Chang/Bickel

NGL-03-002-017

MEAN LIVES OF SOME ASTROPHYSICALLY IMPORTANT EXCITED LEVELS IN CARBON, NITROGEN AND OXYGEN*

Ming-Wen Chang† and W. S. Bickel

Department of Physics, University of Arizona, Tucson, Arizona 85721

Received 1975 December 1; revised 1976 January 27

Abstract

A number of astrophysically important mean lives of levels in carbon, nitrogen and oxygen have been measured with the beam-foil technique. We report new values and a comparison with earlier theoretical and experimental values. Direct references to astrophysical applications are listed.

Subject headings: atomic processes - transition probilities - ultraviolet: spectra

---

*Supported in part by NASA, ONR and NSF.

†Present address: Chung Shan Inst. of Science and Technology, Taiwan, Republic of China

I. INTRODUCTION

We used the beam-foil technique (Bashkin 1973) to measure mean lives of some states of highest astrophysical interest including those giving spectral lines that are very weak. The results of our measurements are given in Tables 1-3.

Many of the mean lives have been measured previously by others, but as mentioned in a summary of transition probabilities made by Morton and Smith (1973), there are many important lines for which the transition probabilities have never been measured or calculated or for which large uncertainties exist. Many transitions of atomic species are worthy of careful further study by appropriate methods. Attempts should be made to get accuracies within 5%. Comparisons with other experimental methods are essential, especially in the case where the data must have very high accuracy to be of real value.

Our high-resolution spectrometer, good statistical data, and the beam-foil method for measuring mean lives directly permitted a re-examination of many mean lives measured previously.

All of our results are compared with those from earlier work where possible.

The accuracy of our mean-life measurements is better than 5%, except for those determined from very weak transitions, for which greater uncertainties are expected. The uncertainties of the long-lived cascade mean lives are 20% or more, whereas a blending "cascade" can be measured as accurately as the main component.

II. IMPORTANCE OF THE RESULTS WITH RESPECT TO ASTROPHYSICS

Each mean life measured has astrophysical significance as indicated by the listing in the last column titled "Astrophysical Reference" in Tables 1-3. Spectral lines studied were selected from those obtained from "Skylark" rocket, sounding rocket, Copernicus satellite (OAO spacecraft), OSO-4, OSO-5, and OSO-6 satellites.

Applications are made to problems involving the interstellar medium, circumstellar envelopes of giant stars, the solar atmosphere, solar corona, solar limb, planetary nebulae, the intergalactic medium, and quasistellar sources, and the Bowen resonance-fluorescence process.

In preparation for this detailed study, a number of modifications, special procedures and internal checks were developed in order to keep uncertainties as low as possible. We will discuss the various parts of the experimental system in detail.

Target Chamber

A target chamber of typical beam-foil design was used for photoelectric wavelength and mean-life measurements. Mean-life data were taken by continuously moving the foil in synchronization with a multichannel analyzer and a PDP computer. The beam emerging from the analyzing magnet first passed through a small aperture and then entered the slit stabilization system connected to the accelerator voltage regulator to maintain a constant beam particle energy. The beam then passed through a 5 mm diameter circular entrance aperture in front of the foil and through one of 24 self-supporting carbon foil targets mounted in a rotatable target wheel. The beam terminated in an electron-suppressed Faraday cup which collected and measured the beam current.

The foil carriage was driven by a stepping motor synchronized with a multichannel analyzer. A set number of motor steps determined by a frequency generator during a set time interval moved the foil an exactly known distance. A dwell time interval on the computer related a distance interval in the target chamber to an equivalent number of channels. Thus every channel number was related to an exact foil position in the target chamber. The uncertainty of foil position was less than 1.0 mm.

The target chamber was blackened to avoid internal reflections which have been shown to give spurious signals in some parts of the decay curve (Chupp, Dotchin and Pegg 1968; Bickel 1974b). Random reflections which contribute to background noise have been eliminated (Bickel 1974b).

Spectrometer

A McPherson 0.5 m Seya-Namioka vacuum UV scanning monochromator and a Jarrell-Ash model 78-751, 1 m, 15° Robin mount vacuum UV scanning spectrometer were used in these experiments. The Seya-Namioka system arrangement has been discussed by Bickel (1967, 1968a, 1968b). The Robin mount normal incidence system is used in the same way. The entrance slit was illuminated with light from a slice of the beam which could be as small as 1.0 mm in length. Motorized rotation of the grating provided a wavelength scan which was calibrated by comparison with a Fe-Ne standard wavelength source. For mean-life measurements, the foil was driven by a stepping motor synchronized to the multichannel analyzer recording system. The intensity as a function of distance downstream from the foil was measured by keeping the entrance slit of the spectrometer fixed while moving the foil downstream and upstream. With the grating and slits set to observe a single spectral line, the intensity I(x) at position x downstream from the foil is related to the decays of excited atomic states by the relation

$$I(x) = \sum_{i=1}^{M} I_i^{\circ} \exp\left(-\alpha_i \frac{x}{v}\right) \qquad (1)$$

where I_i° is the intensity at the foil due to the spontaneous radiative decay of excited state i, α_i is the reciprocal of the mean life of excited state, and v is the beam particle velocity.

In comparison, the Robin mount gives better wavelength resolution (FWHM = 1.5 Å) than the Seya-Namioka, (FWHM = 3.0 Å), but the Seya-Namioka, operating closer to grazing incidence, is more sensitive at the lower wavelengths λ300Å - 500Å not accessible with the Robin mount. The two spectrometers, each with interchangeable gratings, therefore complement each other to give a useful wavelength range from λ300Å to 5000Å.

Computer

Computers were used to take data and analyze the mean-life data. A teletype-controlled PDP-9 manufactured by the Digital Equipment Corporation (DEC) was part of the data-acquisition system. Intensities were recorded on a linear scale which could be converted to a log scale in both the memory storage and screen display. The digital log storage could be plotted directly on semilog stripchart paper which made initial analysis easy and accurate, and permitted good initial guesses of slopes and intercepts for the final computer fit of all decay curves. The log display was also convenient for on-line monitoring of the decay curve during the data-taking procedure.

Cascades and Extraction of Mean Lives

In mean-life measurements, most of the spectral lines are cascaded or blended decays whose effects and corrections have been discussed by many authors (e.g., Bickel 1968b; Curtis et al. 1970; Wiese 1970). The level population is governed by the differential equation

$$\frac{dN_i}{dt} = -N_i \sum_{f<i} A_{if} + \sum_{j>i} N_j(t)A_{ji} \qquad (2)$$

The level i is depopulated to lower level f, but is repopulated by cascades from higher level j, and the mean life of this state is given by

$$\tau_i^{-1} = \sum_{j<i} A_{if} \quad , \tag{3}$$

Eq. (2) can be solved for N_i.

The intensity decay curve can be expressed as the sum of several exponentials (blending is included)

$$I_\lambda = \sum_n a_n e^{-x_n/v\tau_n} + b \quad . \tag{4}$$

where a_n and b are constants. The quantities a_n, τ_n, and b are approximately determined initially by a graphical method and then given to the computer, along with the decay curve data, where a least-squares fit was used to do algebraic analysis. A program was written to find parameters which minimize the function

$$\sum_i W_i \{\gamma_i^{obs} - \gamma^{cal}\}^2 \tag{5}$$

where γ_i^{obs} is the observed quantity and W_i the statistical weight attributed to the point $(\gamma_i^{obs}, \gamma_i^{cal})$, but

$$\gamma_i^{cal} = \sum_i a_i e^{-x_i/v\tau_i} + b \quad . \tag{6}$$

γ_i^{cal} is a function of x_i. In the program, a_i, τ_i, and b are all determined when the curve is fitted to one, two, or three exponentials with or without a constant background.

All decay curves have been studied over a distance downstream from the foil far enough to assure good coverage of the long-lived cascading processes.

Generally every decay was followed into the noise of the photomultiplier or to the maximum distance (30 cm) allowed in the target chamber. Each decay curve contained at least 70 data points and was studied at a number of different incident particle energies in order to obtain good statistics and to assess the importance of blends and cascades which are energy-dependent.

Signal Averaging

The main advantage of a multichannel analyzer is the ability to do signal averaging. The fime for the foil to make one upstream and downstream sweep can be made very short in comparison with the foil lifetime (the time it takes before a foil is destroyed). In our system, 90 points in a one-way decay-measurement usually took less than one minute. Foils lasted from three minutes to as long as 2 hours depending on the energy, current, and atomic number of the beam particles.

By averaging, beam fluctuations, foil-aging effects (Bickel 1974), and different foil thickness variations were reduced in importance since the same conditions were well distributed over many channels and over many sweeps.

Since the foil-aging effect exists even in a one-direction sweep of the foil, we recorded both the downstream moving and the upstream moving foil sweeps independently. The counts in the channels taken during downstream moving and upstream moving are always slightly different. However, these foil aging effects which contribute to incorrect mean lives were eliminated by adding the downstream and upstream sweeps together before computer analysis.

Edge Effects At the Foil and Special Decays

Foil movement downstream, beyond the slit observation position gives channels which do not contain accurate information (true number of counts) about the early part of the decay. In fact, backscattering (Bashkin 1968b;

Bickel 1968a) can add intensities to some channels as the foil moves beyond the slit position, which makes intensity measurements "at the foil" more complicated. Both effects occur at the slit end of the decay curve. Without backscattering the length of the decay that is affected depends on the exact length of the beam observed and the exact foil location. The number of incomplete channels representing this early decay can be calculated giving the exact slit position and location of the first true intensity channel. When backscattering contributes to the intensity, the number of incomplete channels is unknown and the exact slit position is more difficult to define. Incomplete channels can be confused with special decays (Denis et al. 1968; Ceyzeriat et al. 1970; Poulizac, Druetta and Ceyzeriat 1971). For example, observing a 5 mm section of the beam and taking 90 beam points to measure a fast decay over a distance of 3 cm, gives 0.33 mm per channel. This arrangement will give 15-21 incomplete channels (corresponding to the foil moving beyond the slit position 2.5 - 4.5 mm) if backscattering is included. The initial part of the decay curve near t=0 will have a distorted shape which could be interpreted incorrectly as a "special decay".

In order to differentiate incomplete channels from special decays, we eliminated backscattering effects by masking the radiation coming from the upstream side of the foil. This gave a much steeper curve in the incomplete channel region near the foil, and permitted the exact location of the foil (x=0, t=0 point) to be determined. This technique completely blocks the backscattered light from the detector permitting accurate dark current and noise measurements.

Backlash of the foil holder at the starting end of the decay curve was eliminated by running a complete set-up sweep with the multichannel analyzer o. before starting the measurement. With backlash and backscattering under control, the only factors giving incomplete channels are the channel separation (channels per mm in target chamber) and the beam section observed. However, these can be determined exactly from the geometry of the system.

The net result of the above precautions and special procedures were obvious. The data were reproducible from run to run, foil to foil, and they were free of spurious effects that gave incorrect mean lives in the past. All mean lives reported here have been measured several times at several incident particle energies to keep track of energy-dependent effects such as line blending, energy loss, cascades, foil aging, and Rutherford scattering. Data for each mean life were accumulated often using as many as 24 foils making sure none were defective or broken at any time. The geometry of the grating-slit-beam-foil arrangement was exactly known and reproducible for each decay. By masking the grating, the length of beam observed could be varied from a section as small as 1 mm to one as large as 5 mm, giving a time resolution in the target chamber as small as 0.2 nsec. A cascade free mean life as short as 0.10 nsec could easily be measured.

Data for each decay curve were accumulated until statistics were good enough to give reproducible fits to all components of the decay. This procedure turned up cascades in virtually all decays measured. Even though previous measurements of a particular mean life have been done with the same technique, and often with the same or identical apparatus, our refinements have re-emphasized the importance of cascades and their effects on the data. Our experiments could easily resolve two mean lives differing by only 25%. In many cases it was easy to measure the three components of a decay curve and detect a fourth. Of course this depended on the relative intensity of the components at the t=0 point and their decay constants. However, many of the cascade contributions were finally verified by energy dependent studies where at lower energies two components would dominate a third weak component, whereas at higher energies, the relative contribution of the components would change. These studies were made being fully aware of the cascade problem. Therefore, we made special efforts to obtain the best decay curves that could be obtained by the beam-foil technique.

III. MEAN LIVES IN CARBON

Two mean lives in C II were measured. The line at λ904Å ($2s^2 2p\ ^2P^o$ - $2s2p^2\ ^2P$) has yielded from beam-foil measurements the mean life of the $2s2p^2\ ^3P$ level: 0.32 ± 0.03 ns (Heroux 1969), 0.34 ± 0.04 ns (Pegg, Dotchin and Chupp 1970), 0.25 ns (Poulizac and Buchet 1971), and our value of 0.30 ns. Poulizac and Buchet's (1971) is the only one fitted into three cascade components. All are a little higher than and in good agreement with the theoretical value quoted by Wiese, Smith, and Glennon (1966), 0.24 ± 0.12 ns; the value calculated by the method of superposition of configurations (Weiss 1967) 0.24 ± 0.06 ns; and the value calculated by (including electron correlation) Westhaus and Sinanoğlu (1969) 0.25 ns.

Our result, 0.48 ns at the line of λ1037Å ($2s^2 2p^2\ ^2P^o$ - $2s2p^2\ ^2S$), is in fair agreement with those of Poulizac and Buchet (1971), 0.41 ns; and Heroux (1969), 0.45 ± 0.03 ns; and the calculations of Weiss (1967), 0.43 ± 0.11 ns; and Westhaus and Sinanoğlu (1969) 0.44 ns.

Three mean lives in C III were measured. The calculations of Pfennig, Steele, and Irefftz (1965) are by the Roothanan version of the Hartree-Fock method. For triplet transitions the results seem fairly reliable, while for singlet transitions there are large deviations. Comparisons of upper level mean lives of the singlet transition $2s^2\ ^1S$ - $2s2p\ ^1P^o$ at λ977Å and the triplet transition $2s2p\ ^3P^o$ - $2p^2\ ^3P$ at λ1176Å are shown in Table I. Our experimental results match the lower of the theoretically-calculated values. For the upper level of the transition 2s2p $^1P^o$ - $2p^2$ ^1S at λ1247Å the theor--tical mean-life value is higher than our experimental value.

IV. MEAN LIVES IN NITROGEN

The mean life of the upper level in the N I transition at λ964Å ($2p^3$ $^4S^o$ - $2p^2 4s$ ^4P) was measured for the first time. No calculated theoretical value is available in the literature. It was needed for the abundance determination in the interstellar cloud, circumstellar shells and clouds in the direction of quasars (Morton and Smith 1973).

The λ1135Å transition ($2s^2 2p^3$ $^4S^o$ - $2s2p^4$ ^4P) of N I has been studied by Smith et al. (1970) and Berry et al. (1971) by using the beam-foil method and by Lawrence and Savage (1966) by the phase-shift method (mean life 7.2 ± 0.7 ns). All their results are cascade-free. Our measurement which paid detailed attention to the early decay showed a cascade-affected decay and yielded a transition probability twice their values, but close to those values obtained from theoretical calculations by Wiese et al. (1966) and Weiss (1967).

There were several calculations of the transition probability of the resonance line at λ1135Å ($2s^2 2p^3$ $^4S^o$ - $2s2p^4$ ^4P). In comparison with the beam-foil results of the values of Berry et al. (1971) and Smith et al. (1970), all the calculations are higher than experimental values. Westhaus and Sinanoğlu's (1969) value is twice as high as theirs; Varsavsky (1961), using a screened Coulomb potential, produced an even higher result. On the other hand, with the cascade correction, our value for the transition probability is twice as high as the value of Berry et al. (1971) and Smith et al. (1970) and is very close to the latest calculation (Westhaus and Sinanoğlu 1969).

The transition at λ1200Å was attributed to the $2p^3$ $^4S^o$ - $2p^2 3s$ ^4P transition of N I. Berry et al. (1971) made the first beam-foil measurement of the upper level. We found quite good agreement with their value which was cascade-free, while ours was not.

There are several results of experiments other than the beam-foil techniques: Labuhn (1965), by using the stabilized arc burning, got 2.8×10^8 sec^{-1}; and Lawrence and Savage (1966), by using phase shift, got 4.0×10^8 sec^{-1}. The theoretical calculations of Kelly and Armstrong (1962) using analytical Hartree-Fock wave functions yielded results different from the above-mentioned experiment by a factor of 1/2 or 1/3.

The N II transition at λ671Å ($2p^2$ ^3P - $2p3s$ $^3P^o$) has three previous beam-foil measurements (Heroux 1967; Smith et al. 1970; and Buchet et al. 1972) and one phase-shift measurement (Hesser and Lutz 1968), 0.9 ± 0.2 ns. All stated that the decay curve was a two-cascade component and all found a mean life of the upper level higher than the theoretical value given by Wiese et al. (1966).

Our experiment gave a three-cascade components decay curve and the main transition with mean life lower than the theoretical value given by Wiese et al. (1966). We suspect the transition giving the mean life 0.34 ns to be affected by blending since there is a blended transition of N II $2p^2$ ^3P - $2p3s$ $^1P^o$, at λ671Å also, which was predicted by Kelly and Palumbo (1973, p.30).

The upper level of the transition of N II ($2s^22p^2$ ^1D - $2s2p^3$ $^1D^o$) at λ776Å was found to have a mean life higher than the theoretical calculations of Wiese et al. (1966), 0.20 ns; of Westhaus and Sinanoğlu (1969), 0.2[illegible] ns, and of Hesser and Lutz (1968) phase-shift technique which was cascade free, 0.2 ns. Our result is in agreement with the two earlier beam-foil measurements.

The upper level of the transition ($2s^22p^2$ ^3P - $2s2p$ $^3P^o$) at λ916Å has a mean life of 0.82 ns, the same value as Smith et al. (1970), and both were analyzed for cascades. Heroux (1967) gave a mean life of 0.96 ns for this level and stated that the decay curve was a single exponential. Hesser and Lutz (1968), on the other hand, found a mean life of 0.4 ns in the presence of cascading. We can see from this example, that neglecting cascades gives a mean life higher than the true value. The recent calculation of Westhaus and Sinanoğlu (1969) gives a predicted mean life (0.86 ns) that is in very good agreement with our result and that of Smith et al.(1970) and is considerably superior in accuracy to the results quoted by Wiese et al. (1966).

All calculations and experimental results except the result quoted by Wiese et al. (1966) were found to be in good agreement with regard to the N II transition $2s^2 2p^2\ ^3P$ - $2s2p^3\ ^3D^o$ at λ1085Å. Westhaus and Sinanoğlu's calculation (1969) gave a mean life of 2.88 ns. Lawrence and Savage's phase-shift technique (1966) gave 2.7 ± 0.3 ns and was cascade free. Our experiment gave a decay curve that fits two cascade components with a main mean life of 2.70 ns. Other beam-foil measurements either cascade-free (Heroux 1967; Smith et al. 1970; Buchet et al. 1972) or "deduced cascade" (Berry et al. 1971) gave a mean life higher than the phase-shift value and our results.

The upper level decay times of the N III resonances at λ686Å ($2s^2 2p\ ^2P^o$ - $2s2p^2\ ^2P$) and at λ991Å ($2s^2 2p\ ^2P^o$ - $2s2p^2\ ^2D$) have been previously measured by Heroux (1967) and Buchet et al. (1972), using the beam-foil technique. Our result with main mean life 0.22 ns, and an extensive study of three cascade components fitting the λ686Å, confirmed the result of Buchet et al. Heroux' result (1967) of the resonance at λ991Å, cascade-free, gave mean life value a little higher than ours.

The levels decaying via the transitions ($2s^2\ ^1S$ - $2s2p\ ^1P^o$) at λ923Å of N IV gave mean lives in good agreement with earlier experimental studies (Heroux 1967; Buchet et al. 1972).

V. MEAN LIVES IN OXYGEN (INCLUDING BOWEN LEVELS)

The line at λ644Å is a blend of the O II and O III transition, $2s^2 2p^3\ ^2P^o - 2s2p^4\ ^2S$ and $2s2p^3\ ^3P^o - 2s^2 2p3p\ ^3S$. The beam-foil measurement of Martinson et al. (1971) gave a mean life 0.25 ± 0.03 ns, for the upper level which was corrected for cascade. The cascade mean life was not shown but was attributed to a level in O II. Our measurement gave a main mean life 0.23 ns which can be attributed in O II and "cascade" 2.95 ns which can be attributed to the level in O III.

For the O II transition, our results are in fair agreement with Westhaus and Sinanoğlu's calculation (1969) 0.21 ns. The value given by Wiese et al. (1966) of 0.14 ns, is lower than our value. The O III transition is not listed by Wiese et al. (1966) and Kelly and Palumbo (1973). Nussbaumer's (1969) calculation gave 2.28 ns, Berry et al. (1970) 2.9 ns, and Cardon et al. (1975) 2.81 ± 0.07 ns. Our result gave 2.95 ns through blended line measurement.

The O III $2p^2\ ^3P - 2p3s\ ^3P^o$ transition at λ374Å was previously studied by Pinnington et al. (1971) who measured a mean life of 0.30 ns for the upper level. Our measurement gave 0.37 ns for the mean life of the main component of the three cascade components detected. Both values are higher than the theoretical value 0.26 ns (Wiese et al.1966).

There are two calculations of the transition probability of the resonance line at λ508Å ($2s^2 2p^2\ ^3P - 2s2p^3\ ^3S^o$). The theoretical value of Wiese et al. (1966) is 150 x 10^8 sec^{-1}, which implies a mean life of 0.067 ns. Westhaus and Sinanoğlu gave 140 x 10^8 sec^{-1}, which implies a mean life of 0.072 ns. This mean life was apparently too short to be determined in our experiment. Pinnington et al. reported that they had masked the grating to get this very short mean life.

There are three previous beam-foil studies of the line at λ526Å ($2s^2 2p^2\ ^1D - 2s^2 2p^3\ ^1P^o$), whose upper level has theoretical mean life 0.10 ns. All three values and our results are higher than the theoretical value.

The strong line at λ599Å is a blend of two O III multiplets $2s^2 2p^2\ ^1S$ - $2s2p^3\ ^1P^o$ and $2s^2 2p^2\ ^1D$ - $2s2p^3\ ^1D^o$. The theoretical values of the mean lives of the upper levels given by Wiese et al. are 0.48 ns and 0.15 ns respectively. The recent theoretical values (Westhaus and Sinanoğlu 1969) are 0.51 ns and 0.26 ns. Our decay curve yielded the lifetimes of 0.21, 0.56, and 4.9 ns. The 0.21 ns and 0.56 ns can be attributed to the upper levels of the transitions $2s^2 2p^2\ ^1D$ - $2s2p^3\ ^1D^o$ and $2s^2 2p^2\ ^1S$ - $2s2p^3\ ^1P^o$, respectively, and they are in fair agreement with the above mentioned theoretical values. The measurement of Pinnington et al. (1971) also yielded three cascade components which can be attributed to the same transitions; however, their mean lives are slightly higher than ours.

The O III transition $2s2p^3\ ^3D^o$ - $2s^2 2p3p\ ^3P$ at λ574Å was listed by Kelly and Palumbo (1973) but not by Wiese et al. (1966). It is very weak and its upper level mean life has not been measured or calculated before. Our result gave a mean life of 7.56 ns for the upper level and the transition was cascade free.

The mean lives of the Bowen levels of O III were very carefully measured. The results of Cardon et al. (1975) were obtained by using a stationary foil measurement. Our results were obtained by using continuously-moving foil measurement.

The O III transition at λ644Å was blended with O II as was pointed out in the previous discussion of the O II transition at λ644Å. Cardon et al. (1975), by using differen+ energies in the 6 MV Van de Graaff accelerator, got different decay constants at different energies: 2.76 ns at 1.55 MeV and 2.40 ns at 3.0 MeV. For the transitions of the 3s $^3P^o_{2,1,0}$ - 3p $^3S_1$ multiplet, the mean lives of the upper levels at λ3341Å, λ3312Å, and the "spurious" mean lives (Berry et al. 1970) of the 3d $^3P^o$ levels at λ3133Å and 3122Å compare favorably with our values.

VI. CONCLUSION

In Smith's article (1973), "Oscillator Strengths of Astrophysical Interest for Lifetime Data", the importance of knowledge of the chemical abundances in the sun and stars was discussed. However, for many elements, there is an uncertainty of a factor of ten or more in the abundance (Withbroe 1971). Much of this uncertainty could be resolved, if accurate absolute f-values were available for these elements.

For example, the Bowen fluorescence mchanism has been investigated by many authors (Bowen 1928; Nussbaumer 1969; Weyman and Williams 1969; Berry et al. 1970; Weiss 1970; Harrington 1972; Cardon et al. 1975) regarding the discrepancy in experimentally measured and theoretically determined f-values The beam-foil mean-life measurements support this conflict between experiment and theory. The discrepancy between the theoretical and experimental results can not be considered resolved at this time.

There were many cases in which our detailed measurements of decay curves turned up cascades where others saw none. The cascades that did affect those lines and decays were not detected in the early experiments because those experiments were not accurate enough. In our experience, the cascade-free case (or non-linear decay case) is rare; possibly there are only two or three out of 100 mean lives measured. Because of the missing cascades in earlier experiments which we have seen in ours, many mean lives reported are higher than their true values.

Table 1

Mean lives in carbon

Ion	λ Listed (Å) See Footnote a	Transition (f - i)	Energy Observed (MeV)	This work: Upper Level	This work: Cascades
C II	904.09	$2s^2 2p\ ^2P - 2s2p^2\ ^2P$	0.52	0.30#	2.3
C II	1036.8	$2s^2 2p\ ^2P^o - 2s2p^2\ ^2S$	1.10	0.48#	6.4
C III	977.026	$2s^2\ ^1S - 2s2p\ ^1P^o$	1.01	0.50#	6.4
C III	1175.7	$2s2p\ ^3P^o - 2p^2\ ^3P$	1.15	0.77#	1.93
C III	1247.37	$2s2p\ ^1P^o - 2p^2\ ^1S$	1.15	0.56#	4.0

Mean Lives (10^{-9} sec)

λ (Å)	Other BF Experiments (See Footnotes): b	c	d	e	f	Theory (See Footnotes): a	g	h	i	Astrophysical Reference
904.09	0.34 ±0.04*	0.25**	0.32 ±0.03**			0.24†	0.25††	0.24††		j,k
1036.8		0.41*	0.45 ±0.03			0.91†	0.44††	0.43††		j,l,m
977.026		0.64*	0.66 ±0.03*			0.53†††			0.72	j,l
1175.7	0.79 ±0.02*	0.74*	0.80 ±0.04*	0.90*		0.77†††			0.83	j,k
1247.37		0.44*		0.45*	0.58 ±0.07	0.83†††				j

a Wiese, Smith, and Glennon (1966).

b Pegg, Dotchin, and Chupp (1970).

c Poulizac and Buchet (1971).

d Heroux (1969).

e Poulizac, Druetta, and Ceyzeriat (1971).

f Martinson and Bickel (1970).

g Westhaus and Sinanoğlu (1969).

h Weiss (1967).

i Pfennig, Steele, and Trefftz (1965).

j Burton and Ridgeley (1970).

k Dupree _et al._ (1973).

l Morton and Smith (1973).

m Bahcall and Wolf (1968).

* Decay curve corrected for cascades, two components.

** Decay curve corrected for cascades, three components.

† Uncertainty larger than 50%

†† Uncertainty within 25%.

††† Uncertainty within 50%.

\# Uncertainty ≤ 5%.

Table 2

Mean Lives in Nitrogen

Ion	λ Listed (Å)	Transition (f - i)	Energy Observed (MeV)	This work: Upper Level	This work: Cascades
N I	964.4[a]	$2p^3\ ^4S^o - 2p^24s\ ^4P$	0.40	$1.04^{\#\#}$	5.90,31.2
N I	1134.6[b]	$2s^22p^3\ ^4S^o - 2s2p^4\ ^4P$	0.40	$3.18^{\#}$	9.25
N I	1199.9[b]	$2p^3\ ^4S^o - 2p^23s\ ^4P$	0.40	$2.27^{\#}$	52.9
N II	671.48[b]	$2p^2\ ^3P - 2p3s\ ^3P^o$	1.03	$0.69^{\#\#}$	0.34,9.71
N II	775.957[b]	$2s^22p^2\ ^1D - 2s2p^3\ ^1D^o$	1.02	$0.52^{\#}$	2.52
N II	916.34[b]	$2s^22p^2\ ^3P - 2s2p^3\ ^3D^o$	1.10	$0.82^{\#}$	8.40
N II	1085.1	$2s^22p^2\ ^3P - 2s2p^3\ ^3D^o$	1.01	$2.70^{\#}$	7.30
N III	685.71[b]	$2s^22p\ ^2P^o - 2s2p^2\ ^2P$	1.09	$0.22^{\#\#}$	0.95,8.23
N III	990.98[b]	$2s^22p\ ^2P^o - 2s2p^2\ ^2D$	1.00	$1.52^{\#\#}$	2.90
N IV	765.14[b]	$2s^2\ ^1S - 2s2p\ ^1P^o$	1.50	$0.50^{\#}$	4.23
N IV	923.15[b]	$2s2p\ ^3P^o - 2p^2\ ^3P$	1.50	$0.60^{\#}$	2.77

Mean Lives (10^{-9}sec)

λ Listed (Å)	Other BF Experiments See footnote: c	d	e	f	Theory See footnote: b	g	h	i	Astro-physical Reference
964.4									j
1134.6			7.4 ± 0.4	7.0 ± 0.2	$4.35^{\dagger}$	3.6	0.55		j,k,l
1199.9				2.4 ± 0.1	$1.85^{\dagger}$			6.5	j,k,l,m
671.48	0.82*	1.01 ± 0.15*	1.08 ± 0.09*		$0.77^{\dagger\dagger}$				
775.957	0.60*		0.70 ± 0.07*		$0.20^{\dagger\dagger}$	0.28			k
916.34	0.77*	0.96 ± 0.05	0.82 ± 0.06*		$0.56^{\dagger\dagger}$	0.86			j
1085.1	3.2	2.92 ± 0.15	0.92 ± 0.17		$1.75^{\dagger\dagger}$	2.9			j,k,l,m,n,o
685.71	0.22**	0.17 ± 0.03			$0.42^{\dagger}$	0.18			l
990.98	2.2*	2.40 ± 0.24			$1.37^{\dagger\dagger}$	2.1			j,k,l,o
765.14	0.53*				$0.42^{\dagger}$		2.4		l
923.15	0.65*	0.70 ± 0.05*			$0.59^{\dagger}$				l

Table 2 (continued)
(Footnotes)

a Kelly and Palumbo (1973).

b Wiese, Smith, and Glennon (1966).

c Buchet, Poulizac, and Carré (1972).

d Heroux (1967).

e Smith et al. (1970).

f Berry et al. (1971)

g Westhaus and Sinanoğlu (1969).

h Varsavsky (1961)

i Kelly and Armstrong (1962)

j Morton and Smith (1973).

k Burton and Ridgeley (1970).

l Dupree et al. (1973).

m Morton et al. (1973).

n Smith (1972).

o Bahcall and Wolf (1968).

* Decay curve corrected for cascades, two components.

** Decay curve corrected for cascades, three components.

† Uncertainty within 50%.

†† Uncertainty larger than 50%.

Uncertainty ≤ 5%.

Uncertainty > 5%.

Table 3

Mean Lives in Oxygen (Including Bowen Levels)

Ion	λ Listed (Å)	Transition (f - i)	Energy Observed (MeV)	This Work: Upper Level	This Work: Cascades
O II	644.149[a]	$2s^22p^3\ ^2P^o - 2s2p^4\ ^2S$	1.00	0.23#	
O III	644.[b]	$2s2p^3\ ^3P^o - 2s^22p3p\ ^3S$			2.95
O III	374.12[a]	$2p^2\ ^3P - 2p3s\ ^3P^o$	1.02	0.37##	2.0,9.2
O III	507.93[a]	$2s^22p^2\ ^3P - 2s2p^3\ ^3S^o$	1.03	0.18##	1.85
O III	525.795[a]	$2s^22p^2\ ^1D - 2s2p^3\ ^1P^o$	1.00	0.21#	2.24
O III	597.888[a] 599.598[a]	$2s^22p^2\ ^1S - 2s2p^3\ ^1P^o$ $2s^22p^2\ ^1D - 2s2p^3\ ^1D^o$	1.00	0.21##	4.9,0.56
O III	574.065[b]	$2s2p^3\ ^3D^o - 2s^22p3p\ ^3P$	1.05	7.56#	
O III	3132.86[a]	$2p3p\ ^3S - 2p3d\ ^3P^o_1$	1.00	2.02#	15.3
O III	3121.71[a]	$2p3p\ ^3S - 2p3d\ ^3P^o_2$	1.00	2.12#	19.0
O III	3340.74[a]	$2p3s\ ^3P^o_2 - 2p3p\ ^3S$	1.00	3.90#	11.8
O III	3312.30[a]	$2p3s\ ^3P^o_1 - 2p3p\ ^3S$	1.00	2.65#	13.6

Mean Lives (10^{-9} sec)

λ Listed (Å)	Other BF Experiments See Footnote: c	d	e	f	g	h	i	Theory See Footnote: a	j	Astrophysical Reference
644.149			0.25±0.03*					0.14†	0.21	k,l
644.										
374.12	0.30*							0.26†		f
507.93	0.10*				0.105±0.012			0.067†	0.072	k
525.795	0.15**		0.37±0.05*		0.134±0.013			0.10†		k,m
597.888 599.598	0.28**		0.36±0.06*					0.48† 0.15†	0.51 0.26	m
574.065										m
3132.86				1.9±0.1		2.34*		7.35††		f
3121.71				1.9±0.1				7.25††		f
3340.74		2.87±0.07		2.9±0.2*		3.09	3.1	6.41†		f,n
3312.30		2.82±0.07		2.9±0.2*		2.76	3.5	6.41†		f,n

a Wiese, Smith, and Glennon (1966).

b Kelly and Palumbo (1973).

c Pinnington, Lin, Kernahan and Irwin (1971).

d Cardon, Leavitt, and Chang (1975).

e Martinson <u>et al</u>. (1971).

f Berry, Bickel, and Martinson (1970).

g Heroux (1968).

h Druetta and Poulizac (1969).

Table 3 (continued)

i Druetta, Poulizac, and Dufay (1971).

j Westhaus and Sinanoglu (1969).

k Dupree et al. (1973).

l Morton and Smith (1973).

m Burton and Ridgeley (1970).

n Bowen (1928).

* Decay curve corrected for cascades, two components.

** Decay curve corrected for cascades, three components.

† Uncertainty larger than 50%.

†† Uncertainty within 25%.

Uncertainty ≤ 5%.

Uncertainty > 5%.

References

Bahcall, John N. and Wolf, Richard A. 1968, Astrophys. J. 152, 701.

Bashkin, S. 1968. Beam-Foil Spectroscopy, Proceedings of 1st Intl. Conf. Tucson, Arizona (New York; Gordon and Breach).

Berry, H. G., Bickel, W. S., Martinson, I., Weymann, R. J., and Williams, R. E., 1970. Astrophys. Letters 5, 81.

Berry, H. G., Bickel, W. S., Bashkin, S., Desesquelles, J., and Schectman, R. M., 1971, J. Opt. Soc. Am. 61, 947.

Bickel, W. S. and Buchta, R., 1974. Physica Scripta 9, 148.

Bickel, William S. 1967. Appl. Opt. 6, 1309.

________. 1968a, in Beam-Foil Spectroscopy, Vol. I, p. 233 (S. Bashkin, ed., New York; Gordon and Breach).

________. 1968b. Appl. Opt. 7, 2367

________. 1974. Appl. Opt. 13, 1295.

Bowen, I. S. 1928, Astrophys. J. 67, 1.

Buchet, J. P., Poulizac, M. C., and Carré, M. 1972, J. Opt. Soc. Am. 62, 623.

Burton, W. M. and Ridgeley, A. R. 1970. Solar Phys. 14, 3.

Cardon, B. L., Leavitt, J. A., and Chang, M. W. 1975. Bull. Amer. Phys. Soc. 20, 679.

Ceyzeriat, P., Denis, A., Desesquelles, J., Druetta, M., and Poulizac, M. C. 1970. Nucl. Instr. and Meth. 90, 103.

Chupp, E. L., Dotchin, L. W., and Pegg, D. J. 1968. Phys. Rev. 175, 44.

Curtis, L. J., Schectman, R. M., Kohl, J. I., Chojnacki, D. A. and Shoffstall, D. R. 1970. Nucl. Instr. and Meth. 90, 207.

Denis, A., Desesquelles, J., Dufay, M., and Poulizac, M. C. 1968. In Beam-Foil Spectroscopy, Vol. I, p. 341 (S. Bashkin, ed., New York; Gordon and Breach).

Druetta, M. and Poulizac, M. C. 1969. Phys. Letters 29A, 651

Druetta, M., Poulizac, M. C., and Dufay, M. 1971. J. Opt. Soc. Am. 61, 515.

Dupree, A. K., Huber, M. C. E., Noyes, R. W., Parkinson, W. H., Reeves, E. M. and Withbroe, G. L. 1973. Astrophys. J. 182, 321.

Harrington, J. Patrick. 1972. Astrophys. J. 176, 127.

Heroux, L. 1967. Phys. Rev. 153, 156.

_______. 1968. In Beam-Foil Spectroscopy, Vol. I, p. 205 (S. Bashkin, ed., New York; Gordon and Breach)

_______. 1969. Phys. Rev. 180, 1.

Hesser, James E. and Lutz, Barry L. 1968. J. Opt. Soc. Am. 58, 1513.

Kelly, P. S. and Armstrong, B. H. 1962. Phys. Rev. Letters 9, 426.

Kelly, Raymond L. and Palumbo, Louis J. 1973. In Atomic and Ionic Emission Lines below 2000 Angstroms: Hydrogen Through Krypton, (Naval Research Laboratory Report, Washington, D.C.; U.S. Govt. Printing Office).

Labuhn, Franz. 1965. Zeits. fur Natur. 20a, p. 998.

Lawrence, C. M. and Savage, Blair D. 1966. Phys. Rev. 141, 67.

Martinson, I., Berry, H. G., Bickel, W. S. and Oona, H. 1971. J. Opt. Soc. Am. 61, 519.

Morton, Donald C. and Smith, Wm. Hayden. 1973. Astrophys. J. Suppl. Ser. 26, 330.

Nussbaumer, H. 1969. Astrophys. Letters 4, 183.

Pegg, D. J., Dotchin, L. W. and Chupp, E. L. 1970. Phys. Letters 31A, 501.

Pfennig, H., Steele, R., and Trefftz, E. 1965. J. Quant. Spectr. Rad. Transfer 5, 535.

Pinnington, E. H., Lin, C. C., Kernahan, J. A., and Irwin, J. G. 1971. Phys. Letters 36A, 299.

Poulizac, M. C. and Buchet, J. P. 1971. Physica Scripta 4, 191.

Poulizac, M. C., Druetta, M., and Ceyzeriat, P. 1971. J. Quant. Spectr. Rad. Transfer 11, 1087.

Smith, Andrew M. 1972. Astrophys. J. 176, 405.

Smith, Peter L. 1973. Nucl. Instr. and Meth. 110, 395.

Smith, Wm. Hayden, Bromander, J., Curtis, L. J., and Buchta, R. 1970. Physica Scripta 2, 211.

Varsavsky, Carlos M. 1961. Astrophys. J. Suppl. Ser. 7, 75.

Weiss, A. W. 1967. Phys. Rev. 162, 71.

_______. 1970. Nucl. Instr. and Meth. 90, 121.

Westhaus, Paul and Sinanoğlu, Oktay. 1969. Phys. Rev. 183, 56.

Wiese, W. L. 1970. Nucl. Instr. and Meth. 90, 25.

Wiese, W. L., Smith, M. W., and Glennon, B. W. 1966. Atomic Transition Probabilities - Hydrogen Through Neon (NBS Standard Reference Data Series, Vol. 1, No. 4.

Withbroe, George L. 1971. In The Menzel Symposium on Solar Physics, Atomic Spectra, and Gaseous Nebulae, p. 127. (Katharine B. Gebbie, ed. NBS Spec. Publ. 353 (CODEN: XNBSA)).