix code of Berrington, Eissner & Norrington (1995). Unlike the semi-relativistic version of the standard R-matrix code (Berrington et al. [1993], adopted by Fernández-Menchero et al. [2014], DARC is based on the jj coupling scheme. The accuracy of the data calculated (for Ω and subsequently Υ) through this approach is generally higher, because resonances through the energies of degenerating levels are also taken into account. For this reason it particularly affects transitions among the fine-structure levels of a state. The degeneracy among such levels increases with increasing Z –
see for example levels of Ge XXIX in table 3 of [Aggarwal & Keenan 2014c].

Since two independent calculations for 5 Be-like ions with $13 \leq Z \leq 32$ using the same $R$-matrix method (although in different approximations) and of similar complexity are now available, it is possible to make a detailed comparison to assess their accuracy. This is important, given the large discrepancies recently noted for transitions of Fe XIV between our calculations with DARC [Aggarwal & Keenan 2014b] and those of [Liang et al. 2010] with ICFT.

2 DETAILS OF CALCULATION

In our work the fully relativistic GRASP (General-purpose Relativistic Atomic Structure Package) code is employed to determine the wave functions. There are several versions of this code, but all are based on the one originally developed by [Grant et al. 1980], often referred to as GRASP0. The version used by us has been extensively revised by one of its authors (Dr. P. H. Norrington), is freely available at the website [http://web.am.qub.ac.uk/DARC/] and yields comparable results for energy levels and A-values as obtained with using other revisions. It is fully relativistic, based on the $jj$ coupling scheme, and includes higher-order relativistic corrections arising from the Breit (magnetic) interaction and quantum electrodynamics effects (vacuum polarisation and Lamb shift). Additionally, the option of extended average level has been adopted for all ions, under which a weighted (proportional to $2j+1$) trace of the Hamiltonian matrix is minimised.

For all ions the lowest 98 levels belonging to the 17 configurations (namely $1s^2$ $2s^2$, $2s^2 2p^6$ and $2s^4 2p^4$) have been considered. As stated earlier, for the calculations of $\Omega$ we
Table 2. Comparison of effective collision strengths (Υ) for resonance transitions of Al X. $a \pm b \equiv a \times 10^{\pm b}$.

| Transition | DARC (log T$_e$, K) | ICFT (log T$_e$, K) |
|------------|---------------------|---------------------|
|            | 4.60                | 7.30                |
|            | 4.30                | 6.00                | 7.30 |
| 1          | 2                   | 1.751−2             | 1.125−2             |
|            | 3                   | 5.841−2             | 3.421−2             |
|            | 4                   | 1.127−1             | 5.695−2             |
|            | 5                   | 1.128−0             | 1.311−0             |
|            | 6                   | 3.925−4             | 4.619−4             |
|            | 7                   | 1.021−3             | 1.871−3             |
|            | 8                   | 1.975−3             | 3.002−3             |
|            | 9                   | 1.448−2             | 1.734−2             |
|            | 10                  | 5.105−3             | 7.309−3             |
|            | 11                  | 6.103−2             | 1.080−2             |
|            | 12                  | 9.534−2             | 6.066−2             |
|            | 13                  | 4.994−2             | 3.739−2             |
|            | 14                  | 5.753−3             | 1.749−3             |
|            | 15                  | 1.965−2             | 7.004−3             |
|            | 16                  | 3.012−2             | 8.781−3             |
|            | 17                  | 1.232−2             | 6.750−3             |
|            | 18                  | 2.039−2             | 1.125−2             |
|            | 19                  | 2.843−2             | 1.578−2             |
|            | 20                  | 5.683−2             | 7.410−2             |
|            | 21                  | 8.299−4             | 1.803−4             |
|            | 22                  | 2.980−3             | 6.267−4             |
|            | 23                  | 4.853−3             | 1.014−3             |
|            | 24                  | 1.127−2             | 2.773−3             |
|            | 25                  | 3.740−3             | 5.209−4             |
|            | 26                  | 2.525−3             | 4.643−4             |
|            | 27                  | 4.160−3             | 7.776−4             |
|            | 28                  | 4.976−3             | 1.026−3             |
|            | 29                  | 5.235−3             | 5.880−4             |
|            | 30                  | 7.920−4             | 1.069−4             |
|            | 31                  | 4.201−3             | 3.219−4             |
|            | 32                  | 6.179−3             | 4.767−4             |
|            | 33                  | 1.855−3             | 5.452−4             |
|            | 34                  | 1.673−3             | 7.038−4             |
|            | 35                  | 1.645−3             | 5.751−4             |
|            | 36                  | 1.892−3             | 8.610−4             |
|            | 37                  | 1.967−3             | 1.238−3             |
|            | 38                  | 1.888−3             | 2.372−4             |
|            | 39                  | 3.312−4             | 3.172−4             |
|            | 40                  | 4.338−4             | 3.794−4             |

adopted the DARC code. Specific details of the calculations are available in Aggarwal & Keenan (2014a) for Al X, Aggarwal & Keenan (2014c) for Cl XIV, K XVI and Ge XXIX, and Aggarwal & Keenan (2012b) for Ti XIX. Briefly, all partial waves with angular momentum $\ell \leq 40.5$ have been considered, and to ensure convergence of $\Omega$ for all transitions and at all energies a “top-up” based on the Coulomb-Bethe (Burgess & Sheokey 1974) and geometric series approximations was included for the allowed and forbidden transitions, respectively. Furthermore, values of $\Omega$ were determined up to a wide range of energies up to 380 Ryd (Al X), 660 Ryd (Cl XIV), 780 Ryd (K XVI), 1150 Ryd (Ti XIX) and 2500 Ryd (Ge XXIX).

For the subsequent calculations of $\Upsilon$, resonances in a fine energy mesh (0.001 Ryd for most threshold regions) were resolved and averaged over a Maxwellian distribution of electron velocities. This distribution is commonly used and is appropriate for most astrophysical applications. The density and importance of resonances for Be-like ions can be appreciated from figs. 6–11 of Aggarwal & Keenan (2012b) for a few transitions of Ti XIX. Results for $\Upsilon$ were obtained over a wide range of electron temperatures (T$_e$) fully covering that of their maximum fractional abundance in ionisation equilibrium (Bryans, Landi & Savin 2009). Specifically, $\Upsilon$ were reported up to log T$_e$ = 7.2 (Al X), 7.5 (Cl XIV), 7.5 (K XVI), 7.7 (Ti XIX) and 7.8 K (Ge XXIX).

Fernández-Menchero et al. (2014) adopted the AS code of Badnell (1997) to calculate energy levels and A-values. Their calculations are comparatively larger as they included 235 fine-structure levels of the (1s$^2$) 2(s.p) $nl$ (n = 3–7; $\ell = 0$–4 for n ≤ 5 and $\ell = 0$–2 for n = 6–7) configurations. For most Be-like ions considered, their semi-relativistic approach generally yields comparable results with GRASP for energy levels and A-values. For example, in Table 1 we list the two sets of energies for the lowest 80 levels of Al X, where discrepancies are less than 0.02 Ryd and level orderings are also the same. Since detailed comparisons of energy levels with available experimental and other theoretical results

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have already been made by us and Fernández-Menchero et al. (2014), we do not discuss these further. Similarly, we do not discuss the A-values, and rather focus on the more important parameter, i.e., Υ.

For the determination of Ω, Fernández-Menchero et al. (2014) obtained results for fine-structure transitions from the LS calculations (Berrington et al. 1999) through a ICFT approach. They considered a slightly larger range of partial waves (J ≤ 45.5) than ourselves. However, they only included electron exchange up to J = 11.5 and for the rest performed a no-exchange calculation for expediency. This approach sometimes leads to sudden changes (at the overlap point) in the variation of Ω with J — see, for example, table 6 of Aggarwal & Hibbert (1991). However, for most transitions it should not be a significant source of inaccuracy. More importantly, Fernández-Menchero et al. (2014) performed their calculations of Ω for limited energy ranges, namely up to 90 Ryd (Al X), 165 Ryd (Cl XIV), 215 Ryd (K XV), 300 Ryd (Ti XIX) and 680 Ryd (Ge XXIX), lower by a factor of ~ 4 compared to our work. Unfortunately, such energy ranges are insufficient (Aggarwal & Keenan 2008) to determine values of Υ at the high temperatures (up to ~ 1.7×10^9 K or equivalently ~ 10,600 Ryd) for which these authors reported results. They did include high energy contributions to Ω from the suggested formulae of Burgess & Tully (1992), but this approach, although computationally highly efficient, is perhaps a major source of inaccuracy, as discussed earlier by us for transitions of Fe XIV (Aggarwal & Keenan 2014b). Since we had already calculated values of Ω up to sufficiently high energies, there was no need for extrapolation to determine Υ for the ranges of T_e reported by us.

Fernández-Menchero et al. (2014) resolved resonances in the threshold regions and averaged the values of Ω over a
Maxwellian distribution of electron velocities to determine $T_e$, in a similar procedure to that employed by us. However, within thresholds they adopted a uniform mesh of 0.00001 $z^2$, where $z$ is the reduced charge of the ion, i.e. $Z-4$. Consequently, with increasing $Z$ their adopted energy mesh becomes coarser. For example, for Al X it is 0.00081 Ryd, but for Ge XXIX is 0.0078 Ryd. Furthermore, this energy mesh was adopted only for partial waves with $J \leq 11.5$ (i.e. for the exchange calculations only), while for higher $J$ the mesh was coarser by a factor of 100, i.e. 0.001 $z^2$. By contrast, we adopted a uniform mesh ($\sim 0.001$ Ryd) for all partial waves and for all ions.

3 EFFECTIVE COLLISION STRENGTHS

Since Fernández-Menchero et al. (2014) have not reported results for $\Omega$ no direct comparisons with our work are possible. Therefore, we focus on a comparison of $\Upsilon$, which are normally required for modelling applications.

3.1 Resonance transitions

In Table 2 we list both sets of results for $\Upsilon$ for the resonance transitions of Al X among the lowest 80 levels which have the same orderings in both calculations, and at three electron temperatures, i.e. $\log T_e = 4.3, 6.0$ and 7.3 K. The first and the third are the lowest and the highest common temperatures between the two calculations, whereas the second is the most relevant for modelling applications, because $10^{6.1}$ K is the temperature at which Al X has its maximum abundance in ionisation equilibrium (Bryans et al. 2009).

For most transitions listed in Table 2, the $\Upsilon$ of Fernández-Menchero et al. (2014) are larger, by up to a factor of 15, at all temperatures, particularly the lower ones. However, for some transitions our results are higher by up to a factor of 2, such as 1–26/27/28 (i.e. $2s^2\, ^1S_0 - 2p\, ^3D_1\, ^3, ^2, ^1$). These transitions are forbidden in both the LS and $jj$ coupling schemes, and hence resonances for these are significant (particularly towards the lower end of the energy range) as shown in Fig. 1 for $2s^2\, ^1S_0 - 2p\, ^3D_1$ (1–26). We note that even a slight shift in resonance positions can affect the calculated values of $\Upsilon$, particularly at low(er) temperatures. However, as shown in Table 1 the two sets of energies obtained by the AS and GRASP codes are comparable for most levels, including $2p\, ^3D_{1,2,3}$. If these near threshold resonances are missing from the calculations of Fernández-Menchero et al. (2014) then their results for $\Upsilon$ will clearly be lower.

Among the transitions for which $\Upsilon_{\text{ICFT}}$ are larger than $\Upsilon_{\text{DARC}}$ at $\log T_e = 4.3$ K, are 1–64 ($2s^2\, ^1S_0 - 2p\, ^1P_0^o$) and 1–80 ($2s^2\, ^1S_0 - 2p\, ^1F_3$), which are allowed and forbidden, respectively. The 1–64 transition is weak with $f = 5 \times 10^{-4}$ in our work (GRASP) and $f = 1 \times 10^{-4}$ from AS, and yet $\Upsilon_{\text{ICFT}} > \Upsilon_{\text{DARC}}$ by a factor of $\sim 6$ at the lowest common temperature, while $\Upsilon_{\text{ICFT}}$ is smaller by a factor of 2 at $\log T_e = 7.3$ K. For this transition, resonances are
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Figure 2. Ratio (R) of DARC and ICFT effective collision strengths for transitions among the lowest 80 levels of Al X, at electron temperatures of (a) $T_e = 10^{4.3}$ K, (b) $T_e = 10^{6.0}$ K and (c) $T_e = 10^{7.3}$ K. Negative R values indicate that $\Upsilon_{\text{ICFT}} > \Upsilon_{\text{DARC}}$.

not prominent as expected. Similarly, for the 1–80 (forbidden) transition we do not observe any significant resonances, although [Fernández-Menchero et al. (2014)] may do so, because their calculations include 238 levels in comparison to only 98 in ours. Therefore, we now focus our attention on the highest temperature of $10^{7.3}$ K (equivalent to $\sim 126$ Ryd) at which the contributions of resonances, if any, will not be appreciable.

Among the transitions listed in Table 2, the one which shows the largest factor (4) by which $\Upsilon_{\text{ICFT}}$ is higher than $\Upsilon_{\text{DARC}}$ is 1–70 ($2s^2\,^1S_0 - 2p\,^3P_0$). In fact, the difference between the two calculations increases with increasing temperature (from a factor of 2.6 at $T_e = 10^{4.3}$ K to 4.1 at $10^{7.3}$ K). However, this is a forbidden transition for which $\Omega$ decreases (or becomes nearly constant) with increasing energy – see table 4 of [Aggarwal & Keenan (2014a)]. Therefore, the behaviour of $\Upsilon$ in the calculations of [Fernández-Menchero et al. (2014)] is difficult to understand for some transitions.

3.2 All transitions

The comparisons of $\Upsilon$ shown in Table 2 are for a very limited range of transitions. Therefore, in Fig. 2 (a, b and c) we compare the two sets of $\Upsilon$ for all 3160 transitions among the 80 levels of Al X at three temperatures of Table 2. It is clear from these figures that for a majority of transitions the $\Upsilon$ of [Fernández-Menchero et al. (2014)] are significantly larger (by up to a factor of 30) at all temperatures. More specifically, for 60% and 42% of the transitions the two sets of $\Upsilon$ differ by over 20% at the lowest and the highest common temperatures of $10^{4.3}$ and $10^{7.3}$ K, respectively. Also, for a majority of transitions the values of $\Upsilon_{\text{ICFT}}$ are larger. A similar comparison is found for transitions in other ions, namely Cl XIV, K XVI, Ti XIX and Ge XXIX.

3.3 $n = 2$ transitions

We now discuss the discrepancies between the two sets of $\Upsilon$ for specific range of transitions. Among the lowest 10 levels are 45 transitions belonging to the $n = 2$ configurations. At $T_e = 10^{4.3}$ K, for $\sim 30\%$ of transitions discrepancies are up to a factor of 2.5, largest for the $4–6: 2s2p\,^3P_0^o - 2p^2\,^3P_0$, which is forbidden. For half the transitions $\Upsilon_{\text{DARC}} > \Upsilon_{\text{ICFT}}$ and for the other half $\Upsilon_{\text{ICFT}} > \Upsilon_{\text{DARC}}$, and there are no systematics because both types (allowed and forbidden) show the discrepancies. This may be due to the position of resonances, as discussed in section 3.1, because at $T_e = 10^{6.0}$ and $10^{7.3}$ K both sets of $\Upsilon$ agree within $\sim 20\%$.

3.4 $n = 3$ transitions

There are 630 transitions among the $n = 3$ configurations belonging to the levels between 11 and 46. At $T_e = 10^{4.3}$ and $10^{6.0}$ K for about half the transitions (including both allowed and forbidden) $\Upsilon_{\text{DARC}} > \Upsilon_{\text{ICFT}}$, whereas a third of transitions have $\Upsilon_{\text{ICFT}} > \Upsilon_{\text{DARC}}$ at $T_e = 10^{7.3}$ K. It is
difficult to explain these discrepancies at all temperatures, particularly for the allowed transitions.

3.5 \( n = 4 \) transitions

These transitions belong to levels 47 and higher and are 561 in number. For a majority of transitions (about two third) \( \Upsilon_{\text{ICFT}} > \Upsilon_{\text{DARC}} \) at all temperatures. Again, these large discrepancies are difficult to understand, particularly at \( T_e = 10^3 \text{ K} \) and for allowed transitions. Nevertheless, we will return to the source of discrepancies in section 4, apart from those already discussed in section 2.

3.6 Strong allowed transitions

We now discuss the strong allowed transitions, i.e. with \( f \geq 0.1 \). Among the lowest 80 levels of Al X given in Table 1, there are 79 such transitions. At the most relevant temperature of Al X (i.e. \( 10^6 \text{ K} \)) both sets of \( \Upsilon \) agree within \( \sim 20\% \) for all transitions, but for about a third \( \Upsilon_{\text{ICFT}} > \Upsilon_{\text{DARC}} \) at \( T_e = 10^3 \text{ and } 10^4 \text{ K} \). Discrepancies are comparatively larger at the lowest common temperature and many transitions belong to the lowest 46 levels of the \( n = 2 \) and 3 configurations.

3.7 \( 1–3 \) transition of P XII

Finally, we note that the comparison shown by Fernández-Menchero et al. (2014) in their fig. 5 with the \( \Upsilon \) of Keenan (1988) for the \( 2s^2 1S_0 - 2s2p^3P_1^o (1–3) \) transition of P XII is incorrect. For this transition there is no appreciable difference between the \( \Upsilon \) interpolated by Keenan (1988) and those calculated by Fernández-Menchero et al. (2014). In fact, for this transition the interpolated values for other ions are underestimated (by up to a factor of two), rather than overestimated as shown by Fernández-Menchero et al. (2014). This can be seen from table 6 of Aggarwal & Keenan (2014) for Al X, and tables 16 and 17 of Aggarwal & Keenan (2014) for Cl XIV and K XVI. The error in calculating \( \Upsilon \) has occurred by Fernández-Menchero et al. (2014) because they have mistakenly taken the coefficient \( a_1 \) to be positive rather than negative (\( a_1 = -0.026314 \)), as given by Keenan (1988) in his table II.

4 CONCLUSIONS

In this paper we have compared two sets of electron impact excitation effective collision strength (\( \Upsilon \)) for transitions in Be-like ions obtained by the \( R \)-matrix method in semi and fully relativistic approaches, i.e. ICFT and DARC. Both approaches should provide comparable results for a majority of transitions. However, significant differences of up to more than an order of magnitude are noted for at least 50% of the transitions of all ions with \( 13 \leq Z \leq 32 \), and over the entire range of electron temperature. In most cases the \( \Upsilon \) from ICFT are significantly larger than those obtained with DARC. We believe the discrepancies have arisen mainly due to some compromises made by Fernández-Menchero et al. (2014) in calculating \( \Omega \) and subsequently \( \Upsilon \), as noted in section 2. Similar large discrepancies between the two independent \( R \)-matrix approaches have also been noted in the past – see for example, Aggarwal & Keenan (2014b) for Fe XIV, Aggarwal & Keenan (2013b) and references therein for He-like and Aggarwal & Keenan (2012a) for Li-like ions. Therefore, it appears that the implementation of the ICFT approach, although computationally highly efficient (hence allowing data for many ions to be produced over relatively short periods), may not be completely robust. Indeed, this has also been confirmed by Storey, Sochi & Badnell (2014) in their calculations for O III, who noted that for some transitions the ICFT results can be significantly overestimated in comparison to the Breit-Pauli (or other similar approaches, such as DARC). Therefore, we recommend that the excitation rates reported by Fernández-Menchero et al. (2014) should be used with caution and a re-examination of their results would be helpful.

As already stated in section 1, assessing the accuracy of \( \Upsilon \) is a difficult task (Aggarwal & Keenan 2013a), mainly because large calculations cannot be easily reproduced. However, when two (or more) calculations of comparable complexity and with similar approaches (such as \( R \)-matrix) become available, the discrepancies observed are often striking, as noted above for He-like, Li-like and Be-like ions. Therefore, the true accuracy of any atomic data can only be assessed either by modelling applications or the comparisons, as shown in this work. However, since observational data are generally limited, a comparison with theoretical results is often inconclusive. The large discrepancies in \( \Upsilon \) observed here for a majority of transitions of many Be-like ions do create suspicion in the minds of users. Nevertheless, as discussed in our published papers, our accuracy assessment for a majority of transitions in the temperature ranges of interest remains the same, i.e. \( \sim 20\% \). Although no accuracy assessment has been made by Fernández-Menchero et al. (2014), their reported data would appear to be less reliable due to the compromises made in their calculations particularly in the chosen energy mesh and the energy ranges over which values of \( \Omega \) were calculated before extrapolation. However, we also stress that there is scope for improvement in our work (as there is for any calculation), especially for transitions involving levels of the \( n = 4 \) configurations. The inclusion of levels of the \( n \geq 5 \) configurations in the collisional calculations may improve the reported values of \( \Upsilon \) due to the additional resonances arising. However, until then we believe that our reported results for radiative and excitation rates for transitions in Be-like ions are (probably) the most exhaustive and accurate available to date, and should be useful for the modelling of astrophysical plasmas.

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REFERENCES

Aggarwal K. M., Hibbert A., 1991, J. Phys. B, 24, 3445
Aggarwal K. M., Keenan F. P., 2008, Eur. Phys. J., D 46, 205

© 2015 RAS, MNRAS 000, 000
Aggarwal K. M., Keenan F. P., 2012a, At. Data Nucl. Data Tables, 98, 1003
Aggarwal K. M., Keenan F. P., 2012b, Phys. Scr., 86, 055301
Aggarwal K. M., Keenan F. P., 2013a, Fusion Sci. Tech, 63, 363
Aggarwal K. M., Keenan F. P., 2013b, Phys. Scr., 87, 045304
Aggarwal K. M., Keenan F. P., 2014a, MNRAS, 438, 1223
Aggarwal K. M., Keenan F. P., 2014b, MNRAS, 445, 2015
Aggarwal K. M., Keenan F. P., 2014c, Phys. Scr., 89, 125401
Badnell N. R., 1997, J. Phys. B, 30, 1
Berrington K. A., Eissner W. B., Norrington P. H., 1995, Comput. Phys. Commun., 92, 290
Bryans P., Landi E., Savin D. W., 2009, ApJ, 691, 1540
Burgess A., Sheorey V. B., 1974, J. Phys., B7, 2403
Burgess A., Tully J. A., 1992, A&A, 254, 436
Fernández-Menchero L., Del Zanna G., Badnell N.R., 2014, A&A, 566, A104
Grant I. P., McKenzie B. J., Norrington P. H., Mayers D. F., Pyper N. C., 1980, Comput. Phys. Commun., 21, 207
Keenan F. P., 1988, Phys. Scr., 37, 57
Landi E., Doron R., Feldman U., Doscheck G. A., 2001, ApJ, 556, 912
Liang G. Y., Badnell N. R., Crespo López-Urrutia J. R., Baumann T. M., Del Zanna G., Storey P. J., Tawara H., Ulrich J., 2010, ApJS, 190, 322
Storey P. J., Sochi T., Badnell N. R., 2014, MNRAS, 441, 3028