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Lifetimes of excited levels in neutral carbon

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Abstract. An atomic lifetime study of *VUV* transitions in C I, utilizing the method of beam-foil spectroscopy, is reported. Six multiplets in the triplet system and five in the singlet system were investigated. The results are found to be in excellent agreement with the theoretical calculations of Nussbaumer & Storey (1984) and Luo & Pradhan (1989), as well as with recent *gf*-value measurements using the emission method (Goldbach & Nollez 1987, Goldbach et al. 1989).

Key words: atomic and molecular data – spectroscopy

1. Introduction

The resonance transitions of C I appear in a number of astrophysical spectra, including those of interstellar clouds, sunspots, stellar winds, and quasi-stellar objects (QSO). Using the Copernicus satellite de Boer & Morton (1974) observed C I interstellar absorption lines in the spectrum of ζ Ophiuchi, and the work was later extended to ζ Puppis (see Morton 1978, de Boer & Morton 1979). Cardelli & Böhm-Vitense (1982) have observed several C I lines in the IUE spectra of μ Ophiuchi. Many C I lines were found in the high-resolution solar spectrum, 1175–1710 Å (Sandlin et al. 1986) and C I lines are also present in the IUE spectra of cool stars (Jordan 1988). A search list of QSO absorption systems which includes 8 resonance transitions of C I in the *VUV* has recently been published by Morton et al. (1988).

Many authors have reported experimental *gf*-values and lifetimes for the *VUV* transitions of C I. Among the early work, critically compiled by Wiese et al. (1966), the emission measurement of Boldt (1963) which covered many multiplets between 1100 and 1800 Å deserves mentioning. The first direct lifetime measurement for C I was performed by Lawrence & Savage (1966) who employed the electron-beam phase-shift method. About 10 years later a refined version of this method was extended to additional *VUV* multiplets of C I (Brooks et al. 1977). In the late 1960's and early 1970's a number of lifetime studies were carried out using the beam-foil excitation method (Bromander et al. 1969, Mickey 1970, Pegg et al. 1970, Bromander 1971, Poulizac et al. 1971). However, in those days the beam-foil method was often criticized and the data (which in the C I case were internally consistent) were considered to suffer from systematic uncertainties. Indeed, in several of the early beam-foil publications the quoted error limits were over-optimistic.

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In the present article we report an additional beam-foil study of *VUV* transitions in C I. The beam-foil excitation method has undergone a number of significant improvements in recent years, resulting in higher sensitivity and better wavelength resolution. Furthermore, the problems of cascading – which in the early work could result in multi-exponential decay curves that were very difficult to analyze in an unambiguous way – have been practically solved in recent years. Because of these developments it is now possible to extend reliable lifetime studies to heavily cascaded systems or lines which were too weak to be measurable in the early beam-foil experiments. The present work has been largely stimulated by two recent emission studies of *gf*-values for C I (Goldbach & Nollez 1987, Goldbach et al. 1989). Using a wall-stabilized arc light source these authors recorded high-resolution spectra of C I in the region 1200–2000 Å. The relative oscillator strengths thereby obtained were then normalized, using previous lifetime data for two strong C I multiplets. In this context Goldbach & Nollez (1987) pointed out that "in the 1200–1700 Å range, only for two multiplets (No. 3 at 1561 Å and No. 2 at 1657 Å) are the oscillator strengths precisely known". Attention should also be drawn to a careful study of C I branching ratios (Tozzi et al. 1983) which in some cases showed deviations from LS-coupling.

In recent years, there have further appeared several theoretical studies of C I oscillator strengths. For example, Nussbaumer & Storey (1984) report two sets of ab initio data, from a large configuration interaction (CI) calculation, using the code SUPERSTRUCTURE (SS), and a close-coupling (CC) calculation. Within the "Opacity Program" Luo & Pradhan (1989) have performed very elaborate CC calculations for the C I isoelectronic sequence. Using the relativistic Hartree-Fock (HFR) method of Cowan (1981), Fawcett (1987) has made calculations for C I–O III. Victor & Escalante (1988), finally, report data based on semiempirical model potential calculations, their emphasis being placed on transitions from higher n-states. (These theoretical papers also provide references to earlier work in which single-configuration or very limited multiconfiguration methods were employed, resulting in less reliable results for transitions within the $n=2$ and $n=3$ shells where configuration mixing can be severe.)

2. Experiment

Ions of C^+, accelerated to 100 keV in the 330 kV Danfysik heavy ion accelerator at the University of Toledo, were sent through a thin (2 $\mu g\ cm^{-2}$) exciter foil of carbon. At such a comparatively

low ion energy, electron capture in the foil has a high probability, and about 65% of the beam particles on the downstream side of the foil are neutral carbon atoms, many of which emerge from the foil in excited states. The radiation emitted at the spontaneous decay of these states was observed with an Acton 1 m normal-incidence *VUV* monochromator, equipped with a solar-blind EMI photomultiplier at the exit slit. Spectra were registered in the region 1140–1950 Å, using photon-counting methods. The wavelength resolution was about 0.9 Å which was achieved by refocussing the spectrometer for a moving light source (Stoner & Leavitt 1971). In this way the Doppler effects inherent in the beam-foil light source can be conveniently reduced. The remaining line broadening is largely due to the instrumental resolution and scattering processes in the foil which result in a weakly divergent beam on the downstream side. With this resolution it was not possible to resolve the *J*-structure of multiplets. The lifetimes were measured by recording the intensity of the spectral lines (number of photons) as a function of the distance from the foil. To convert this distance into time after excitation, the velocity of the foil-excited particles must be accurately known. The velocity of the incoming ions could be determined with a 1% uncertainty, whereas a typical value of energy loss in the foil was computed to (4 ± 2) keV, using theoretical and semi-empirical formulae for the stopping power of fast ions in solid targets. We can therefore estimate that the velocity of the ions after the foil was known with an uncertainty of about 2%. At 100 keV ion energy the "time window", a measure of the time resolution along the foil-excited beam, was set at 0.3 nsec, i.e. about 10–15% of the shortest lifetimes expected in the spectral region studied. To compensate for fluctuations in the intensity of the ion beam current, an optical normalization technique was used. By means of an optical fibre, connected to a photomultiplier, a well-defined region very close to the foil was viewed. Data were taken at each distance from the foil until a present number of optical normalization pulses was reached. This method is more reliable at low ion energies than the alternative technique of charge normalization (i.e. counting until a preset, constant amount of electric charge from the ion beam has been collected in a Faraday cup, situated on the downstream side of the foil). The reason for this is that the foil properties change during the ion bombardment, and these changes are more quickly and reliably monitored by means of optical normalization. Besides contributing to line broadening, the beam divergence after the foil may distort the decay curves and result in apparent lifetimes that differ from the correct ones. With 100 keV C^+ ions passing a 2 $\mu g\,cm^{-2}$ foil 50% of the beam particles have a scattering angle larger than 1.5°. This effect has been taken into account, by increasing the uncertainties of the final lifetime data. However, we also found that because of this scattering, lifetimes longer than 10 nsec could not be reliably measured with the present experimental arrangement. For additional details about the experimental setup we refer to a previous paper which deals with transitions between some higher-lying C I levels (Haar et al. 1989).

3. Results and discussion

We observed about 40 multiplets in the region 1100–2000 Å. The strongest transitions belonged to C I and C II, but even some C III and C IV lines were fairly prominent. A survey spectrum is depicted in Fig. 1. Decay curves were recorded for 11 well resolved C I multiplets as well as for two blended structures. After

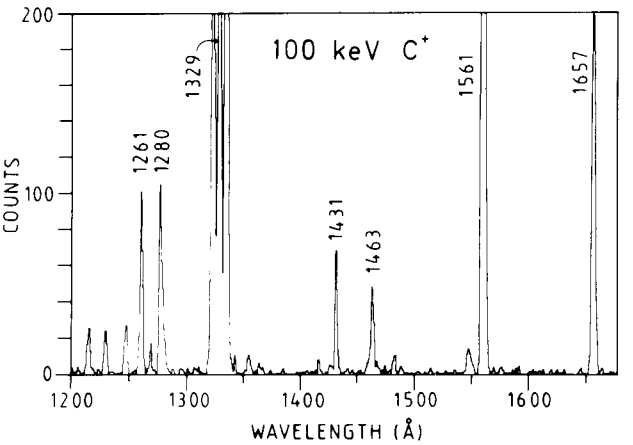

Fig. 1. A survey spectrum of carbon, using 100 keV incoming ions. This spectrum was recorded at lower resolution than used for some of the lifetime measurements. For instance, in the latter case the multiplets at 1277 Å and 1280 were spectrally resolved. The strongest C I multiplets are indicated by wavelength

correction for background the data were analyzed using the program DISCRETE (Provencher 1976) which fits the measured decay curve to a sum of exponentials. In this way it is possible to correct for cascading processes from higher levels, provided that the latter have lifetimes which significantly differ (preferably a factor of 3 or more) from that of the level of primary interest. If this is not the case a decomposition into exponentials can lead to unreliable results. Another more rigourous method, usually called arbitrarily normalized decay curves or ANDC (Curtis et al. 1971), can then be successfully used. It involves a direct measurement of the decay curves of the levels that combine with the primary level. A set of linear equations is thereby obtained from which the primary lifetime is derived by means of a least squares fit. In a previous beam-foil study of C II lifetimes, Reistad et al. (1986) found that ANDC and DISCRETE analyses yielded very similar lifetimes in about 80% of the cases. In the present C I experiment the situation is simpler because the possible cascading levels have lifetimes that are at least an order of magnitude longer than the primary ones (Bromander et al. 1978, Miller et al. 1974, Jones & Wiese 1984). Indeed, in all the cases now studied, the DISCRETE program showed that the data were best approximated by one single exponential plus a small constant background, whereas the inclusion of additional exponentials resulted in less satisfactory fits. This is apparent also from two typical decay curves, for the $2s2p^3\,^3D$ and ^3P terms, displayed in Figs. 2 and 3.

Our results are given in Table 1 (triplets) and Table 2 (singlets). The estimated errors take into account the 2% velocity uncertainty, the above-mentioned angular scattering (which introduces a 1% uncertainty for decay times shorter than 7 nsec, and 2% for the interval 7–9 nsec) as well as a statistical uncertainty. These uncertainties were combined in quadrature. The tables also list the results of previous experimental and theoretical determinations. It should be noted that the list of earlier results is not complete. For instance, when the same authors have made several experimental studies we have selected the most recent results. This holds for the work of Bromander (1971) which represents a more thorough analysis of the data earlier given by

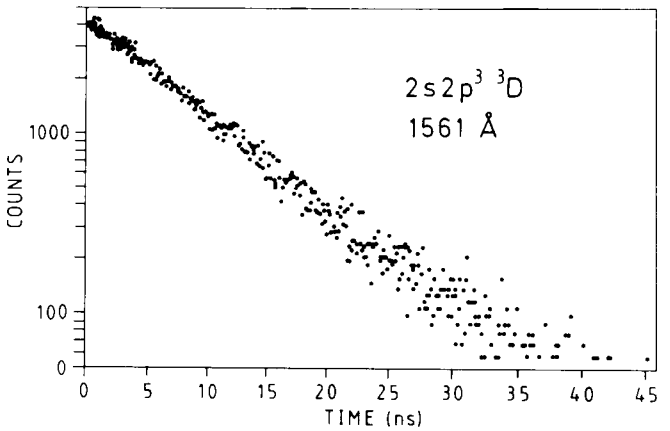

Fig. 2. Decay curve of the $2s2p^3\ ^3D$ term in C I (1561 Å)

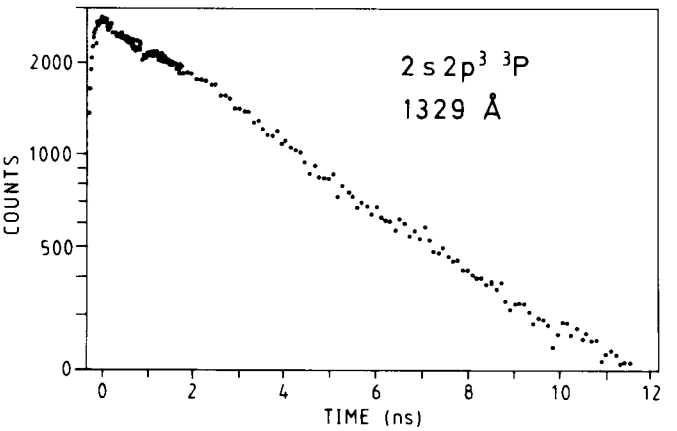

Fig. 3. Decay curve of the $2s2p^3\ ^3P$ term in C I (1329 Å)

Bromander et al. (1969). Furthermore, of the various theoretical results we include here only the more recent sets of data, i.e. by Nussbaumer & Storey (1984), Fawcett (1987), Victor & Escalante (1988) and Luo & Pradhan (1989).

As already noted, the lifetimes of the $2s2p^3\ ^3D$ and $2s^22p3s\ ^3P$ levels have been measured by several authors, largely because the corresponding lines, at 1561 and 1657 Å respectively, are quite pronounced in the spectra. In both cases our present results are in agreement with practically all previous experimental data. This fact demonstrates that reliable beam-foil and phase-shift data could be obtained already 20 years ago, at least for strong and well-resolved transitions. Goldbach & Nollez (1987) and Goldbach et al. (1989) have used the weighted mean values of previous lifetime determinations for these multiplets to normalize their emission data. The values selected by them are in very good agreement with our results.

While the $2s2p^3\ ^3D$ and $2s^22p3s\ ^3P$ levels decay only to the $2s^22p^2\ ^3P$ ground state [neglecting spin-forbidden transitions to the $2s^22p^2\ ^1S$ and ^1D terms which have comparatively low transition probabilities, see Nussbaumer & Storey (1984)], the higher triplets studied in this work have additional decay channels, to the various levels of the $2s^22p3p$ configuration. These transitions are mainly in the IR region and their probabilities have been calculated (Nussbaumer & Storey 1984, Victor & Escalante 1988, Luo & Pradhan 1989). In all cases the transitions to the ground state have much higher probabilities than the decay modes to the $2s^22p3p$ configuration.

Table 1 shows that our lifetime for the $2s2p^3\ ^3P$ level (1329 Å) confirms the phase-shift result (Brooks et al. 1977), whereas a difference between our value and that reported by Brooks et al. (1977) can be noted in the case of the $2s^22p4s\ ^3P$ term. At 1279–1280 Å there are actually two multiplets which are very difficult to spectrally resolve, $2s^22p^2\ ^3P$–$2s^22p4s\ ^3P$ (1280.4 Å) and $2s^22p^2\ ^3P$–$2s^22p3d\ ^3F$ (1279.3 Å). However, since the calculated lifetime for the ^3F term is longer than 70 nsec (Nussbaumer & Storey 1984), our measured decay time of 8.8 nsec must be assigned to the ^3P term. It is worth noting that our data for the $2s^22p3d\ ^3P$ and ^3D levels (1261 and 1277 Å) agree quite well with the early beam-foil data of Bromander (1971), whose measurements were carried out at lower wavelength resolution than in the present work. For all the six triplet multiplets studied by us, agreement with the results of Nussbaumer & Storey (1984) and Luo & Pradhan (1989) is very good. As mentioned, Nussbaumer & Storey provide two sets of data, of which the SS calculations fall slightly closer to the experimental data than do the CC results. For completeness we quote both the dipole-length and dipole-velocity results obtained by Luo & Pradhan (1989), although the difference is here fairly small. A direct comparison of the present beam-foil lifetimes and the *gf*-values obtained by Goldbach & Nollez (1987) and Goldbach et al. (1989) becomes possible if we (as in Tables 1 and 2) use their data, which only refer to the *VUV* lines, to compute upper limits of term lifetimes. These can further be corrected by taking into account the theoretical data for the IR lines to the $2s^22p3p$ configuration. This correction further improves the agreement between our data and those obtained by the emission technique (Goldbach & Nollez 1987, Goldbach et al. 1989).

In the C I singlet system (Table 2), the strongest *VUV* line is that at 1930 Å ($2s^22p^2\ ^1D$–$2s^22p3s\ ^1P$), and its decay has been studied earlier by several authors. Our measurements were here slightly hampered by a fast (about 0.5 nsec decay time) component in the decay curves, probably caused by the light emitted by slow, excited carbon atoms, sputtered from the foil. The $2s^22p3s\ ^1P$ lifetime was therefore also determined from another branch, to $2s^22p^2\ ^1S$ (at 2478 Å), and the result given in Table 2 is a weighted mean for these two branches. (For the other C I singlet transitions the wavelengths at which the lifetimes were measured are given, for each level there are two dominant decay channels, to $2s^22p^2\ ^1S$ and $2s^22p^2\ ^1D$.) As in the case of the triplets, our data are in very good agreement with the calculated values of Nussbaumer & Storey (1984) and Luo & Pradhan (1989), and – taking into account the branching ratios – with the emission measurements (Goldbach & Nollez 1987, Goldbach et al. 1989). For the 1463.3 Å line ($2s^22p^2\ ^1D$–$2s^22p3d\ ^1F$) Goldbach & Nollez (1987) note a disagreement between their result (taking into account the possible uncertainty in the branching ratios) and the beam-foil lifetime of Bromander (1971). Our result now confirms the emission measurement which should be important because this singlet transition has been used to connect the absolute *f*-value scales for the "strong" and "weak" C I lines, see Goldbach et al. (1989). For the cases calculated by Victor & Escalante (1988) there is also quite satisfactory agreement with the present work,

Table 1. Lifetimes of triplet levels in C I

Transition	Wavelength (Å)	Multiplet	Lifetime (nsec)	
			Experiment*	Theory
$2s^2 2p^2\ ^3P$–$2s2p^3\ ^3D$	1561.0	3	7.8(3)[a]	8.73[m]
			6.8(17)[b]	8.01[n]
			8.0(8)[c]	4.3[o]
			7.3(2)[d]	8.52[p]
			7.3(7)[e]	7.95[q]
			7.5(2)[f]	
			3.6(4)[g]	
			8.0(8)[h]	
			8.3(8)[i]	
$2s^2 2p^2\ ^3P$–$2s2p^3\ ^3P$	1329.3	4	4.5(2)[a]	4.76[m]
			6.9(17)[b,j]	2.3[o,j]
			4.2(4)[h]	4.29[p]
			4.3(6)[i,j]	
$2s^2 2p^2\ ^3P$–$2s^2 2p3s\ ^3P$	1657.2	2	3.1(2)[a]	2.95[m]
			2.4(6)[b]	3.03[n]
			3.1(3)[c]	2.80[o]
			2.9(1)[f]	2.79[p]
			3.0(12)[g]	2.70[q]
			2.9(4)[i]	2.56[r]
			3.1(6)[k]	
$2s^2 2p^2\ ^3P$–$2s^2 2p4s\ ^3P$	1280.4	5	8.8(5)[a]	9.12[m]
			12(3)[b,j]	9.00[n]
			5.0(5)[h]	6.4[o,j]
			13(3)[l,j]	9.15[p]
				9.42[q]
				10.0[r]
$2s^2 2p^2\ ^3P$–$2s^2 2p3d\ ^3P$	1261.3	9	5.2(3)[a]	4.64[n]
			8.3(18)[b,j]	2.9[o,j]
			5.4(2)[f]	5.31[p]
			5.6(6)[i,j]	5.51[q]
				5.61[r]
$2s^2 2p^2\ ^3P$–$2s^2 2p3d\ ^3D$	1277.5	7	4.0(2)[a]	3.97[m]
			6.5(16)[b,j]	3.3[o]
			4.4(3)[f]	3.45[p]
			4.3(5)[i,j]	3.60[q]
				3.74[r]

* The errors are given in parentheses, e.g. 7.8(3) stands for 7.8 ± 0.3

[a] This work
[b] Boldt (1963)
[c] Lawrence & Savage (1966)
[d] Pegg et al. (1970)
[e] Poulizac et al. (1971)
[f] Bromander (1971)
[g] Mallow & Burns (1972)
[h] Brooks et al. (1977)
[i] Goldbach & Nollez (1987)
[j] Upper limit of the lifetime (see text)
[k] Stuck & Wende (1974)
[l] Goldbach et al. (1989)
[m] Nussbaumer & Storey (1984) CC
[n] Nussbaumer & Storey (1984) SS
[o] Fawcett (1987)
[p] Luo & Pradhan (1989), length
[q] Luo & Pradhan (1989), velocity
[r] Victor & Escalante (1988)

whereas much of the theoretical data of Fawcett (1987) – both for triplets and singlets – tends to differ markedly from most other results. This is surprising because the Cowan HFR program (Cowan 1981) is known to provide quite reliable *gf*-values, especially when the ab initio Slater parameters are adjusted to minimize the difference between theoretical and experimental level energies. A possible explanation would be that some important configurations were overlooked by Fawcett (1987).

Table 2. Lifetimes of singlet levels in C I

Transition	Wavelength (Å)	Multiplet	Lifetime (nsec)	
			Experiment	Theory
$2s^22p^2\ ^1D$–$2s^22p3s\ ^1P$	1930.9	33	2.5 (2)[a]	2.70[i]
			2.9 (3)[b]	2.1[j]
			3.1 (2)[c]	2.56[k]
			3.3 (2)[d]	2.51[l]
			2.9 (6)[e,f]	
$2s^22p^2\ ^1D$–$2s^22p4s\ ^1P$	1467.5	36	> 10[a]	13.9[i]
			21 (5)[g,f]	4.4[j,f]
			17.0 (35)[e,f]	13.7[k]
				13.5[l]
$2s^22p^2\ ^1S$–$2s^22p3d\ ^1P$	1751.9	62	4.0 (7)[a]	5.82[i]
			8.4 (21)[g,f]	2.1[j]
			8.3 (15)[e,f]	6.11[k]
			17.7[h,f]	6.70[l]
$2s^22p^2\ ^1D$–$2s^22p3d\ ^1D$	1481.8	34	> 12[a]	16.3[i]
			26 (5)[e,f]	15.2[k]
			29 (8)[g,f]	17.9[l]
$2s^22p^2\ ^1D$–$2s^22p3d\ ^1F$	1463.3	37	4.7 (2)[a]	5.20[i]
			5.0 (13)[g,f]	4.5[j]
			6.1 (2)[d]	4.41[k]
			5.3 (6)[e,f]	4.65[l]

[a] This work
[b] Lawrence & Savage (1966)
[c] Mickey (1970)
[d] Bromander (1971)
[e] Goldbach et al. (1989)
[f] Upper limit of lifetime (see text)
[g] Boldt (1963)
[h] Stuck & Wende (1974)
[i] Nussbaumer & Storey (1984)
[j] Fawcett (1987)
[k] Luo & Pradhan (1989), length
[l] Luo & Pradhan (1989), velocity

In addition to the transitions included in Tables 1 and 2, we have also recorded decay curves for two blended regions. Measurements at 1194 Å gave a decay time of 7.3 ± 0.5 nsec which is consistent with the phase-shift result 8.0 ± 0.8 nsec (Brooks et al. 1977). Citing the analysis by de Boer & Morton (1974), Brooks et al. (1977) suggest that this decay time should be assigned to the $2s^22p^2\ ^3P$–$2s^22p4d\ ^3D$ transition (multiplet 11). Here the calculations of Victor & Escalante (1988) predict a $2s^22p4d\ ^3D$ lifetime of 9.0 nsec which is in reasonable agreement with the experimental data. We made a similar measurement of the structure at 1355 Å where the lines $2s^22p^2\ ^1D$–$2s^22p4d\ ^1D$, ^1F (at 1354.3 and 1355.8 Å, respectively) could not be spectrally resolved by us, obtaining the value 6.9 ± 1 nsec. In this case the theoretical values are 12 nsec ($2s^22p4d\ ^1D$) and 3.2 nsec ($2s^22p4d\ ^1F$), see Victor & Escalante (1988), and our measured "lifetime" probably represents a weighted average of these two numbers.

4. Concluding remarks

The results presented above have confirmed most previous measurements for the strongest *VUV* multiplets of C I. For some of the weaker lines we have corrected earlier experimental data, whereas in other cases we provide the first experimental lifetimes. The measurements are of sufficient accuracy to test the reliability of various theoretical methods that have been applied to this system. These lifetimes give additional support to a number of more recent results, in particular the calculations of Nussbaumer & Storey (1984) and Luo & Pradhan (1989) as well as the emission data obtained by Goldbach et al. (1987, 1989). We are now extending similar beam-foil measurements to other systems of astrophysical interest, including N I, N II, O I, and O II.

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