The Astrophysical Journal, 541:506–511, 2000 September 20

EXPERIMENTAL M1 TRANSITION RATES OF CORONAL LINES FROM Ar x, Ar xiv, AND Ar xv

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Received 2000 March 20; accepted 2000 May 9

ABSTRACT

Transition probabilities of three magnetic dipole (M1) transitions in multiply charged ions of Ar have been measured using the Livermore electron-beam ion trap. Two of the transitions are in the ground configurations of Ar xiv (B-like) and Ar ix (F-like), and are associated with the coronal lines at 4412.4 and 5533.4 Å, respectively. The third is in the excited $2s2p$ configuration of Be-like Ar xv and produces the coronal line at 5943.73 Å. Our results for the three atomic level lifetimes are 9.32 ± 0.12 ms for the Ar x $2s^22p^5\ ^2P^o_{1/2}$ level, 9.70 ± 0.15 ms for the Ar xiv $2s^22p\ ^2P^o_{3/2}$ level, and 15.0 ± 0.8 ms for the Ar xv $2s2p\ ^3P^o_2$ level. These results differ significantly from earlier measurements and are the most accurate ones to date.

Subject headings: atomic data — methods: laboratory

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; Eidelsberg, Crifo-Magnant, & Zeippen 1981) and are of great interest for plasma diagnostics (Edlén 1984). Among the simplest systems producing coronal lines are the B- and F-like ions, featuring just a single such line each, which correspond to the $2s^22p\ ^2P^o_{1/2}$–$^2P^o_{3/2}$ and $2s^22p^5\ ^2P^o_{3/2}$–$^2P^o_{1/2}$ transitions, respectively. These lines have been observed in the ions of many elements, and their wavelengths have been systematized by Edlén and others (Edlén 1981, 1982, 1980; Curtis 1982).

In addition to these transitions within the ground configuration, forbidden transitions between excited levels are also of interest. The simplest systems with such (measurable) transitions are the four-electron ions, i.e., Be-like ions. For this isoelectronic sequence, too, Edlén provided a systematic analysis of the atomic structure data (Edlén 1980, 1985). For low charge state ions of this sequence, the $2s2p\ ^3P^o_2$ level predominantly decays via magnetic quadrupole (M2) transition to the singlet ground state, $2s^2\ ^1S_0$. Further along the isoelectronic sequence, beyond $Z = 12$, the M1 decay branch to the $2s2p\ ^3P^o_1$ level dominates by several orders of magnitude (Shorer & Lin 1977; Tunnell & Bhalla 1979).

All cases mentioned so far give rise to coronal lines from argon ions. The associated wavelengths are 4412.4, 5533.4, and 5943.73 Å for B-like Ar xiv, F-like Ar x, and Be-like Ar xv, respectively (Kaufman & Sugar 1986; Bieber et al. 1997). Besides the general context of forbidden coronal lines in all spectral ranges (recently discussed, e.g., by Greenhouse et al. 1993), there are abundance and abundance ratio measurements (Young et al. 1997) that involve the Ar lines of present interest. Also, Ar (as He and Ne) has no photospheric lines, nor is it found in meteorites, and the solar abundance determination thus depends on the evaluation of coronal spectra and on the precision and reliability of the atomic data that are needed for the procedure.

The transition probability of electric dipole forbidden decays is an atomic property that is useful for elemental density determinations from absolute emission measurements. It depends mostly on angular coupling factors and the energy interval (Curtis 1984). The energy interval is typically much better known from experiment than can be calculated, and the calculation of the transition rate adds further uncertainty. In order to reduce the energy-related uncertainty of the calculated transition rates, it is common nowadays to adjust the calculated energy intervals to the experimental data. However, the extent of involved calculations and the scatter of the results reveal that reliable calculations are still much more difficult than was perceived for a long time. However, once sufficiently precise measurements exist to test such calculations of the transition probability, theory can then with greater confidence predict transition rate data for more complex cases or for transitions that are not readily amenable to similarly precise lifetime measurements.

The interest in the transitions studied here is reflected in the number of published calculations (for B-like ions, e.g., Krueger & Czyzak 1966; Cheng, Kim, & Desclaux 1979; Oboladze & Safronova 1980; Vajed-Samii, Ton-That, & Armstrong 1981; Froese Fischer 1983; Kaufman & Sugar 1986; Bhatia, Feldman, & Seely 1986a; Verhey, Das, & Perger 1987; Baluja & Agrawal 1995; Galavis, Mendoza, & Zeippen 1998; for F-like ions Krueger & Czyzak 1966; Cheng et al. 1979; Oboladze & Safronova 1980; Kaufman & Sugar 1986; Sampson, Zhang, & Fontes 1991; Bhatia 1994; Baluja & Agrawal 1995; and for Be-like ions Krueger & Czyzak 1966; Oboladze & Safronova 1980; Anderson & Anderson 1982; Glass 1983; Kaufman & Sugar 1986; Bhatia, Feldman, & Seely 1986b; Idrees & Das 1989; Safronova, Johnson, & Derevianko 1999). There also are calculations that implicitly use the transition rate information

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for spectral modeling. However, we will compare our results only with those calculations that yield the testable transition rates explicitly. For the three cases of present interest, the electric quadrupole (E2) contribution to the decay amplitude is lower than the magnetic dipole (M1) amplitude by more than 3 orders of magnitude, and we therefore will disregard the E2 contribution in the rest of this presentation.

Because of the experimental difficulties in producing and measuring long-lived metastable states, there are very few measurements of M1 transition rates in ions of coronal interest. Earlier experiments on Ar were done using an electrostatic (Kingdon-type) ion trap (Yang et al. 1994; Moehs & Church 1998), and electron-beam ion traps (EBIT) at NIST Gaithersburg (Serpa, Gillaspy, & Träber 1998) and Oxford (Back et al. 1998). Here we present a measurement of the transition probabilities of coronal Ar lines in the visible spectrum with results that are significantly more accurate than—and significantly different from—most of the previous results.

2. EXPERIMENT

The measurements were carried out at Lawrence Livermore National Laboratory, using the electron beam ion trap EBIT-2. The actual ion trap region in EBIT was imaged by two *f*/4 10 cm diameter quartz lenses onto a photodetector. We used a low dark rate, half-inch diameter, end-on-cathode photomultiplier (Hamamatsu type R2557 with a 401K spectral sensitivity curve). In this way the photomultiplier could be operated outside the magnetic stray fields of the 3 T superconducting magnets of the EBIT device while at the same time subtending a sizeable solid angle of observation.

For the lifetime measurements, EBIT was operated in a cyclic mode. About every 0.2 s the accumulated ion cloud was purged from the trap. The electron beam was switched on for about 0.13 ms, ionizing and exciting the ion cloud in the trap. Then the electron beam was switched off, and the trap was maintained as a Penning trap in the so-called magnetic trapping mode (Beiersdorfer et al. 1996). The switching time of the electron beam needs to be faster than the lifetime of the level of interest. It was 20 μs in the present measurements, for expected atomic lifetimes in the 10–15 ms range. Nevertheless, the data evaluation was restricted to the part of the decay curves after about the first 1 ms in order to avoid possible stray influences of the switching processes or of ion cloud relaxation on the decay curves.

The true signal rate for Ar X and Ar XIV was as high as 200,000 counts hr^{-1}. In total, more than 10^6 counts above background were accumulated in the decay curve part of the data, corresponding to an overall statistical reliability of better than 0.1%. For Ar XV, the signal rate was lower by more than an order of magnitude, permitting a statistical reliability of order 1%. 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 for each photon signal in an event-mode system. Afterward, the individual signal counts were sorted for their time stamps and accumulated in time bins to construct a decay curve. Since the frequency generator was not synchronized with the trap, this introduces a time jitter of 10 μs that is negligible for lifetime measurements in the millisecond range.

A number of parameters were varied during the experiment in order to investigate their influences as possible systematic error. Each data set was collected until a statistical reliability of better than 0.5% was achieved. A total of 10 such data sets was collected for Ar XIV, 16 data sets for Ar X, and three data sets for Ar XV.

EBIT was operated under ultra high vacuum conditions ($p < 10^{-10}$ mbar), as is ensured by the nearest surfaces being kept at the temperature of liquid He. Ar was being bled into the trap continually, via a leak valve and a set of collimating apertures in a ballistic gas injection system. The injection pressure was varied from 3×10^{-8} mbar to 4×10^{-7} mbar. The overall pressure measured in the chambers above and below the trap region changed very little by this, showing that the gas injection causes only a small contribution to the overall gas load. Gas injection, however, changes the ratio of Ar to other ions in the trap, such as heavy elements which are easily trapped. Because the pressure in the trap region cannot be measured directly, the ion survival lifetime was determined in separate experiments employing charge exchange (Beiersdorfer et al. 1996).

The electron-beam energy was varied from below production threshold of the desired ion (i.e., below the ionization energy of the next lower charge state ion) to a few hundred volts above. In practice, this meant a range of 400–900 eV for Ar X, 730–1100 eV for Ar XIV, and 850–1000 eV for Ar XV. The low-energy measurement in each case was used to assure that no blend with light from lower charge state ions would affect the lifetime measurement. At electron energies barely above threshold, the charge state of interest is the highest one reached, but the production cross section is low and the measurements thus suffer from a relatively poor signal rate. At higher electron-beam energies, the optical signal rate from the desired ion reaches its optimum, but also the next higher charge state(s) may be reached as well. At the highest electron-beam energies, the signal yield drops again because of the reduction of the charge state fraction for the ion of interest.

If the ion storage time is affected by the ion mixture in the trapped ion cloud, there might be a dependence of the storage time, and thus, of the apparent atomic lifetime on the trap depth. Keeping the electron energy constant, the trap potential of 200 V was varied by 10% either way, without any result outside statistical scatter. As the electron beam current under such low-energy conditions (for EBIT) was only of the order of 10–25 mA, no current density variation (as discussed earlier; Träbert et al. 1999b) was deemed reasonable.

Judging from earlier survey spectra (Crespo López-Urrutia et al. 1995), the lines of interest are fairly isolated. Thus, interference filters (4400 and 5500 Å) of typical peak transmission 70% and 100 Å bandwidth (FWHM) were deemed sufficient for spectral selectivity. For Ar X there were also measurements done using a filter of 5700 Å central wavelength and 500 Å bandpass. At electron-beam energies near 500 eV the lifetime results obtained with the wide-band filter were indistinguishable from those using the narrowband filter (although the noise contribution was higher). Increasing the electron energy further toward 900 eV (still working with the wide-band filter), the apparent lifetime dropped by about 3% while the dynamic range of the decay curves (peak-to-tail ratio) dropped from better than 10 to about 2. The M1 transition in Ar XV was expected to be excited at the highest of these energies, but did not appear notably in the wide-band filter decay curves, where the combined curves would have appeared as a lengthening of the decay curve of the Ar X level of interest. The nonappearance of the Ar XV signal results from a combination of the filter limit and the low Ar XV signal level, as was then found in a dedicated search for Ar XV with a proper filter. The low signal level for Ar XV, combined with the stray light level from the incompletely shielded hot electron gun that increases toward the red spectral region, resulted in a poorer signal-to-background ratio in these measurements on the " reddest " of the lines of present interest and hence in a lower statistical significance of the data.

3. DATA ANALYSIS AND RESULTS

Typical decay curve data are shown in Figures 1, 2, and 3. 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. Second decay components, to be associated with either spectral blends or cascade transitions, were searched for using multiexponential fits but were not detected. The observed decay curves represent a superposition of optical decay and ion loss from the trap. In order to obtain the desired optical decay rates, the ion loss rates have to be subtracted from the apparent (total) decay rates. Measured trapping times of close to 0.5 s thus forced systematic corrections of the raw lifetime results by 2%–3%. Half of this correction was assumed as the uncertainty of the correction. This uncertainty also comprises possible level repopulation from recombination events. However, the electron energies chosen always render the charge state of interest as one of the highest, if not the highest. Thus, higher charge state ions are much less abundant, and any recombination into the charge state of interest must be expected to be much less than the typical overall ion loss mentioned before.

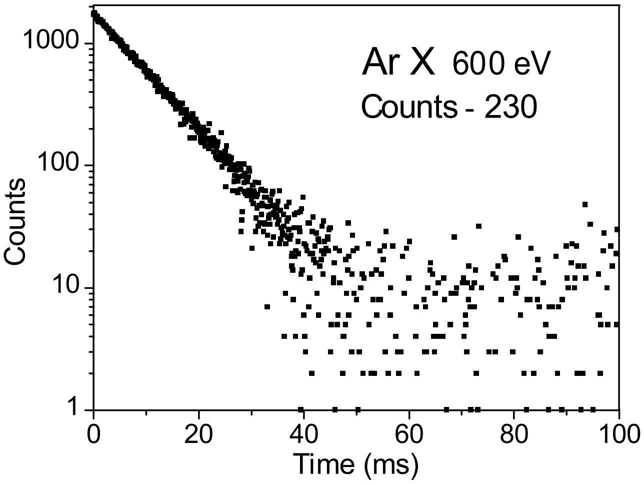

FIG. 1.—Photon signal (logarithmic scale) obtained with Ar X, after the electron beam in EBIT is switched off (magnetic trapping mode). A background of 230 counts per channel has been subtracted from the data.

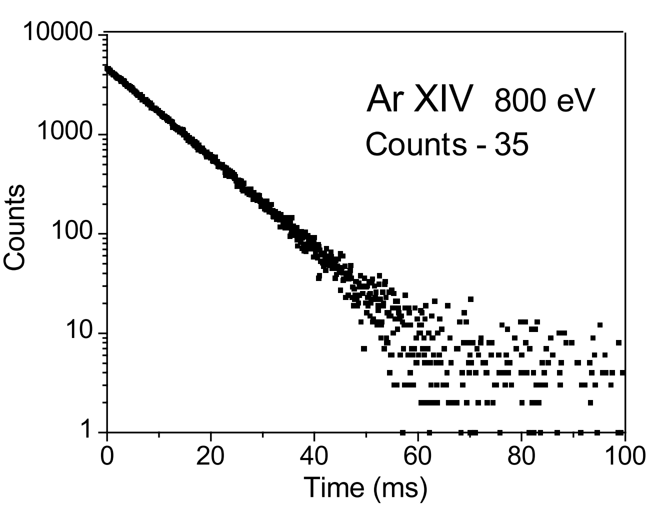

FIG. 2.—Photon signal (logarithmic scale) obtained with Ar XIV. A background of 35 counts per channel has been subtracted from the data.

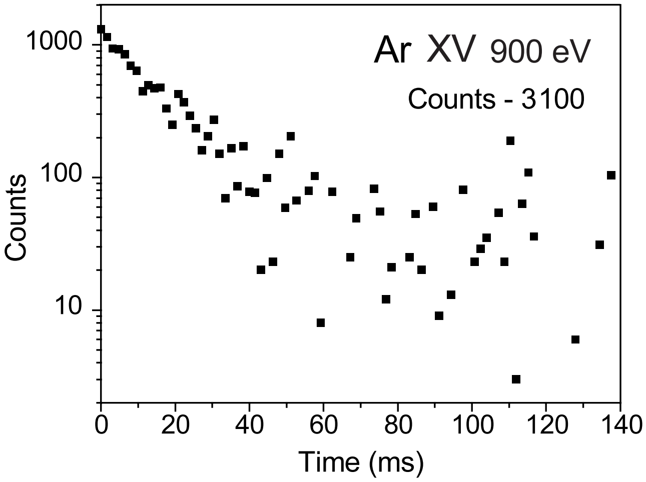

FIG. 3.—Photon signal (logarithmic scale) obtained with Ar XV. A background of 3100 counts per channel has been subtracted from the data, after binning the data over every 16 channels.

The counting statistical uncertainty of most of the individual data sets was typically 0.3%. This is much smaller than the scatter of the lifetime results that spans a band of about 2% width. A similar variation of the fit results was found when truncating early or late parts of the decay curve data (by up to 5 ms) in the search for systematic errors. Apparently there are fluctuations within a given data set that are notable at this level of precision. The cause for these fluctuations that weakly correlate with the peak-to-tail ratio of the decay curves is not yet known. Finding no systematic error that exceeds this range, we therefore adopt the (larger) scatter of the results as a measure of reproducibility and uncertainty. We thus find lifetimes (with 1 σ error estimates) of 9.32 $\pm$ 0.12 ms for Ar X (transition rate 107.3 $\pm$ 1.4 s^{-1}) and of 9.70 $\pm$ 0.15 ms for Ar XIV (transition rate 103.1 $\pm$ 1.6 s^{-1}).

With Ar XV, the experimental options tested involved runs with, and without, gas injection, normal and reversed drift tube voltages (to avoid ion trapping), and vacuum gauges switched on and off. Real signal was obtained only under regular conditions, but some small foreign contribution could not be fully excluded. The three best data sets were fitted with one or two exponentials. The fast one of these showed a time constant of 0.5–1 ms and can be related to switching transients or to the ion cloud relaxation upon switching off the electron beam that provided both an attractive force and some space charge compensation. The slow component, on average, had a characteristic time of 15.0 ± 0.8 ms.

4. DISCUSSION

Our lifetime measurement technique was first developed using X-ray transitions in two electron ions (the M1 transition $1s^2\ ^1S_0$–$1s2s\ ^3S_1$ in N VI to Mg XI) and achieved a precision of better than 0.5% (Crespo López-Urrutia et al. 1998; Träbert et al. 1999b; Neill et al. 2000). That work was in excellent agreement with theory in this case of a well-calculable system. We therefore feel certain that we have all systematic errors under control at the 2% level for optical measurements as well. The new lifetime results for Ar X and Ar XIV lie outside the 1 σ error bars stated for the previous data (Yang et al. 1994; Serpa et al. 1998) and are more precise. The present results for Ar X and Ar XIV agree well with the theoretical expectations (after correction for experimental transition energies), and they fit well to the same isoelectronic trend as the results of heavy-ion storage ring work (Träbert et al. 1999a, 1999c) (see Table 1, Figs. 4 and 5).

As stated (Träbert et al. 1999c), the agreement with theory is very good for the M1 transition in B-like ions, while similar calculations for F-like ions possibly underestimate the transition rate by about 1%–3%. Assuming that systematic errors would work similarly for both ions, the present measurement is particularly suited to check on this since the predicted lifetimes for B- and F-like ions of Ar (with the level lifetime in the B-like ion being the longer one) differ by only 2% (Cheng et al. 1979). Interestingly, the ab initio calculational results from this source show the F-like ions as the longer lived ones, and only after the experimental wavelength correction the prediction correctly indicates that the B-like ions are the longer lived ones. The presently observed experimental lifetime difference is almost twice as large as predicted. As found with data from the heavy-ion storage ring, the theoretical shortcomings seem to lie more with the F-like ions than with the B-like ions. Although superficially both transitions are similar $2p$–$2p$ transitions, the case with more electrons seems less successfully treated by computation so far.

TABLE 1

COMPARISON OF PREDICTED AND MEASURED LIFETIMES (τ) FOR THE UPPER LEVELS OF THE GROUND CONFIGURATION IN Ar X AND Ar XIV

τ (ms)	Trap Type[a]
Ar X $2s^22p^5\ ^2P^o_{1/2}$	
Theory:	
9.52[b]	
9.58[c]	
9.44[c,d]	
9.43[e]	
Experiment:	
8.53 ± 0.24-0.17[f]	EKT
8.70 ± 0.37[g]	EKT
9.32 ± 0.12[h]	EBIT (at LLNL)
Ar XIV $2s^22p\ ^2P^o_{3/2}$	
Theory:	
9.30[b]	
9.41[c]	
9.57[c,d]	
9.51[i]	
9.62[e]	
9.62[j]	
9.36[k]	
9.57[l]	
Experiment:	
8.7 ± 0.5[m]	EBIT (at NIST)
9.12 ± 0.18[g]	EKT
9.70 ± 0.15[h]	EBIT (at LLNL)

[a] EBIT Electron beam ion trap, EKT Electron cyclotron resonance ion source plus Kingdon ion trap.

[b] Krueger & Czyzak 1966.

[c] Cheng et al. 1979.

[d] Theory results adjusted for experimental transition energy.

[e] Kaufman & Sugar 1986.

[f] Yang et al. 1994.

[g] Moehs & Church 1998.

[h] This work.

[i] Froese Fischer 1983.

[j] Verhey et al. 1987.

[k] Bhatia et al 1986a.

[l] Galavis et al. 1998.

[m] Serpa et al. 1998.

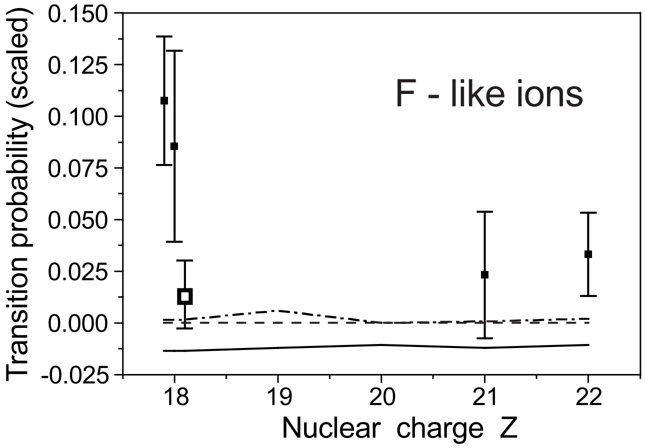

FIG. 4.—Transition rate data for the transition in the $2s^22p^5\ ^2P^o$ ground state of F like ions. The open-symbol experimental data for Ar ($Z = 18$) are from this work, the others are from (Yang et al. 1994; Moehs & Church 1998: Ar), (Träbert et al. 1999a Sc, $Z = 21$), and (Träbert et al. 1999c: Ti, $Z = 22$). All data shown represent the (normalized) difference to the semiempirically corrected theory data by Cheng et al. (1979).

The early EBIT data (Serpa et al. 1998) as well as the results from the electrostatic ion trap (Moehs & Church 1998) lie farther away from the theoretical trend than the new data do. The uncertainty of our results is close to the 1% scatter of the various predictions, but the new experimental data are clearly more precise than those calculations that carry uncertainty estimates, if stated at all, of no less than 10%. The new data also reveal a small, but distinct, lifetime difference between the upper fine-structure levels of the ground terms in B-like Ar XIV and F-like Ar X, a difference that is much smaller than the overall theoretical uncertainty.

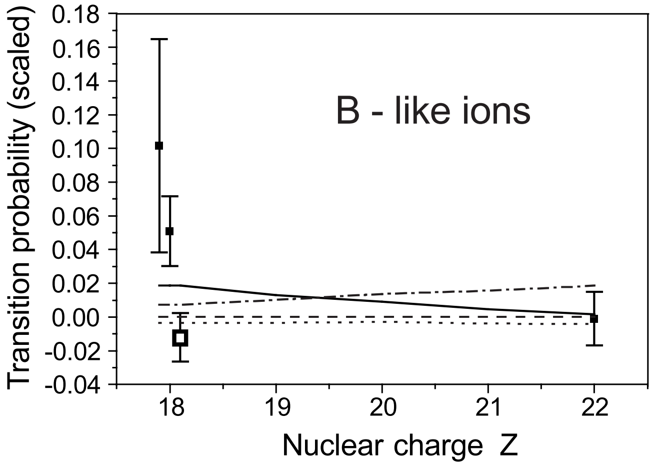

FIG. 5.—Transition rate data for the transition in the $2s^22p\ ^2P^o$ ground state of B like ions. The open-symbol experimental data for Ar ($Z = 18$) are from this work, the others for Ar are from an electrostatic ion trap (Moehs & Church 1998) and from another electron beam ion trap (EBIT) (Serpa et al. 1998); the data for Ti ($Z = 22$) are from a heavy-ion storage ring (Träbert et al. 1999c). All data shown represent the (normalized) difference to the semiempirically corrected theory data by Cheng et al. (1979).

When comparing the 15.0 ± 0.8 ms lifetime result for the Ar XV $2s2p\ ^3P^o_2$ level (that coincides perfectly with the Oxford EBIT result (Back et al. 1998)) with the inverse of the predicted M1 decay rates (Table 2), one has to keep in mind that the M1 decay is not the only decay branch, even though, with a calculated branch fraction of 0.988 (Tunnell & Bhalla 1979), it is the dominant one by far. The difference of 1.2% is of the magnitude of our measurement uncertainty, and thus, does matter. Out of the various predictions we chose to compare only with those that give numbers for Ar XV (no extrapolations or interpolations). As not all theoretical results are corrected for experimental energies, we quote the ab initio M1 rates except where already converted by the authors. The predictions for the M1 rate cluster near 65 s^{-1}, with the exception of a single prediction (Idrees & Das 1989) that deviates by about 50% from this range.

TABLE 2

PREDICTED AND MEASURED LIFETIMES (τ) FOR THE $2s2p\ ^3P^o_2$ LEVEL IN AR XV

A (s^{-1})	τ (ms)	Trap type[a]
Theory:		
62.45	15.8[b]	
65.9	15.2[c]	
63.3	15.6[d]	
63.8	15.5[e]	
64.3	15.4[f]	
105	9.41[g]	
64.0	15.4[h]	
63.8	15.5[h i]	
Experiment......	13.4 ± 0.7[j]	EKT
	15.0 ± 0.7[k]	EBIT (at Oxford)
	15.0 ± 0.8[l]	EBIT (at LLNL)

NOTE.—The theoretical M1 transition rate values A for the $^3P^o_1$–$^3P^o_2$ transition ($\lambda = 5943.73$ Å (Bieber et al. 1997)) have been converted to the upper level lifetime τ by taking the 1.2% M2 ground state decay (Tunnell & Bhalla 1979) into account.

[a] EBIT Electron beam ion trap, EKT Electron Cyclotron Resonance ion source plus Kingdon ion trap.

[b] Krueger & Czyzak 1966.

[c] Tunnell & Bhalla 1979.

[d] Glass 1983.

[e] Oboladze & Safronova 1980.

[f] Bhatia et al. 1986b.

[g] Idrees & Das 1989.

[h] Safronova et al. 1999.

[i] Theory results adjusted for experimental transition energy

[j] Moehs & Church 1998.

[k] Back et al. 1998.

[l] This work.

With so many different calculations yielding results that closely spaced, it was indeed surprising when an electrostatic ion trap experiment (Moehs & Church 1998) gave a clearly different lifetime value. In fact, in the light of improved calculations that did not corroborate those experimental findings, the authors of that study revisited the case and discussed possible systematic error sources but did not find any significant clues to the discrepancy (Church, Moehs, & Bhatti 1999). Because of the aforementioned low signal level from the decay of the excited configuration level (a similar observation has been made in the Kingdon trap experiments; Church et al. 1999), our experimental result is not statistically better than theirs. However, we believe that we have our systematic errors under better control. Our result turns out to be closer to the range of the predictions, and the 1 σ error bar overlaps with the latest calculational results (Table 2). Our result also agrees fully with that obtained at the Oxford EBIT, where a more complex experimental scheme employs a laser (Back et al. 1998). The previously claimed 3 σ discrepancy of Ar XV with theory (Moehs & Church 1998) is therefore not confirmed. Theory instead is corroborated at the 5% level of our present experiment for an excited configuration, and to better than 2% for the ground complex in Ar X and Ar XIV.

5. CONCLUSION

All three of the EBIT results presented in this study differ from the Kingdon trap data in the same way, by about 10% toward longer lifetimes. Furthermore, our results are isoelectronically supported by those from the heavy-ion storage ring technique with its particularly small systematic errors. We therefore conclude that the systematic errors of the present EBIT lifetime measurements are significantly smaller than those of the recent Kingdon trap experiments. Theoretical predictions of M1 transition rates in few electron ions are fully corroborated by our data, and the usual theoretical uncertainty estimates of 10%–20% are shown to be too conservative, as experiment confirms the theoretical results to be more reliable than that by an order of magnitude.

We are happy to acknowledge the dedicated technical support by Dan Nelson, Jeff Van Lue, and Phil D'Antonio and the loan of the photomultiplier by Lukas Gruber. The work at Lawrence Livermore National Laboratory was performed under the auspices of the Department of Energy under contract W-7405-Eng-48. E. T. acknowledges travel support from the German Research Association (DFG). D. W. S is supported by NASA High Energy Astrophysics X-Ray Astronomy Research and Analysis grant NAG 5-5123. Martin Laming deserves thanks for valuable comments and for pointing out the Oxford EBIT result.

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