§7. Energy Levels, Radiative Rates, and Electron Impact Excitation Rates for Transitions in He-like C V

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Emission lines of He-like ions have been widely observed in a variety of astrophysical and laboratory plasmas. For example, lines of many He-like ions observed in solar plasmas in the x-ray region (1-50 Å) have been listed by Dere et al.[1]. Of particular interest are the resonance (w: 1s^2 ^{1}S$_0$ – 1s2p ^{1}P$^o_1$), intercombination (x and y: 1s^2 ^{1}S$_0$ – 1s2p ^{3}P$^o_{2,1}$), and forbidden (z: 1s^2 ^{1}S$_0$ – 1s2s ^{3}S$_1$) lines, which are highly useful for solar plasma diagnostics - see, for example, Gabriel and Jordan[2]. However to analyse observations, atomic data are required for a variety of parameters, such as 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).

Emission lines from several ionisation stages of carbon, including He-like C V, have been observed in solar plasmas from rockets and satellites[1], and are useful for the determination of electron densities and temperatures in the solar corona and transition region. Similarly, the resonance w line at 40.2 Å has been studied in a laser-produced carbon plasma[3], because it lies in the water window spectral region, and hence has potential application in x-ray microscopic imaging of biological samples in wet conditions. Recently lines of C V have also been measured in the EUV range at NIFS[4] in fusion plasmas from Large Helical Device (LHD), as carbon is one of the main impurities in fusion reactors. Therefore, atomic data for C V are highly required for modelling and diagnostics of a variety of plasmas.

Experimentally, energy levels have been compiled by NIST (National Institute of Standards and Technology) and are available at their website `http://physics.nist.gov/PhysRefData`. Similarly, A- values are also available for some transitions on the NIST website. However, the collisional atomic data for C V are restricted to transitions only from the lowest three levels to higher excited levels. Therefore, we have performed a complete set of results (namely energy levels, radiative rates, lifetimes, and effective collision strengths) for all transitions among the lowest 49 levels of C V. These levels belong to the 1s^2, 1s2ℓ, 1s3ℓ, 1s4ℓ, and 1s5ℓ configurations. Finally, we also calculate the A- values for four types of transitions, namely electric dipole (E1), electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2), because these are also required for plasma modelling.

For our calculations we employ the fully relativistic GRASP (general-purpose relativistic atomic structure package) code for the determination of wavefunctions, originally developed by Grant et al.[5] and revised by Dr. P. H. Norrington. It is a fully relativistic code, and is based on the jj coupling scheme. Further relativistic corrections arising from the Breit interaction and QED effects (vacuum polarization and Lamb shift) have also been included. Additionally, we have used the option of *extended average level* (EAL), in which a weighted (proportional to $2j+1$) trace of the Hamiltonian matrix is minimized. This produces a compromise set of orbitals describing closely lying states with moderate accuracy. Similarly, for our calculations of Ω, we have adopted the *Dirac atomic R-matrix code* (DARC) of P.H. Norrington and I.P. Grant (private communication). Finally, for comparison purposes we have performed parallel calculations from the *Flexible Atomic Code* (FAC), available from the website `http://sprg.ssl.berkeley.edu/~mfgu/fac/`. This is also a fully relativistic code which provides a variety of atomic parameters, and (generally) yields results comparable to GRASP and DARC. Thus results from FAC are helpful in assessing the accuracy of our energy levels, radiative rates, and collision strengths.

For computating Ω, the R-matrix radius adopted for C V is 19.36 au and 60 continuum orbitals have been included for each channel angular momentum for the expansion of the wavefunction. This allows us to compute Ω up to an energy of 52 Ryd, sufficient to calculate values of Υ up to T$_e$ = 10^6 K. The maximum number of channels for a partial wave is 217, and the corresponding size of the Hamiltonian matrix is 13076. In order to obtain convergence of Ω for all transitions and at all energies, we have included all partial waves with angular momentum $J \leq 40.5$, although a larger number would have been preferable for the convergence of some allowed transitions, especially at higher energies. However, to account for the inclusion of higher neglected partial waves, we have included a top-up, based on the Coulomb-Bethe approximation for allowed transitions and geometric series for others. To delineate resonances, we have performed our calculations of Ω at over 3300 energies in the threshold region. Close to thresholds ($\sim$ 0.1 Ryd above a threshold) the energy mesh is 0.001 Ryd, and away from thresholds is 0.002 Ryd. Thus care has been taken to include as many resonances as possible, and with as fine a resolution as is computationally feasible.

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