

EXPERIMENTAL TRANSITION RATE OF THE GREEN CORONAL LINE OF Fe XIV

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Received 2002 July 25; accepted 2003 January 2

ABSTRACT

The transition probability of the electric dipole forbidden transition in the ground state of Fe XIV (Al-like), the “green coronal line” at 5302.86 Å, has been measured using the Livermore electron beam ion trap. Our result for the $3s^23p^2\ ^2P^o_{3/2}$ atomic level lifetime is 16.74 ± 0.12 ms, which differs significantly from an earlier measurement, and is the most accurate one to date. The measured transition rate of 59.7 ± 0.4 s⁻¹ corroborates some earlier calculations, but not all of the more recent ones.

Subject headings: atomic data — methods: laboratory — Sun: corona — techniques: spectroscopic

1. INTRODUCTION

Electric-dipole forbidden transitions between the fine structure levels of the ground configuration of ions are the origin of many of the solar coronal lines (Edlén 1942; Wagner & House 1968; Eidelsberg et al. 1981) and are of great interest for plasma diagnostics (Edlén 1984). Iron is the heaviest element that appears with a relatively high abundance in the Sun. In the solar corona, emission lines from many ionization stages of Fe are present. Among the most prominent coronal lines in the visible spectrum are the “red” and “green” lines of iron, which originate from the $3s^23p^5\ ^2P^o\ J = 3/2$ to $J' = 1/2$ transition in the Cl-like ion Fe⁹⁺ (Fe X) and the $3s^23p\ ^2P^o\ J = 1/2$ – $J' = 3/2$ transition in the Al-like ion Fe¹³⁺ (Fe XIV), with wavelengths of 6374.6 and 5302.86 Å (Kaufman & Sugar 1986), respectively. These transitions are $n = 3$ shell equivalents to the $n = 2$ shell transitions in the B- and F-like ions of Cl, Ar, and K, which are also seen in the solar corona and on which we have reported earlier (Träbert et al. 2000, 2001, 2002a).

The lines have been seen in the spectrum of the Sun where they served, for example, in coronal hole studies (Fisher & Musman 1975; Esser et al. 1995), for large-scale temperature diagnostics (Guhathakurta, Fisher, & Altrock 1993) as well as for polarization measurements. They have also been observed in symbiotic stars (Wallerstein & Brugel 1988), in Seyfert galaxies (Osterbrock 1981), supernova remnants (Woodgate et al. 1974; Woodgate, Angel, & Kirshner 1975; Lucke et al. 1979; Itoh 1979; Lucke et al. 1980; Brown, Woodgate, & Petre 1988), as interstellar absorption lines (Hobbs 1984), and in a cooling flow cluster (Anton, Wagner, & Appenzeller 1991).

The large interest in the iron coronal lines is reflected in a number of calculations (Krueger & Czyzak 1966; Warner 1968; Smith & Wiese 1973; Kastner 1976; Kafatos & Lynch 1980; Eidelsberg et al. 1981; Huang et al. 1983; Froese Fischer & Liu 1986; Huang 1986; Kaufman & Sugar 1986; Lynch & Kafatos 1991; Bhatia & Kastner 1993; Bhatia & Doschek 1995) of the radiative rates. Interestingly, most of the transition rate predictions for a given line lie in a narrow

interval. Some of the latest calculations (Bhatia & Kastner 1993; Bhatia & Doschek 1995), however, differ drastically from the others, increasing the need for good experimental values to guide calculations. It should be noted that most of the calculations have been adjusted for the experimental term differences, which *ab initio* calculations cannot yet deliver with spectroscopic precision. Even for such adjusted transition rate predictions, the usual theoretical uncertainty estimates are in the 10%–20% range.

Only a single experiment has reported measurements of the transition rates of interest. Moehs & Church (1999) used an electrostatic ion trap to capture, store, and study multiply charged ions of Fe from an electron cyclotron resonance ion source (ECRIS). Their results differed markedly from the recent calculations by Bhatia & Doschek (1995; on Fe X) and by Bhatia & Kastner (1993; on Fe XIV). Although closer to the older calculations, their results differed well beyond the error estimates from these predictions as well.

Our measurements on coronal lines of Ar (Träbert et al. 2000) indicated systematic errors in the Ar measurements of Moehs & Church (1998) that were unaccounted for. The same systematic errors may play a role in their Fe measurements. In fact, recent Fe data from a heavy-ion storage ring (Träbert et al. 2002b) are at variance with the corresponding results obtained by Moehs et al. (2001) using an electrostatic ion trap. In order to address this possibility, we have measured the green Fe XIV line with our apparatus, which has been carefully checked for systematic errors. We indeed find a value for the transition rate that differs from the one reported by Moehs & Church (1999) by more than the combined error bars. Moreover, our result is in good agreement with most of the calculations.

2. EXPERIMENT

Our measurements were carried out at the University of California Lawrence Livermore National Laboratory, using the EBIT-I electron beam ion trap. The actual ion trap region in EBIT-I was imaged using a “stovepipe” spectrometer (Träbert & Beiersdorfer 2003) onto the photodetector, a low dark rate (2 counts s⁻¹), half-inch (1.27 cm) diameter, end-on-cathode photomultiplier. In this way the photomultiplier could be operated outside the stray magnetic fields of the 3 T superconducting magnet of the EBIT-I device, while at the same time subtending a sizeable solid

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angle of observation. In optical spectra from an electron beam ion trap, the M1 transitions usually stand out among the most intense. Thus, interference filters (5300 Å, 6400 Å) with typical peak transmission 70% and 100 Å bandwidth (FWHM) were deemed sufficient for spectral selectivity. Unfortunately, the photomultiplier was not sensitive enough at the wavelength of the red line, so that only data on the Fe xiv line could be obtained.

For the lifetime measurements, EBIT-I was operated in a cyclic mode. The electron beam was switched on for about 0.06 s, ionizing and exciting the ion cloud in the trap. Then the electron beam was switched off, and the trap was maintained for about 0.14 s as a Penning trap in the so-called magnetic trapping mode (Beiersdorfer et al. 1996). Finally, the accumulated ion cloud was purged from the trap. The switching time of the electron beam ($\approx 30 \mu\text{s}$) was much faster than the lifetime of the level of interest.

The true signal rate for Fe xiv was as high as 20,000 counts hr^{-1} . In total, more than 8×10^5 counts above background were accumulated in the decay curve part of the combined data from all measurements. The number of clock pulses (from a continuously running 100 kHz frequency generator) in the time interval between receiving a reference signal (starting the trap cycle) and the arrival of a photon signal pulse was stored as the time information in an event mode system (Beiersdorfer et al. 2001).

EBIT-I was operated under ultrahigh vacuum conditions ($p \lesssim 10^{-10}$ torr outside the trapping region and less than that inside). Fe was continually being bled into the trap as a molecular compound (iron pentacarbonyl), via a leak valve and a set of collimating apertures in a ballistic gas injection system. This compound had been successfully used before by Brown, Beiersdorfer, & Widmann (2001) for measuring Fe xvi and Fe xvii lines. The injection pressure was 5×10^{-9} torr. The overall pressure measured in the chambers surrounding the trap region changed very little when admitting the iron compound, showing that the gas injection caused only a small contribution to the overall gas load.

Charge exchange with neutral background gases is the dominant ion-loss mechanism in the magnetic trapping mode (Beiersdorfer et al. 1996). The pressure in the trap region, and thus the amount of background gas, cannot be measured directly. Hence, ion loss had to be determined differently. Keeping all trap parameters constant, the electron beam energy was raised to 1450 eV in order to produce Fe ions with an open L shell (Fe^{17+} , Fe^{18+}). Charge exchange involving these ions produced L-shell X-rays, which could be monitored with an IGLET X-ray detector during the beam “off” period. The signal rate was assumed to be proportional to the number of ions in the trap, and a survival time constant of the stored ions of about 5 s was derived.

We have developed our assessment of systematic errors with the study of precisely calculable atomic systems (for example, the lifetime of the $1s2s\ ^3S_1$ level in helium-like ions (Wargelin, Beiersdorfer, & Kahn 1993; Beiersdorfer et al. 1996; Crespo López-Urrutia et al. 1998; Träbert et al. 1999; Neill et al. 2000) and in correspondence with experiments that employ the heavy-ion storage ring technique (Schmidt et al. 1994; Schmidt 1994). As a result, we feel certain that the systematic errors are under control at a comparable level for this optical measurement as well. A number of parameters were varied in precursor experiments as well as during the present measurements in order to find out about

possible systematic errors. The electron beam energy was varied from below production threshold (the ionization energy of 392 eV of the next lower charge state ion) to a few hundred volts above. In practice, Fe xiv data were recorded at energy settings in the range from 550 to 1100 eV. At higher electron beam energies, ions of the next higher charge state(s) may be produced. However, the ionization rates were kept low because of the rather low electron beam ion currents (4–10 mA) and the short time interval during which ionization may occur in our measurements severely limited the abundance of higher ionization states. Thus, the optical signal rate from the wanted ion reaches its optimum for beam energies higher than those necessary in steady state plasmas. The electron beam current was kept low in order to keep ion heating processes in the trap at bay, since they would have increased the rate coefficients for ion loss by charge exchange. Each time, the decay curve data was collected until a statistical reliability of roughly 1% was ascertained. A total of six such curves was collected for Fe xiv.

3. DATA ANALYSIS AND RESULTS

Typical decay curve data are shown in Figure 1. The raw data contain some background from the detector dark rate and possibly from stray light (from the hot electron gun) falling into the narrow filter range. In the analysis the background was treated as flat. The results from fitting a single exponential with a constant offset to each of the six decay curves is shown in Figure 2. The statistical average (weighing each measurement by its statistical error) and the 1σ error estimate (0.35%) are indicated by the solid and dashed lines, respectively. The average shown does not yet account for systematic effects. Measured trapping times close to 5 s required systematic corrections of the raw lifetime results by

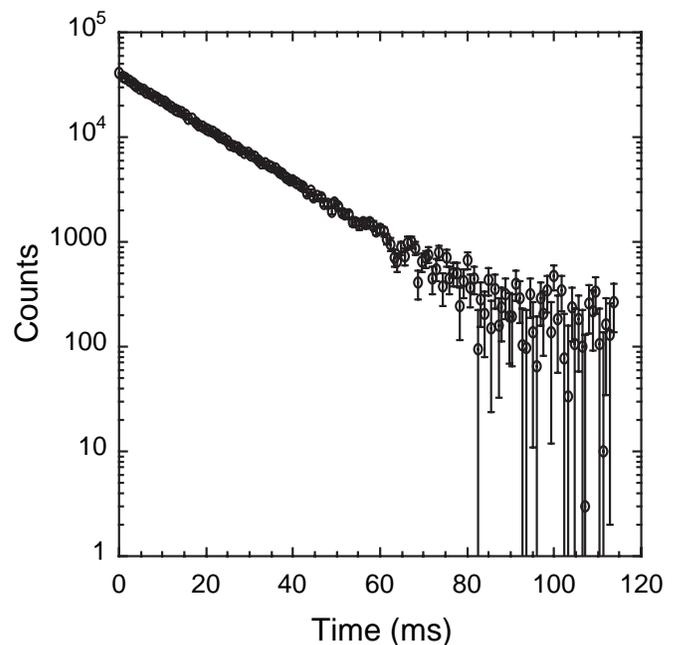


FIG. 1.—Photon signal (logarithmic scale) obtained with Fe xiv. Only the decay part of the full data, after switching off the electron beam, is being displayed. A background of 16000 counts per channel has been subtracted from the data.

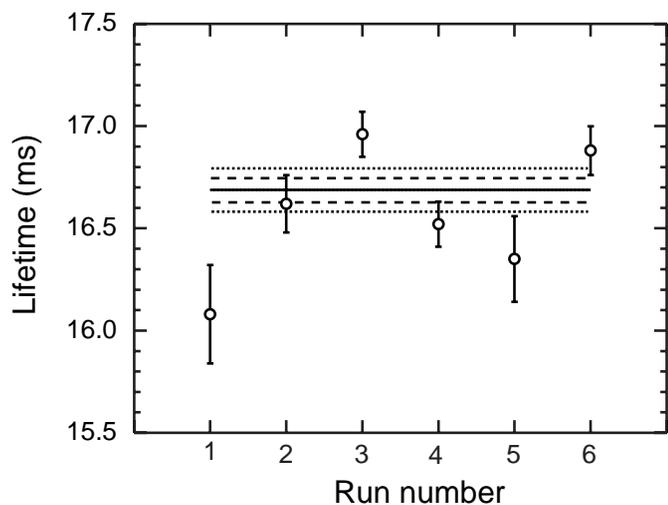


FIG. 2.—Inferred lifetime values from six separate data sets. The weighted average is indicated by the solid line. *Dashed lines*: Uncertainty due to counting statistics; *dotted lines*: uncertainty due to statistical and systematic errors, as discussed in the text.

0.3%, and this systematic correction must be included in the final result.

Second decay components, to be associated with either spectral blends or cascade transitions, were tried in multi-exponential fits, but were not corroborated. This lack of a second discernable exponential decay component agrees with calculations we made showing that possible cascade contributions from higher lying levels are negligible. A discussion of these theoretical estimates is given in the next section.

The fit algorithms included those with and without human choice of start parameters. The variation of the fit results when truncating early or late parts of the decay curve data (by up to 5 ms) was about 0.2% and thus remained within the statistical uncertainty.

The scatter of the six individual measurements in Figure 2 from their mean is roughly consistent with statistical expectations, especially when factoring in the roughly 0.2% uncertainty associated with the choice of different fitting parameters. Nevertheless, we investigated the possibility of nonstatistical variations in the decay results. Among the reasons for possible, nonstatistical scatter may be variations of the charge-exchange-induced ion-loss time and variations in the stray light contribution to the background. The charge-exchange-induced ion-loss time was measured twice, giving values of 6.9 ± 0.6 and 4.1 ± 0.4 s. Thus, the overall correction from charge-exchange-induced ion loss is about 0.3%. Scatter induced by variations in the ion loss are thus assumed to be no larger than this value. Stray light originates from the hot filament of the electron gun. In other measurements we have observed time-varying contributions to the decay signal that appeared only at high electron-gun heating and extracted-electron beam currents. We therefore used low electron-gun parameter settings in the present experiment for which variations are estimated to be at the 0.3% level or better. Combining these sources of potential scatter of the results with the statistical uncertainty, we obtain a 1σ uncertainty of 0.57%. These uncertainty limits are indicated as dotted lines in Figure 2.

The lifetime of the Fe xiv line we infer from the six data sets is 16.69 ± 0.10 ms. Adjusting this value by the ion-loss correction yields the final value of 16.74 ± 0.12 ms. Here we assumed that the error of the ion-loss correction is half of the overall value, i.e., 0.15%. We added this linearly to the overall uncertainty. The corresponding transition rate is $59.7 \pm 0.4 \text{ s}^{-1}$.

4. DISCUSSION

The identification of the measured lifetime with the level of interest assumes that there is no other decay of a similar time constant in any of the ions in the trap that would lead to radiation within the bandpass of the filter, and that the decay curve is not being affected by cascade contributions within the same ion. No other spectral line of comparable parameters is known in this or a neighboring ion that would radiate within the present detection range, and we rule out contributions from such blending.

The situation is more complex within the same spectrum, Fe xiv. A multitude of levels exists in the $3d^k$ configurations (with $k > 1$) about which no experimental information is available. However, these levels represent multiple excitations from the ground configuration, and such levels are hardly produced under electron beam ion trap conditions of low particle density. Consequently, single excitation from the ground state (with fine structure levels of $J = 1/2$ and $J = 3/2$) is bound to reach only low J levels that easily decay back to the ground state and that thus feature level lifetimes in the picosecond range, if not shorter.

There is just one level, $3s3p3d^4F^o J = 9/2$, that may be considered as singly excited and that also has a longer lifetime, because it features M1 and M2 decay channels only. Apparently the lifetime of this level has not been covered in any published theoretical study. We therefore performed our own calculations using several codes, for example the Grant code version GRASP92 (Parpia et al. 1996). These calculations comprised the $n = 3$ complex up to $3d^3$ configurations and came close to the results of dedicated published calculations for the energies of the low-lying levels as well as for the M1 transition rate within in the ground term. The M2 decay branch from the $3s3p3d^4F_{9/2}^o$ level to the $3s3p^2^4P_{5/2}$ level was found to dominate (about 60% of the total) over the M1 decay to the $3s3p3d^4F_{7/2}^o$ level. Via further (much faster) steps the level population then also reaches the level of present interest, $3s^23p^2P_{3/2}^o$ in the ground configuration. The lifetime of the upper level was calculated to be near 19 ms, which is close to the one of primary interest (just below 17 ms). Such close-lying time components cannot be separated in any multiexponential fit. If the cascade from the $3s3p3d^4F_{9/2}^o$ level was important, it would make the lifetime of the level of interest appear somewhat longer than it really is.

We note that the $3s3p3d^4F_{9/2}^o$ level cannot be reached by any monopole or dipole excitation from the ground state. This already indicates that the level is not likely to be strongly populated. To check this, we made electron-impact excitation calculations of all levels in the $n = 3$ complex for three different electron energies using the FAC code by Gu (2003). Our calculations indicate that the excitation cross sections of the $J = 9/2$ level are lower than those of the level of interest by about 4–5 orders of magnitude. Moreover, the readily excited low J levels decay to other low J levels and thus replenish the level of interest (rapidly), while very little

TABLE 1

PREDICTED AND MEASURED TRANSITION RATES OF THE GREEN CORONAL LINE $\lambda 5302.86 \text{ \AA}$ OF Fe XIV AND UPPER-LEVEL LIFETIME τ

A (s^{-1})	τ (ms)	Trap Type	Reference
Theory			
60.06	16.65	...	1
60.3	16.58	...	2
60.3	16.58	...	3
60.23	16.60	...	4
60.056	16.65	...	5
60.20	16.61	...	6
50.5	19.8	...	7
60.04	16.66	...	8
60.2	16.6	...	9
60.54	16.52	...	10
46.77	21.38	...	11
Experiment			
(57.08 ± 1.05)	(17.52 ± 0.29)	EKT ^a	12
(59.7 ± 0.4)	(16.74 ± 0.12)	EBIT ^b	13

^a Electron cyclotron resonance ion source plus Kingdon ion trap.^b Electron beam ion trap (at Lawrence Livermore National Laboratory).

REFERENCES.—(1) Krueger & Czyzak 1966; (2) Warner 1968; (3) Smith & Wiese 1973; (4) Kastner 1976; (5) Kafatos & Lynch 1980; (6) Eidelsberg et al. 1981; (7) Froese Fischer & Liu 1986; (8) Huang 1986; (9) Kaufman & Sugar 1986; (10) Biémont et al. 1988; (11) Bhatia & Kastner 1993; (12) Moehs & Church 1999; (13) This work.

cascade repopulation reaches the $J = 9/2$ level. This situation is different in beam-foil excitation, which favors the population of high J levels (Träbert et al. 1993). For our electron beam ion trap work we conclude that the only singly excited long-lived level available does not contribute to the decay curve of the level of interest in any amount detectable by present means.

The present result for Fe XIV disagrees with the experimental result presented by Moehs & Church (1999) by more than the combined error limits (Table 1 and Fig. 3). Comparing with theory, our result turns out to be in agreement

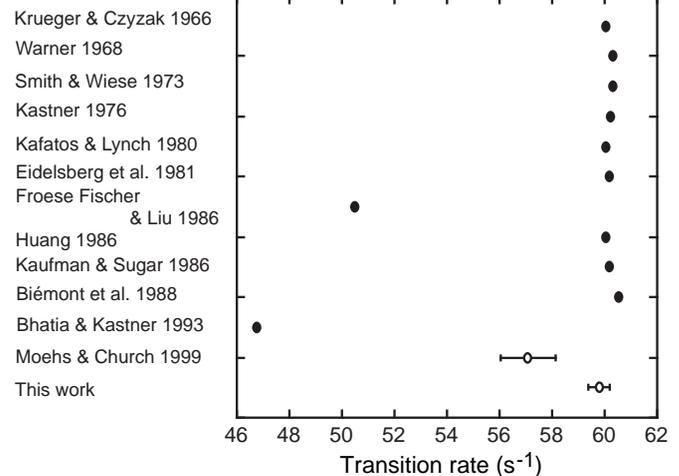


FIG. 3.—Transition rates in the ground term of Fe XIV. Entries without error bars (*filled circles*) represent calculational results; entries with error bars (*open circles*) are for experimental data.

with most of the predictions, with the notable exceptions of an ab initio calculation by Froese Fischer & Liu (1986) and the calculations by Bhatia & Kastner (1993). This also raises concern about the results of a rather similar calculation for Fe X (Bhatia & Doschek 1995), which similarly deviate from the majority of calculated radiative rates. It may well be advisable to use the results of earlier calculations on that transition in Fe X until a reliable experimental lifetime value becomes available.

The work at Lawrence Livermore National Laboratory was performed under the auspices of the Department of Energy under contract W-7405-Eng-48 and was supported in part by NASA's Space Astrophysics Research and Analysis program under work order W19,878. E. T. acknowledges travel support from the German Research Association (DFG). E. H. P. received support by Natural Sciences and Engineering Research Council of Canada.

REFERENCES

- Anton, K., Wagner, S., & Appenzeller, I. 1991, *A&A*, 246, L51
 Beiersdorfer, P., Brown, G. V., Hildebrandt, L., Wong, K. L., & Ali, R. 2001, *Rev. Sci. Instrum.*, 72, 508
 Beiersdorfer, P., Schweikhard, L., Crespo López-Urrutia, J., & Widmann, K. 1996, *Rev. Sci. Instrum.*, 67, 3818
 Bhatia, A. K., & Doschek, G.A. 1995, *At. Data Tables Nucl. Data Tables*, 60, 97
 Bhatia, A. K., & Kastner, S. O. 1993, *J. Quant. Spectrosc. Radiat. Transfer*, 49, 609
 Biémont, E., Cowan, R. D., & Hansen, J. E. 1988, *Phys. Scr.*, 37, 850
 Brown, G. V., Beiersdorfer, P., & Widmann, K. 2001, *Phys. Rev. A*, 63, 032719
 Brown, L. W., Woodgate, B. E., & Petre, R. 1988, *ApJ*, 334, 852
 Crespo López-Urrutia, J. R., Beiersdorfer, P., Savin, D. W., & Widmann, K. 1998, *Phys. Rev. A*, 57, 238
 Edlén, B. 1942, *Z. Astrophys.*, 22, 30
 ———. 1984, *Phys. Scr.*, 8, 5
 Eidelsberg, M., Crifo-Magnant, F., & Zeippen, C. J. 1981, *A&AS*, 43, 455
 Esser, R., Brickhouse, N. S., Habbal, S. R., Altrock, R. C., & Hudson, H. S. 1995, *J. Geophys. Res.*, 100, 19829
 Fisher, R., & Musman, S. 1975, *ApJ*, 195, 801
 Froese Fischer, C., & Liu, B. 1986, *At. Data Nucl. Data Tables*, 34, 261
 Gu, M.-F. 2003, *ApJ*, 582, 1241
 Guhathakurta, M., Fisher, R. R., & Altrock, R. C. 1993, *ApJ*, 414, L145
 Hobbs, L. M. 1984, *ApJ*, 284, L47
 Huang, K.-N. 1986, *At. Data Nucl. Data Tables*, 34, 1
 Huang, K.-N., Kim, Y.-K., Cheng, K. T., & Desclaux, J. P. 1983, *At. Data Nucl. Data Tables*, 28, 355
 Itoh, H. 1979, *Nature*, 28, 656
 Kafatos, M., & Lynch, J.P. 1980, *ApJS*, 42, 611
 Kastner, S. O. 1976, *Sol. Phys.*, 46, 179
 Kaufman, V., & Sugar, J. 1986, *J. Phys. Chem. Ref. Data*, 15, 321
 Krueger, T. K., & Czyzak, S. J. 1966, *ApJ*, 144, 1194
 Lucke, R. L., Gull, T. R., Woodgate, B. E., & Socker, D. G. 1980, *ApJ*, 235, 882
 Lucke, R. L., Woodgate, B. E., Culhane, J. L., Socker, D. G., & Zarnecki, J. C. 1979, *ApJ*, 228, 763
 Lynch, J. P., & Kafatos, M. 1991, *ApJS*, 76, 1169
 Moehs, D. P., & Church, D. A. 1998, *Phys. Rev. A*, 58, 1111
 ———. 1999, *ApJ*, 516, L111
 Moehs, D. P., Idrees Bhatti, M., & Church, D. A. 2001, *Phys. Rev. A*, 63, 032515
 Neill, P. A., Träbert, E., Beiersdorfer, P., Brown, G. V., Harris, C. L., Smith, A. J., Utter, S. B., & Wong, K. L. 2000, *Phys. Scr.*, 62, 141
 Osterbrock, D. E. 1981, *ApJ*, 246, 696
 Parpia, F. A., Fischer, C. F., & Grant, I. P. 1996, *Comput. Phys. Commun.*, 94, 249
 Schmidt, H. T. 1994, Ph.D. thesis, Aarhus

- Schmidt, H. T., et al. 1994, *Phys. Rev. Lett.*, 72, 1616
Smith, M. W., & Wiese, W. L. 1973, *J. Phys. Chem. Ref. Data*, 2, 85
Träbert, E., & Beiersdorfer, P. 2003, *Rev. Sci. Instrum.*, 74, 2127
Träbert, E., Beiersdorfer, P., Brown, G. V., Chen, H., Thorn, D. B., & Biémont, E. 2001, *Phys. Rev. A*, 64, 034501
Träbert, E., Beiersdorfer, P., Brown, G. V., Smith, A. J., Utter, S. B., Gu, M. F., & Savin, D. W. 1999, *Phys. Rev. A*, 60, 2034
Träbert, E., Beiersdorfer, P., Gwinner, G., Pinnington, E. H., & Wolf, A. 2002a, *Phys. Rev. A*, 66, 052507
Träbert, E., Gwinner, G., Wolf, A., Knystautas, E. J., Garnir, H.-P., & Tordoïr, X. 2002b, *J. Phys. B*, 35, 671
Träbert, E., Wagner, C., Heckmann, P. H., Möller, G., & Brage, T. 1993, *Phys. Scr.*, 48, 593
Träbert, E., et al. 2000, *ApJ*, 541, 506
Wagner, W. J., & House, L. L. 1968, *Sol. Phys.*, 5, 55
Wallerstein, G., & Brugel, E. W. 1988, *A&A*, 197, 182
Wargelin, B. J., Beiersdorfer, P., & Kahn, S. M. 1993, *Phys. Rev. Lett.*, 71, 2196
Warner, B. 1968, *Z. Astrophys.*, 69, 399
Woodgate, B. E., Angel, J. R. P., & Kirshner, R. P. 1975, *ApJ*, 200, 715
Woodgate, B. E., Stockman, H. S., Angel, J. R. P., & Kirshner, R. P. 1974, *ApJ*, 188, L79